UNIVERSITY OF CALIFORNIA
RIVERSIDE

Perceptual Learning, Aging, and Attention: Theoretical and Applied Studies

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Psychology

by

Kieu Ngoc Nguyen

September 2020

Dissertation Committee:
Dr. G. John Andersen, Chairperson
Dr. Chandra A. Reynolds
Dr. Aaron R. Seitz

The Dissertation of Kieu Ngoc Nguyen is approved:

Committee Chairperson

University of California, Riverside

Acknowledgements

First and foremost, to my loving partner and middle-school sweetheart, Viet, who has been the most incredibly supportive partner. It has been such an adventure growing with you and to share both in our successes and failures. I am so deeply grateful for all that you do for our family. Thank you for all the times that you have taken me to school, taken care of me when I was too busy or forgetful to eat, checking up on me when I was awake late into the night, and comforting me when I was overwhelmed. These have not gone unnoticed! How'd I get so lucky?! I love you forever and ever and look forward to our future endeavors together!

I am so incredibly blessed to have my sweet daughter, Amanda, who all her life has only ever known me to be a student. Thank you for suffering through all of my presentations. Your cheeky humor and your quick wit have been such a bright light in my life. You inspire me and have been such a driving force for me to be the best I can be for you. And for that, I am so grateful beyond words for the influence you have on me. Thank you, my little love.

To my wonderful family members who have been a great source of relief from my graduate studies. My wonderful sisters, Jackie, Jennifer & Jessica, for always checking in on me. You are the best friends and best cheerleaders a sister could ask for! And without fail, at every family gathering, my family members always ask, "you're still in school?!" I can finally answer, no – they finally kicked me out, I'm PhDone! ☺

To my dissertation committee members, Chandra Reynolds and Aaron Seitz, thank you for sharing your insights and feedback. I consider myself fortunate to have had the opportunity to learn from two leading experts in their respective fields.

I am also grateful to all the individuals I have met along the way that have contributed to my development in graduate school and have made it an enjoyable experience. The members of the Visual Cognition and Human Performance laboratory. Special thanks to Ben Miller, my lab mate, it has been an enjoyable experience navigating graduate school with you. Your friendship has been invaluable over the years in graduate school together. Thank you to my wonderful team of research assistants for their help with the lab and with data collection.

My deepest gratitude to the most incredible advisor, John Andersen, whose work inspired me to pursue graduate school. For the level of dedication and commitment to my development as an academic scholar. You are the epitome of what it means to be a great academic advisor, careful scientist, and leading scholar. Thank you for sharing your wealth of knowledge, your wisdom and for your incredible patience with me. More importantly, thank you for trusting me with this endeavor. It has been a great honor and privilege to have been mentored by you.

Of course, I cannot forget to thank the participants of these studies. This research would not be possible without the participants who dedicated their time to coming into the lab and their contribution to this dissertation.

Funding Sources

University of California Center on Economic Competitiveness in Transportation (UCCONNECT)

ABSTRACT OF THE DISSERTATION

Perceptual Learning, Aging, and Attention: Theoretical and Applied Studies

by

Kieu Ngoc Nguyen

Doctor of Philosophy, Graduate Program in Psychology
University of California, Riverside, September 2020
Dr. George John Andersen, Chairperson

Perceptual learning (PL) is experience-dependent enhancement of our perceptual abilities. These enhancements can occur well into adulthood and thus reflect an inherent property of our perceptual systems. The expression of these enhancements can be modulated by attention. Recent research has focused on how attention modulates learning that may be informative for the development of training interventions aimed at rehabilitation. The present dissertation examined the effect of attention on perceptual learning in the context of aging in simple and complex perceptual tasks. Three studies organized into three chapters were conducted to investigate different facets of the role of attention in PL. The first study examined the effect of exogenous and endogenous attention in task-relevant PL and feature specificity. Younger adults were trained, over the course of two days, in a novel paradigm that involved detection of the presence of an additional sinewave. Participants were randomized into one of six attention by cue-validity conditions. The findings for the first study indicate rapid generalized learning irrespective of the type of attention trained. The second study examined the role of endogenous attention in PL and location transfer in the context of aging. Older and younger adults participated in a low-level perceptual orientation discrimination task, over the course of 6 sessions, and were trained with either valid or neutral cues. The findings of the second study suggest different patterns of learning and location transfer between age groups, which may indicate engagement of different mechanisms. The third study examined the effect of attention and aging in PL in the context of a high-level complex perceptual driving paradigm. Older and younger adults participated in a dual-task collision detection and steering control task, over the course of 5 sessions, and were trained with either valid or neutral cues. The findings in the third study suggest attention-related training on collision detection in a driving context improves the detection of and provides additional time needed to respond to collision objects. The findings in this dissertation regarding the role of attention and aging in PL are informative for the development of theory and for applied considerations for improving driving performance.

Table of Contents

Appendix C: **Chapter 3 Statistical Details**

List of Figures

Chapter 3: Aging, perceptual learning and attention on driving performance

List of Tables

General Introduction

Early research on the development of the visual system established the concept of a critical period in which the functional properties of the brain is especially sensitive to and modifiable by experience during a restricted period of development. A series of influential experiments by Hubel and Wiesel (Hubel & Wiesel, 1970; Wiesel & Hubel, 1963) demonstrated functional blindness in kittens after visually depriving one eye for the first few months of postnatal life. Remarkably, visually depriving one eye in adult cats for a year or more had no effect on visual processing when testing the re-opened eye. This suggested that visual cortical plasticity was restricted to the critical period in early development after which the visual system would be hard-wired in adulthood.

However, research on perceptual learning challenged the notion that experience-dependent plasticity is limited to a critical period in early development. Perceptual learning (PL) is defined as perceptual improvement via training or repeated exposure on some perceptual task. These perceptual improvements have been found to be long-lasting (Crist, Li, & Gilbert, 2001; Sagi & Tanne, 1994; Ball & Sekuler, 1981) and can result in changes in neural processing, known as neural plasticity (Yotsumoto, Watanabe, & Sasaki, 2008; Mukai et al., 2007). In the laboratory, PL is commonly assessed by training participants on some perceptual task. The amount of training varies with thousands of trials over a course of several days or weeks. Though rapid learning has been found over several hundred trials (Fiorentini & Berardi, 1980). Learning is measured by comparing changes in performance or neural activity before and after training. There are numerous behavioral and neurophysiological evidence that the adult visual cortex is also capable of experience-dependent plasticity (see Gilbert & Li, 2012, for review). And so, plasticity seems to be an inherent property of the perceptual system in the service of development and optimization.

PL is not limited to the visual domain having been found in other sensory modalities such as audition, tactile, olfactory, and taste. Yet, extensive research has been focused in the visual domain and so the research discussed here will be in vision. In the study of visual PL, improvements have been found along basic visual dimensions such as retinal location (Karni & Sagi, 1991; Fiorentini & Berardi, 1980), orientation (Dosher & Lu, 1998; Schoups et al. 1995; Vogel & Orban, 1985), spatial frequency (Fiorentini & Berardi, 1981), contrast (Adini et al. 2004), vernier acuity, and motion (Ball & Sekuler, 1981;1987).

Research on PL has revealed a diverse set of findings that make it difficult for a single theory of PL. Much of the debate has centered on issues regarding the specificity of PL, locus of learning, and the type of PL. Specificity – which is failure for trained performance benefits to transfer or generalize to an untrained stimuli or task– was initially thought to be a defining characteristic of PL. But subsequent evidence found that variations in the training paradigm could influence the manifestation of specificity or transfer. Long training trials (Jeter, Dosher, Liu & Lu, 2010), fine discriminations (Jeter, Dosher, Petrov, & Lu, 2009) and task difficulty (Ahissar & Hochstein, 1997; Liu, 1999) all contribute to specificity. Generalization is typically found for tasks that employ easy training (Ahissar & Hochstein, 1997, 2004), shorter training sessions (Jeter et al. 2010), shorter training trials (Aberg, Tartagla, & Herzog, 2009), variation in the training procedure as in double-training (Xiao, Zhang, Wang, Klein, Levi & Yu, 2008) or training-plus-exposure (Zhang, Zhang, Xiao, Klein, Levi, Yu, 2010). Specificity and generalization may be thought of as being along a continuum, either of which could theoretically be the ideal learning solution depending on the training conditions (Green & Bavelier, 2012).

PL research is not only important to understanding learning in visual processing and learning in general, it is also important as a practical application in perceptual expertise and perceptual deficits. Elucidating the mechanisms that underlie learning has important implications for the development and application of PL in clinical and practical settings. Those suffering from visual disorders, such as macular degeneration (Baker et al., 2005), presbyopia (Polat, Schor, Tong, Yomet, Yehezkel, Sterkin, & Levi, 2012; Polat, 2009) or amblyopia (Levi & Li, 2009; Levi, 2005; Polat, Ma-Naim, Belkin, & Sagi 2004; Levi & Polat, 1996), myopia (Yan, Zhou, Zhao, Li, Xi, Lu, & Huang, 2015; Durrie & Mcminn, 2007) might benefit from PL. Many aspects of early visual processing decline with normal aging. Improvements in older adults' visual function have been found in a number of PL training studies indicating the utility of PL in ameliorating age-related declines in visual function (Bower Watanabe, & Andersen, 2013; Bower & Andersen, 2012; Andersen, Ni, Bower & Watanabe, 2010; Ball & Sekuler, 1986). These declines in early sensory processing involve spatial vision, contrast sensitivity, orientation, and motion, all of which are important for higher-level visual tasks such as driving (Andersen, 2012).

Although most literature in PL focus on improving aspects of early-level visual function, there are studies that focus on improving higher-level perceptual tasks such as batting performance in college baseball players (Deveau & Seitz, 2014), action video-gaming (Green, Li & Bavelier, 2010), radiology (Sowden et al. 2000), and collision detection (Lemon, Deloss & Andersen, 2017; Deloss, Bian, Watanabe & Andersen, 2015). The ability to detect an impending collision is one driving-relevant, high-level perceptual task. There are a number of scenarios in which collision events can occur: driver motion into static objects, object motion into static drivers or collisions involving both object and driver motion. Failure to successfully detect a collision in any of these scenarios could result in potentially fatal consequences not only for the driver but for others in or around the roadway as well. The National Highway Traffic Safety Administration (NHTSA) reported in 2016, 7,277,000 motor vehicle crashes with 5,014,000 involving another vehicle. Of the crashes involving another motor vehicle, 32.6% were rear-end collisions, 20.9% were collisions when turning, and 2.6% were head-on collisions. Previous research on collision detection reveal multiple factors that can impact one's ability to detect an impending collision. Increased speed (Andersen & Enriquez, 2006) and multiple objects in a scene (Andersen & Kim, 2001) can reduce one's ability to detect a collision. In addition, there are age-related differences in collision judgments during deceleration; with older adults, as compared to younger adults, exhibiting decreased sensitivity in detecting collisions as well as older adults, as compared to younger adults, more likely to report a collision event when no such collision event was present (Andersen, Cisneros, Saidpour & Atchley, 2000).

An important issue for research is identifying potential ways to reduce crash risk by examining drivers' ability to detect impending collisions. Deloss, Bian, Watanabe and Andersen (2015) found that collision detection can be improved with training, which translates to approximately 750ms of additional time for a driver to react to an impending collision. These performance improvements also transferred to untrained higher observer speeds, with speeds typically associated with decreased sensitivity to detect collisions. Older adults have been found to benefit from such training as well (Lemon, Deloss & Andersen, 2017). This is important considering older adults show declines in the ability to detect a collision, require more time to respond appropriately, and have greater difficulty driving at higher speeds (Lemon, Deloss & Andersen, 2017). The relationship between crash involvement and driver age is a U-shaped function; with crash rates higher for older and younger drivers (Sanders & McCormick, 1993).

Driving, though, does not only involve detecting collisions. It involves performing several tasks at a time; such as monitoring traffic signals, maintaining lane position, monitoring the car in front of you and maintaining a safe distance from it. But there are inherent limits to our ability to attend and process visual information. Drivers may be operating at or beyond their visual capabilities. Previous research has shown limitations in directing attention (Posner, 1980; Posner, Nissen, & Ogden, 1978), spatial resolution (Eriksen & Yeh, 1985; LaBerge, 1983), and visual search (Treisman & Gelade, 1980). The driver must prioritize aspects of information in the environment that are behaviorally important or based on when the situation demands.

Despite the ability of the visual system to adapt to its changing environment, constraints are needed to protect the system from continual modification and change. Acquisition or gating of learning has been found to occur in one of two ways --- through reinforcement or attention. With reinforcement, learning occurs through spatially diffuse signals that enhance incoming sensory signals irrespective of whether the feature is task-relevant or task-irrelevant (Seitz & Watanabe, 2005). This form of passive learning, in which mere exposure to a stimulus within the visual field, facilitates both task-relevant PL (TR-PL) or task-irrelevant PL (TI-PL). TR-PL is defined as PL of a feature relevant to a given training task. TI-PL is defined as PL of a feature irrelevant to a given training task (Seitz & Watanabe, 2005). By comparison, attention selects what is behaviorally relevant and thus what is learned on a task.

It is important to note that the vast amount of information in the environment can overwhelm the brain's limited processing capacity. It is assumed that this capacity limit arises from a limited but unspecified pool of cognitive resources (Kahneman, 1973). And so, the limited resources must be allocated to select information among multiple inputs. One aspect of attention is that it is a selective process by which aspects of information is prioritized over others thereby guiding learning and behavior. Selection could be achieved by allocating attention spatially to enhance processing of selected regions without eye movements. Two types of attention may be relevant for PL--- exogenous and endogenous attention.

Exogenous, or bottom-up, attention is a passive, transient, automatic, stimulus-driven process. Peripheral cues, presented near or at target stimuli, used to guide exogenous attention could be automatically captured by salient stimuli. With exogenous attention, feed-forward signals propagate from lower sensory areas to higher cognitive processing areas. Exogenous attention is driven by properties of a stimulus- such as color, orientation, luminance, inadvertently goes against the intentions of an observer (Yantis & Jonides, 1990; 1984; Jonides & Yantis; 1988), is deployed when salient novel stimuli are presented (Yantis & Hillstrom, 1994; Yantis, 1993), and is often difficult to ignore (Jonides, 1981). It can be triggered reflexively by a salient sensory event, such as a flash in the periphery. It works via signal enhancement of relevant signals (Lu & Dosher, 2000;1998). The time course of the shift of attention to an exogenous cue is approximately 100-120ms (Theeuwes, 2010; Cheal and Lyon, 1991; Nakayama & Mackeben, 1989).

Endogenous, or top-down, attention is a voluntary, sustained, goal-driven process. Information that aligns with an observer's behavioral goals are internally selected for further processing. It involves a more effortful process such as being instructed to orient attention to a particular location. The capture of attention is contingent upon top-down attentional control, a phenomenon known as contingent capture (Folk, Remington & Johnston, 1992). Posner (1980) demonstrated an endogenous cueing paradigm in which participants *willfully* directed attention to a particular spatial location. A centrally presented symbolic cue, an arrow, would indicate the possible location of a subsequently presented target. The endogenous cue could point to the location of the target (valid trial), point away from the location (invalid trial), or give no indication to the location of the target (neutral trial). Performance is typically faster, more accurate, or both for valid trials than for invalid trials and neutral trials. The source of endogenous attention is proposed to be through recurrent feedback connections that descend from higher cortical processing areas to lower sensory processing areas. Endogenous attention operates via signal enhancement of relevant signals and external noise reduction of irrelevant signals (Lu & Dosher, 2000). Depending on task demands, endogenous attention can override or even reverse the effects on neural activity. Crist, Li and Gilbert (2001) had monkeys perform a task at fixation while surrounded by previously trained stimuli. Cells initially enhanced when the previously trained stimuli were task-relevant were now being suppressed. This was thought to reflect that the previously trained stimuli were actively competing with the task-relevant stimuli now being presented at fixation. The time course of the shift of attention to an endogenous cue is approximately 300ms (Carrasco, 2011).

Although both types of attention share common perceptual effects (Suzuki & Cavanagh, 1997; Hikosaka, Miyauchi, & Shimojo, 1993), each is capable of affecting information processing in distinct ways (for extensive list of unique perceptual effects see Carrasco, 2011). These two types of attention may differentially modulate perceptual processes. As a result, the effect on performance is likely to vary in accordance with the type of attention that is engaged. For instance, the benefits and costs in discriminability and processing speed differ between exogenous and endogenous attention (Giordiano, McElree & Carrasco, 2009). For endogenous attention, benefits and costs increased with cue-validity whereas for exogenous attention, benefits and costs were constant across cue-validity. In conditions of external noise, exogenous attention enhance contrast sensitivity under both low- and high- noise conditions whereas endogenous attention works under high-noise conditions (Lu & Dosher, 2000;1998). Whereas endogenous attention is susceptible to interference and requires more cognitive resources, exogenous attention does not (Muller & Rabbitt, 1989; Jonides, 1981; Posner et al. 1978). The earliest stage of visual cortical processing is enhanced by exogenous attention whereas endogenous attention impacts later stages of processing (Hopfinger & West, 2006). Furthermore, endogenous attention may be maintained at a location for extended periods. On the other hand, exogenous attention exhibits inhibition of return, such that there is delay in responding from exogenous orienting after initial facilitation at same cued location (Posner & Cohen, 1984).

In the context of aging, there is evidence for age-related changes in attention. With increased age, there is an associated reduction in the processing speed to which older adults can successfully execute processing operations in a limited time (Salthouse, 1996). In studies of visual search, older adults are often slower and less accurate (Whiting, Madden, Pierce, & Allen, 2005; Madden & Whiting, 2004; Plude & Doussard-Roosevelt, 1989). Given exogenous attention is driven by sensory factors or physical characteristics/features of the environment, it is difficult to entirely separate sensory and attentional functioning since any declines in sensory processing will likely impact higher-level cognitive functions such as visual attention. One common measure of sensory processing is the contrast sensitivity chart. The contrast sensitivity chart is a reliable and sensitive measure of spatial vision. It measures a person's visual sensitivity to a wide range of target sizes (Sekuler, Owsley & Hutman, 1982). The sizes correspond to varying spatial frequencies. It was found that there are significant declines on intermediate and high spatial frequencies with older adults, approximately age 60. Older adults, then, could suffer from degraded representations of their environment due to the inability to resolve fine details. This could be further exacerbated when older adults have to see under low luminance conditions such as night-time or inclement weather. It is possible that any declines in sensory processing likely impact the ability to perform any early-level perceptual task when attention is engaged.

For age-related declines in endogenous attention or top-down attention, older adults show greater activation than younger adults on top-down attentional mechanisms, supported by the fronto-parietal network, which may reflect compensatory recruitment (Madden et al. 2007). Even under conditions that do not lead to a pronounced age-related decline in occipital activation, older adults show greater activation than younger adults on top-down attentional mechanisms. Greater reliance on frontal and parietal regions as compensation for bottom-up deficits may be counterproductive as these regions are more susceptible to age-related declines (Madden 2007; Madden, Spaniol, Whiting, Bucur, Provenzale, Cabeza, White, & Huettel, 2007; Raz, Lindenberger, Rodrigue, Kennedy, Head, Williamson, Dahle, Gerstorf, & Acker, 2005); Salat, Tuch, Hevelone, Fischl, Corkin, Rosas & Dale, 2005). One possible explanation may be that of task complexity. It could be that older adults may successfully emulate performance of younger adults for relatively easy tasks but when tasks become sufficiently difficult, only then will performance differences be more salient. It was found in studies of divided attention that older adults have greater difficulty dividing their existing resources under conditions of task complexity (Salthouse, Fristoe, Lineweaver, & Coon, 1995; McDowd & Craik, 1988). Another possible explanation as to why older adults show over-utilization of top-down processes may be accounted for by increased random firing due to decreased cortical inhibition. Decrease efficiency in cortical inhibition has been implicated in single-cell recordings in senescent rhesus monkeys (Schmolesky, Wang, Pu, & Leventhal, 2000). It was found that decreased selectivity and increased excitability of cells in older monkeys were consistent with an age-related degeneration of intra-cortical inhibition. Increased activation in top-down attentional processes may reflect declines in cortical inhibition. Older adults exhibit difficulty in inhibiting/ignoring irrelevant information known as attentional inhibition. Older adults are more susceptible to distracting effects of irrelevant and interfering stimuli (Sekuler & Ball, 1986). Two paradigms yield consistent support for age-related declines in inhibitory function; Stroop tasks (Stroop, 1935) and stop-signal tasks. For the Stroop task, older adults had significantly high response times as compared to younger adults, which indicate that there is a decrease in the efficiency of inhibitory processing due to increased susceptibility of interference from irrelevant information (Spieler, Balota, & Faust, 1996; Hartley, 1993). Variants of the stop-signal paradigm demonstrated that older adults, as compared to younger adults, were slower to abort a physical response once initiated which has been interpreted as failure in attentional inhibitory control (Bedard, Nichols, Barbosa, Schachar, Logan, & Tannock, 2002; Kramer, Humphrey, Larish, Logan, & Strayer, 1994). According to Kraemer et al. (1994), the Stroop and stop-signal tasks seem to be mediated by the frontal lobe which is associated with attentional processing.

In addition to inhibitory declines, there are age-related declines in the spatial extent of attention. A standard test for spatial attentional processing in older adults is the Useful Field of View (UFOV) (Ball, Beard, Roenker, Miller, & Griggs, 1988). The UFOV test has three subtests for three different attentional abilities: subtest 1 for processing speed, subtest 2 for divided attention, and subtest 3 for selective attention. Older adults, as compared to younger adults, consistently showed larger deficits in the divided-attention task of the UFOV (Sekuler, Bennett, & Mamelak 2000; Sekuler & Ball, 1986). Declines in spatial extent of attention were evident in early adulthood (approximately 20 years of age and younger) and decade-by-decade, steadily increased with increasing age (Sekuler, Bennett & Mamelak, 2000). Notably, the UFOV is a useful predictor of driving performance (Sims, McGwin, Allman, Ball, & Owsley, 2000). This is of interest given that the population over the age of 65 will more than double by 2050 (Houser, Fox-Grage, & Ujvari, 2012) and that older drivers have a greater crash risk (Tefft, 2008).

Previous research has shown that the UFOV could change as a function of age and training (Ball, Berch, Helmers, Jobe, Leveck, & Marsiske, 2002; Ball et al., 1988; Sekuler & Ball, 1986). One such study directly assessed the effects of aging and training on the cost associated with divided attention by comparing focused-attention to divided-attention (Richards, Bennett, & Sekuler, 2006). Richards, Bennett, and Sekuler (2006) demonstrated that training with UFOV resulted in improved performance in divided attention for older observers. They found that the spatial extent of the UFOV increased (indicating greater function of divided attention) for older adults following 4 days of training and the improvement was retained for up to 3 months.

In fact, training may optimize the effectiveness of top-down attention control (see Byers & Serences, 2012). Training on a high-level perceptual task such as action video games have been found to improve many aspects of attention (refer to Green & Bavelier, 2012), and could translate to changes in UFOV in college-aged adults (Green & Bavelier, 2006; 2003; Achtman, Green, & Bavelier, 2008) as well as older adults (Belchior, Marsiske, Sisco, Yam, Bavelier, Ball, & Mann, 2014). Improving attentional control via training could induce plasticity in local connections so that intervention by top-down attentional modulations can be minimized. In line with this, studies have demonstrated reduction in the magnitude of activation, following training, in areas of the frontoparietal cortex commonly thought to mediate attentional control (Mukai et al., 2007; Sigman, Pan, Yang, Stern, Silbersweig, & Gilbert, 2005). This suggests that, initially, top-down attentional control is recruited but through the course of training its effect becomes minimized. This may explain why video game players, who score high on various attentional measures, show greater rates of learning on novel tasks as compared to non-video game players (Green & Bavelier, 2012).

Attention has often been argued as an important component of PL. One study assessed varying effects of exogenous and endogenous attention on TR-PL (Mukai, Bahadur, Kesavabhotla, & Ungerleider, 2011). Both attentional cues were found to increase in accuracy, but only exogenous attention was found to result in lower contrast thresholds. Although this finding might suggest that the type of attention modulates PL via distinct mechanisms, attentional cues were not systematically varied as participants were exposed to all validity cues, attended, divided-attended, and neutral, and thus make it difficult to assess the effect of attention. One such study did experimentally isolate the effect of exogenous attention on PL (Szpiro & Carrasco, 2015). Learning was found when participants were trained with exogenous attentional cues as compared to neutral cues. Additionally, transfer of training was assessed for an untrained task and untrained feature and found learning only transferred to an untrained task. For location transfer, training with exogenous attentional cues facilitated transfer to untrained locations within and across visual hemifields whereas training with neutral cues exhibited location specificity (Donovan, Szpiro, & Carrasco, 2015). A subsequent study, but with endogenous attention, also found transfer to untrained locations within and across visual hemifields whereas training with neutral cues exhibited location specificity (Donovan & Carrasco, 2018). Despite similar performance improvements, distinct mechanisms underlie facilitation of location transfer with exogenous attention operating via response gain (Donovan, Szpiro, & Carrasco, 2015) and with endogenous attention operating via contrast gain (Donovan & Carrasco, 2018). These mechanisms are thought to reflect neuronal activity as a function of stimulus contrast, which creates a contrast response function (Reynolds & Heeger, 2009). Attentional modulation via contrast gain leads to an increase in contrast sensitivity with no change in the relative firing rate. Whereas, response gain leads to a multiplicative increase in firing rate across the contrast response function with no change in threshold. Altogether, these findings demonstrate a role, albeit complicated, of the type of attention in PL.

The extensive literature on PL has resulted in several different models that considered the role of attention. These models differ in terms of several different factors that include what cortical area is activated, the degree of specificity of PL, and the type of PL. The Reverse Hierarchy Theory (Ahissar & Hochstein, 2004; 1997; Hochstein & Ahissar, 2002) assumes learning is a top-down attention-guided process. According to this model, the locus of learning starts at higher processing areas that enable learning on tasks that involve coarse discrimination. Learning cascades to lower processing areas for tasks that require fine discrimination. Specificity, thus, arises from extensive training that enable access to lower level processing sites. This theory assumes that top-down attention is required for the occurrence of PL and does not account for findings regarding TI-PL.

Dual-Plasticity theory posits learning can occur in the presence of or absence of attention (Shibata, Sagi & Watanabe, 2014; Watanabe & Sasaki, 2015). This theory proposes two types of plasticity; task-based plasticity and feature-based plasticity. Feature-based plasticity is defined as changes in the representation of features and stems from changes in early-level sensory areas. The sensory areas changed in association with feature-based plasticity will depend on the feature that is being trained. For instance, training with primitive features such as spatial frequency or orientation should be induce changes in V1. Feature-based plasticity results from mere exposure to a feature during training irrespective of whether the feature is task-relevant or task-irrelevant and is specific to the exposed feature or trained location. It occurs in both TR-PL and TI-PL. Task-based plasticity is defined as changes in processing related to a trained task. It stems from involvement on a trained task, occurs only in TR-PL, and is specific to the trained task. Task-based plasticity will be associated with changes in high-level cognitive processing areas or connectivity between visual and cognitive processing areas. Evidence for two types of plasticity, that occur in different cortical regions, has been found in neuroimaging studies suggesting that, to some degree, separate mechanisms exist (Shibata, Sasaki, Kawato, & Watanabe, 2016).

Given the findings reviewed here, the purpose of the dissertation is to investigate PL in the context of attention, aging and driving. There are multiple aims to this dissertation.

Chapter 1: Role of endogenous and exogenous attention in task-relevant perceptual learning

Previous findings have demonstrated that both exogenous and endogenous attention improves performance at both trained and untrained locations in TR-PL (Donovan & Carrasco, 2018; Donovan, Szpiro, Carrasco, 2015). However, exogenous attention was not found to improve performance in untrained features (Szpiro & Carrasco, 2015). This seems to suggest different types of PL for feature and location. It is possible that the type of attention may differentially affect the type of PL transfer. This study aims to address the following questions:

(1) What is the role of exogenous attention in feature-specific TR-PL?

(2) What is the role of endogenous attention in feature-specific TR-PL?

(3) Does feature-specific TR-PL differ as a function of cue-validity?

This study was conducted to test these predictions by measuring contrast thresholds.

Two types of attentional cues were manipulated to assess the effect of the type of attention on performance; exogenous and endogenous. To assess the effectiveness of the type of attentional cue, the two attention cues were further divided into three cue-validity conditions. College-aged participants were trained, on a novel task, to detect the presence of a complex gabor patch embedded in fixed Gaussian contrast noise while contrast thresholds were varied. Changes in performance as a result of training was examined by comparing at pre-test and post-test with no attention cues presented.

Chapter 1: Hypotheses

Endogenous Attention and TR-PL

Hypothesis 1: Endogenous attention is important for TR-PL.

Prediction 1. Learning will be enhanced when participants are trained with endogenous attention. With greater learning for higher cue-validity conditions as opposed to lower cue-validity conditions.

Exogenous Attention and TR-PL

Hypothesis 2: Exogenous attention is not important for TR-PL.

Prediction 2. Performance will be comparable between exogenous cue-validity conditions when participants are trained with exogenous attention. Performance should not be impacted by cue-validity, but some learning may be observed due to task practice.

Endogenous Attention and Feature Transfer

Hypothesis 3**:** Task-based plasticity involves endogenous attention.

Prediction 3. This assumes that task-based plasticity is associated with higher-level cognitive processing or read-out from lower-level sensory processing areas and that endogenous attention is primarily driven by higher-level cognitive processing. If Hypothesis 3 is correct, then performance improvements for a trained stimulus feature will transfer to an untrained stimulus feature when participants have been trained with endogenous attention.

Exogenous Attention and Feature Transfer

Hypothesis 4: Feature-based plasticity involves exogenous attention.

Prediction 4. This assumes that feature-based plasticity reflect changes in lower-level sensory processing and that exogenous attention is primarily driven by lower-level sensory processes. If hypothesis 4 is correct, then performance improvements for a trained stimulus feature should be specific to the trained stimulus feature when trained with exogenous attention. However, transfer to an untrained stimulus feature is possible due to variation of the target stimulus location. According to the Dual-Plasticity model, feature-based plasticity should be specific to the exposed feature or the location the stimulus was presented during training (Watanabe & Sasaki, 2015). Given that the target stimulus location was varied, feature-based constraints should be eliminated. Thus, TR-PL should transfer to different locations/features (Harris et al. 2012). This is consistent with previous research that found task-transfer but not feature-transfer as a result of training with exogenous attention (Szpiro & Carrasco, 2015).

Chapter 2: Aging, endogenous attention, and perceptual learning

A number of studies have examined aging and PL with texture discrimination (Andersen et al. 2010), motion discrimination (Ball & Sekuler, 1986), orientation discrimination (Deloss, Watananbe, & Andersen, 2014), divided attention (Richards, Bennett, & Sekuler, 2006), collision detection (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss, & Andersen, 2017), and action video game play (Belchior et al., 2014). Previous findings in college-aged adults reported that both exogenous and endogenous attention improves performance at both trained and untrained locations in TR-PL (Donovan & Carrasco, 2018; Donovan, Szpiro & Carrasco, 2015). For endogenous attention, learning and location transfer was facilitated via contrast gain. Additionally, PL training with UFOV transferred to untrained peripheral locations in both older adults and younger adults (Richards, Bennett, & Sekuler, 2006). This study is concerned with evaluating whether patterns of learning and location-transfer and the underlying processes in older adults are similar to that of younger adults as a result of training with endogenous attention. Specifically:

(4) Whether and how the type of attention impacts location-specific TR-PL in older adults?

(5) Whether training with an early-level perceptual task could generally improve attentional processing in older adults?

Both older and younger adults were randomly assigned to train in one of two endogenous attention cue conditions; a valid cue or a neutral cue. Participants were trained on an orientation discrimination task for three days and change in performance was evaluated prior to and following the training days. To assess changes in attention as a result of PL training, UFOV scores were administered prior to and after the training days.

Chapter 2: Hypotheses

Endogenous Attention and Aging

Hypothesis 5: The ability to learn increases with age.

Prediction 5. The presence of endogenous attention is likely to lead to learning for both older adults and younger adults. Given that older adults are less effective at processing endogenous cues and that initial task performance level is commonly worse in older adults than in younger adults (Ball et al., 1988; Sekuler & Ball, 1986), older adults should benefit more than younger adults from training with an endogenous cue. Thus, the magnitude of learning is predicted to be greater for older adults as compared to younger adults.

Hypothesis 6: Older adults as compared to younger adults exhibit generalized learning.

Prediction 6. Previous research has found location transfer as a result of training with endogenous attention in college-aged participants (Donovan & Carrasco, 2018). If Hypothesis 6 is correct, then transfer of learning to an untrained location should differ between older adults and younger adults. For older adults, performance improvements should transfer to an untrained location irrespective of being trained with a valid or neutral cue. For younger adults, performance improvements should transfer to an untrained location when trained with a valid cue, but performance improvements should be specific to the trained location when trained with a neutral cue.

Hypothesis 7: PL training with attention cues improves attentional processing.

Prediction 7. UFOV could be conceptualized as an assessment of visual-spatial attention, which is an aspect of endogenous attention. If Hypothesis 7 is correct, then improvements as a result of training with endogenous attention should transfer to improvements in UFOV. Improvements in UFOV should be reflected in pre-test and post-test UFOV measurements in both older and younger adults. But the magnitude of improvements in UFOV should be greater in older adults as compared to younger adults.

Chapter 3: Aging, perceptual learning and attention on driving performance

The focus of this study was to investigate attention and PL training on collision detection in both older and younger adults in the context of a real-world driving task. The incidence of automotive crashes is particularly high among drivers under the age of 25 (Evans, 2004; Williams & Carsten, 1989) and over the age of 65 (Tefft, 2008; Evans, 2004). Driving is a highly complex task that depend on a number of abilities, any of which could impact driving performance and crash risk. Several studies have evaluated performance on collision detection with a single object in the driving scene (Andersen & Enriquez, 2006; Ni, Bian, Guindon & Andersen, 2012) and have observed training-related improvements with a single object (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss & Andersen, 2017). However, multiple objects in a driving scene can impact driving performance. There is reported evidence of decrements in performance in cluttered driving scenes (Andersen & Kim, 2001; Lemon & Andersen, 2015). Multiple objects in the scene may be reflective of real-world driving scenes and so it is important to understand how performance and training is impacted by multiple objects in the driving scene.

Of particular relevance to this study is the role of visual-spatial attention and the ability to detect a collision in driving performance. As discussed above, there are age-related differences in collision detection and visual-spatial attention. Previous studies have demonstrated both older and younger adults benefit from PL training in collision detection (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss & Andersen, 2017) and PL training with UFOV (Richards, Bennett & Sekuler, 2006). UFOV could be conceptualized as a measure of visual-spatial attention. Assessments of UFOV have been shown to be predictive of crash risk among older adults (Sims et al. 2000). Given attention is important in PL and the reported age-related declines in aspects of attention, it is plausible that improvements related to PL training with attention may differ among older and younger adults and that driving-related improvements as a result of PL training may translate to better UFOV scores. And so, the following questions will be addressed in this study:

(6) Whether training with attentional cues improve collision detection in a high-level perceptual driving task?

(7) Whether and how the type of attentional cue impact driving performance in older adults?

(8) What is the impact of performance and training with multiple objects?

(9) Whether training with a high-level perceptual driving task could generally improve attentional processing?

Older and younger drivers were presented with a computer-simulated roadway scene simulating forward locomotion at a constant speed and along a linear trajectory. Drivers were asked to maintain within-lane vehicle steering while also deciding which object among a number of non-collision objects (number of objects; 2,4,8) will collide with the driver. During training, drivers were trained with several number of objects (2,4,8) and were presented with endogenous attention cues (valid or neutral cue). Accuracy, response time (RT), RMSE was measured.

Chapter 3: Hypotheses

Attention, Aging, PL and Driving

In a previous study, (Study 2), it was hypothesized (Hypothesis 5) that the ability to learn increases with age. This was proposed in the context of an early-level perceptual task, but it follows that Hypothesis 5 has relevance in the context of a high-level perceptual task such as driving. Therefore, Prediction 5 made in regard to Study 2 can be applied to Study 3.

Prediction 5. If Hypotheses 5 is correct, then the magnitude of learning is predicted to be greater for older drivers as compared to younger drivers.

Hypothesis 8: Processing efficiency of endogenous attention declines with age.

Prediction 8. If Hypothesis 8 is correct, then learning when trained with endogenous attention cues will differ with age. For older adults, it was predicted that learning as a result of PL will not differ when trained with either valid or neutral cues. For younger adults, learning as a result of PL will be greater for those trained with valid cues than those trained with neutral cues.

Hypothesis 9: Performance declines with increased number of objects.

Prediction 9. If Hypothesis 9 is correct, then performance decrements should be observed with increased number of objects. Given the inherent limits on the ability to attend and process visual information, increasing number of objects in the driving scene should have a negative impact on performance.

In a previous study (Study 2), it was hypothesized (Hypothesis 7) that PL training with attention cues improves attentional processing. This was proposed in the context of an early-level perceptual task, but it follows that Hypothesis 7 has relevance in the context of a high-level perceptual task such as driving. In fact, previous studies have found training on action video game play, another type of high-level perceptual task, translated to improvements in UFOV (Green & Bavelier, 2003; 2006; Achtman, Green, & Bavelier, 2008; Belchior et al., 2014).

Prediction 7. If Hypotheses 7 is correct, then improvements as a result of training with attention cues should transfer to improvements in UFOV. PL training with attention cues on a high-level perceptual driving task should generally improve attentional processing which should be reflected in UFOV measurements before and after training.

References

Aberg, K. C., Tartaglia, E. M., & Herzog, M. H. (2009). Perceptual learning with Chevrons requires a minimal number of trials, transfers to untrained directions, but does not require sleep. *Vision Research, 49*(16), 2087–2094.

Achtman R.L., Green C.S. & Bavelier D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience. 26*(4), 435–446. [PubMed: 18997318].

Adini, Y., Sagi, D., & Tsodyks, M. (2002). Context-enabled learning in the human visual system. *Nature* ,415,790–93.

Ahissar, M., & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences, 8*, 457–464.

Ahissar, M., & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature* 387:401–6.

Andersen G.J. (2012). Aging and vision: changes in function and performance from optics to perception. *Wiley Interdiscip. Rev. Cogn. Sci.* 3:403–10.

Andersen GJ, Cisneros J, Atchley P, Saidpour A. (1999). Speed, size, and edge-rate information for the detection of collision events. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 256–269.

Andersen, G. J., & Enriquez, A. (2006). Aging and the detection of observer and moving object collisions. *Psychology and Aging, 21*(1), 74-85.

Andersen, G. J., Ni, R., Bower, J. D., & Watanabe, T. (2010). Perceptual learning, aging, and improved visual performance in early stages of visual processing. *Journal of Vision, 10*(13):4, 1–13.

Andersen, G. J., & Kim, R. D. (2001). Perceptual information and attentional constraints in visual search of collision events. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(5), 1039.

Baker, C. I., Peli, E., Knouf, N., & Kanwisher, N. G. (2005). Reorganization of visual processing in macular degeneration. *J. Neurosci.* 25, 614–618. doi: 10.1523/JNEUROSCI.3476-04.2005.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. K. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America A, 5(*12), 2210–2219.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., (2002). Effects of cognitive training interventions with older adults: a randomized controlled trial. *Journal of the American Medical Association, 208*, 2271–2281.

Ball, K., & Sekuler, R. (1987). Direction-specific improvement in motion discrimination. *Vision Research, 27*, 953–65.

Ball, K., & Sekuler, R. (1986). Improving visual perception in older observers. *Journal of Gerontology, 41*(2), 176-182.

Ball, K., & Sekuler, R. (1981). Adaptive processing of visual motion. *J. Exp. Psychol. Hum. Percept. Perform.* 7, 780–794. doi: 10.1037/0096-1523.7.4.780.

Bedard, A.-C., Nichols, S., Barbosa, J.A., Schachar, R., Logan, G.D., & Tannock, R., (2002) The development of selective inhibitory control across the life span. *Developmental Neuropsychology, 21,* 93–111.

Belchior, P., Marsiske, M., Sisco, S.M., Yam, A., Bavelier, D., Ball, K., & Mann, W.C., (2014). Video game training to improve selective visual attention in older adults. *Comput Human Behavior,29*(4): 1318–1324.

Bower, J. D., Watanabe, T., & Andersen, G. J. (2013). Perceptual learning and aging: Improved performance for low-contrast motion discrimination. *Frontiers in Psychology, 4*, 1–7.

Bower, J. D., & Andersen, G. J. (2012). Aging, perceptual learning, and changes in efficiency of motion processing. *Vision Research, 61*, 144–156.

Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research, 51*, 1484–1525.

Cheal, M., Lyon, D. R., & Hubbard, D. C. (1991). Does attention have different effects on line orientation and line arrangement discrimination? *Quarterly Journal of Experimental Psychology A, 43*(4), 825–857.

Crist R.E., Li W, & Gilbert C.D. (2001). Learning to see: experience and attention in primary visual cortex. *Nat. Neurosci., 4*, 519–25.

Deloss, D. J., Bian, Z., Watanabe, T., & Andersen, G. J. (2015). Behavioral training to improve collision detection. *Journal of Vision, 15*(10), 2-2.

Deloss, D.J., Watanabe, T., & Andersen, G.J. (2014). Optimization of perceptual learning: effects of task difficulty and external noise in older adults. *Vision Research, 99*, 37–45.

Deveau, J., & Seitz, A. R. (2014). Applying perceptual learning to achieve practical changes in vision. *Frontiers in Psychology, 5,* 1–6.

Donovan, I. & Carrasco, M. (2018). Endogenous attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7, 1-16.

Donovan, I., Szpiro, S., & Carrasco, M. (2015). Exogenous attention facilitates perceptual learning transfer within and across visual hemifields. *Journal of Vision*, *15*(10), Article 11. doi:10.1167/15.10.11.

Dosher, B.A., & Lu, Z.L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proc. Natl. Acad. Sci.* USA, *95*, 13988–93.

Durrie, D., & McMinn, P. S. (2007). Computer-based primary visual cortex training for treatment of low myopia and early presbyopia. *Transactions of the American Ophthalmological Society, 105,* 132–140.

Eriksen, C. W. & Yeh, Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 583-597.

Evans, L. (2004). Overview of traffic fatalities. In Traffic safety (pp. 36–62). Bloomfield Hills, MI: Science Serving Society.

Fiorentini, A., & Berardi, N. (1981) Learning in grating wave form discrimination: specificity for orientation and spatial frequency. *Vision Research*, *21*, 1149–1158.

Fiorentini A, Berardi N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature, 287*, 43–44.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*(4), 1030−1044.

Gilbert, *C*.D. & Li, W. (2012). Adult Visual Cortical Plasticity. *Neuron, 75*(2), 250–264.

Giordano, A. M., McElree, B., & Carrasco, M. (2009). On the automaticity and flexibility of covert attention: A speed-accuracy trade-off analysis. *Journal of Vision, 9*(3), 10–31.

Green, C.S. & Bavelier, D. (2012) Learning, attentional control and action video games. *Current Biology, 22*(6), R197–R206.

Green C.S. & Bavelier D. (2003). Action video game modifies visual selective attention *Nature, 423*(6939), 534–537. http://dx.doi.org/10.1038/nature01647. [PubMed: 12774121].

Green, C.S., Li, R. & Bavelier, D. (2010). Perceptual learning during action video game playing. *Topic in Cognitive Science 2*, 202-16.

Green S.C. & Bavelier D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology: Human Perception and Performance. 2006 32*(6):1465– 1478. http://dx.doi.org/10.1037/0096-1523.32.6.1465. [PubMed: 17154785].

Harris H., Gliksberg M. & Sagi D. (2012). Generalized perceptual learning in the absence of sensory adaptation. *Curr Biol.* 22, 1813–17.

Hartley, A.A., (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychol. Aging, 8*, 371–379.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*(9), 1219–1240.

Hochstein, S., & Ahissar, M. (2002). View from the top: hierarchies and reverse hierarchies in the visual system. *Neuron, 36,* 791–804.

Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage, 31*(2), 774–789.

Houser, A., Fox-Grage, W., and Ujvari, K., (2012). Across the States 2013: Profiles of Long-Term Services and Supports [WWW Document]. AARP Public Policy Inst. http://www.aarp.org/content/dam/aarp/research/public_policy_institute/ltc/2012/across-the-states-2012-full-report-AARP-ppi-ltc.pdf.

Hubel, D.H. & Wiesel, T.N. (1970). Period of susceptibility to physiological effects of unilateral eye closure in kittens. *Journal of Physiology-London, 206*, 419–436.

Jeter, P. E., Dosher, B. A., Liu, S. H., & Lu, Z. L. (2010). Specificity of perceptual learning increases with increased training. *Vision Research, 50*(19), 1928–1940.

Jeter, P. E., Dosher, B. A., Petrov, A., & Lu, Z. L. (2009). Task precision at transfer determines specificity of perceptual learning. *Journal of Vision, 9*(3), 1–13.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In: Long, JB.; Baddeley, AD., editors. Attention & performance IX. Erlbaum; Hillsdale, NJ: 187-203.

Jonides J. & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43*(4):346-54.

Kahneman, D. 1973. Attention and Effort. Englewood Cliffs, NJ: Prentice-Hall.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: evidence for primary visual cortex plasticity. *Proc. Natl. Acad. Sci.* USA, *88*, 4966–70.

Kramer, A.F., Humphrey, D.G., Larish, J.F., Logan, G.D., & Strayer, D.L. (1994) Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychological Aging, 9,* 491–512.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 371-379.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2017). Training to improve collision detection in older adults. *Driving Assessment Conference.* DOI: 10.17077/drivingassessment.1651.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2015). Collision detection in cluttered driving scenes. In: Proceedings of the Eighth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, June 22-25, 2015, Salt Lake City, Utah. Iowa City, IA: Public Policy Center, University of Iowa, 2015: 233-239. https://doi.org/10.17077/drivingassessment.1577.

Levi, D. M., & Li, R. W. (2009). Improving the performance of the amblyopic visual system. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 364(*1515), 399–407.

Levi, D.M. (2005) Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Dev Psychobiol,46,* 222–232.

Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences of the United States of America, 93*(13), 6830–6834.

Liu, Z. (1999). Perceptual learning in motion discrimination that generalizes across motion directions. *Proc. Natl. Acad. Sci.* USA, *96*, 14085–87.

Lu, Z. L., & Dosher, B. A. (2000). Spatial attention: Different mechanisms for central and peripheral temporal precues? *Journal of Experimental Psychology: Human Perception and Performance, 26*(5), 1534–1548.

Lu, Z.L., & Dosher, B.A. (1998) External noise distinguishes attention mechanisms. *Vision Research, 38*,1183–1198.

Madden, D. J. (2007). Aging and visual attention. *Current Directions in Psychological Science*, *16*(2), 70–74.

Madden D.J., Spaniol, J., Whiting W.L., Bucur, B., Provenzale, J.M., Cabeza, R., White, LE. & Huettel, S.A. (2007) Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging, 28*, 459–476.

Madden, D.J. & Whiting, W.L. (2004) Age-related changes in visual attention. In: Costa, PT.; Siegler, IC., editors. *Recent advances in psychology and aging*. Amsterdam: Elsevier, 41-88.

Mayfrank, L., Kimmig, H., & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. In J. K. O'Reganm & A. Levy-Schoen (Eds.), Eye movements: From physiology to cognition (pp. 37–45). NY: North-Holland.

McDowd, J.M., & Craik, F.I.M. (1988) Effects of aging and task difficulty on divided attention performance. *J. Exp. Psychol. Hum. Percept. Perform*., *14*, 267–280.

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision, 11*(1), Article 25. doi:10.1167/11.1.125.

Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience*, 27, 11401–11411.

Muller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*(2), 315–330.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*(11), 1631–1647.

Peli, E. (1990). Contrast in complex images. *J. Opt. Soc. Am. A., 7*(10), 2032-2040.

Plude, D. J., & Doussard-Roosevelt, J. A. (1989). Aging, selective attention, and feature integration. *Psychology and Aging, 4*(1), 98-105.

Polat, U. (2009) Making perceptual learning practical to improve visual functions. *Vision Research, 49*, 2566–2573.

Polat, U., Schor, C., Tong, J.-L., Zomet, A., Lev, M., Yehezkel, O. Sterkin, A., & Levi, D. M. (2012). Training the brain to overcome the effect of aging on the human eye. *Scientific Reports*, *2*, 278. http://doi.org/10.1038/srep00278.

Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences of the United States of America, 101*(17), 6692–6697.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. Bonwhuis (Eds.), *Attention and performance X: Control of language processes*, 551–556. Hillsdale, NJ: Erlbaum.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Raz, N., Lindenberger, U., Rodrigue, K.M., Kennedy, K.M., Head, D., Williamson, A., Dahle, C., Gerstorf, D. & Acker,J.D. (2005) Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex, 15*(11*)*,1676–1689. doi: 10.1093/cercor/bhi044.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron, 61*(2), 168–185, https://doi.org/10.1016/j.neuron.2009.01.002.

Sagi, D. & Tanne, D. (1994) Perceptual-learning – learning to see. *Current Opinion in Neurobiology*, *4*(2),195–199.

Salat, D.H., Tuch, D.S., Hevelone, N.D., Fischl, B., Corkin, S., Rosas, H.D., Dale, A.M. (2005). Age-related changes in prefrontal white matter measured by diffusion tensor imaging. *Annals of the New York Academy of Sciences, 1064*, 37-49.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition*. Psychol. Rev. 103*, 403–428.

Salthouse, T.A., Fristoe, N.M., Lineweaver, T.T., & Coon, V.E. (1995) Aging of attention: Does the ability to divide decline*? Mem. Cognit., 23*, 59–71.

Sanders, M.S. & McCormick, E.J. (1993). Human Factors in Engineering and Design (7th ed.). New York: McGraw-Hill.

Schmolesky, M.T., Wang, Y., Pu, M., & Leventhal, A.G. (2000) Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, 3(4), 384-390.

Schoups A.A., Vogels, R. & Orban, G.A. (1995). Human perceptual learning in identifying the oblique orientation: retinotopy, orientation specificity and monocularity. *Journal of Physiology, 483,* 797– 810.

Seitz, A., & Watanabe, T. (2005). A unified model for perceptual learning. *Trends Cogn. Sci.* 9:329–34.

Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America A, 3*, 863–867.

Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research, 26*, 103–120.

Sekuler R., Owsley C., & Hutman L. (1982) Assessing spatial vision of older people. *American Journal of Optometry and Physiological Optics*, *59*(12), 961–968.

Shibata, K., Sasaki, Y., Kawato, M., & Watanabe, T. (2016) Neuroimaging evidence for two types of plasticity in association with visual perceptual learning. *Cerebral Cortex*, 26 (9): 3681-3689.

Shibata, K., Sagi, D., & Watanabe, T. (2014) Two stage model of perceptual learning, *the Year in Cognitive Neuroscience, Annual Review of New York Academy of Sciences, 1316*, 18-28.

Shibata, K., Yamagishi, N., Ishii, S., & Kawato, M. (2009). Boosting perceptual learning by fake feedback. *Vision Research, 49*, 2574–2585.

Sigman M, Pan, H., Yang, Y., Stern, E., Silbersweig, D., & Gilbert C.D. (2005) Top-down reorganization of activity in the visual pathway after learning a shape identification task. *Neuron, 46*, 823– 835.

Sims, R. V, McGwin Jr, G., Allman, R. M., Ball, K. K., & Owsley, C. (2000). Exploratory study of incident vehicle crashes among older drivers. *Journal of Gerontology, 55*(1), M22–M27. doi:10.1093/gerona/55.1.M22.

Sowden, P.T., Davies, I.R.L., & Roling, P. (2000). Perceptual learning of the detection of features in X-ray images: A functional role for improvements in adults' visual sensitivity? *Journal of Experimental Psychology: Human Perception and Performance, 26*(1), 379-390.

Spieler, DH., Balota, D.A., & Faust, M.E. (1996) Stroop performance in healthy younger and older adults and in Individuals with dementia of the alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 461-479.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*. *18*(6): 643–662.

Suzuki, S., & Cavanagh, P. (1997). Focused attention distorts visual space: An attentional repulsion effect. *Journal of Experimental Psychology: Human Perception and Performance, 23*(2), 443–463.

Szpiro, S. F. A., & Carrasco, M. (2015). Exogenous attention enables visual perceptual learning. *Psychological Science.*

Tefft, B. C. (2008). Risks older drivers pose to themselves and to other road users. *Journal of Safety Research, 39*(6), 577–82. doi:10.1016/j.jsr.2008.10.002.

Theeuwes, K. (2010). Top-down and bottom-up control of visual selection. *Acta Psychlogica, 135*(2), 77-99.

Treisman, A. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Vogels, R. & Orban, G. A. (1985). The effect of practice on the oblique effect in line orientation of perceptual learning across retinal locations enabled by double training. *Current biology, 18,* 1922–6.

Watson, A. A. B., & Pelli, D. G. D. (1983). QUEST: A Bayesian adaptive psychometric method. *Attention, Perception, & Psychophysics, 33*(2), 113–120.

Watanabe T., Sasaki Y. (2015). Perceptual learning: toward a comprehensive theory. A*nnual Review Psychology, 66,*197-221.

Whiting, W.L., Madden, D.J., Pierce, T.W. & Allen, P.A. (2005). Searching from the top down: Ageing and attentional guidance during singleton detection. *Quarterly Journal Experimental Psychology A, 58*(1), 72–97.

Williams, A., & Carsten, O. (1989). Driver age and crash involvement. *American Journal of Public Health, 79*(3), 326–327.

Yan, F.F., Zhou, J., Zhao, W., Li, M., Xi, J., Lu Z.L. & Huang C.B. (2015). Perceptual learning improves neural processing in myopic vision. *Journal of Vision, 15*(10):12, 1-14.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 676−681.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 95−107.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 121−134.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10*(5):601-21.

Yotsumoto, Y. & Watanabe, T. (2008). Defining a link between perceptual learning and Attention. *PLoS Biology,* 6(8), e221.

Zhang J.Y., Zhang, G.L., Xiao, L-Q., Klein, S.A., Levi, D.M., & Yu, C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *Journal of Neuroscience, 30,* 12323- 12328.

Chapter 1

Role of endogenous and exogenous attention in task-relevant visual perceptual learning

Kieu Ngoc Nguyen[1¶], Takeo Watanabe[2&], George John Andersen[1¶*]

Author Affiliations:

[1] Department of Psychology, University of California, Riverside, Riverside, California, United States of America

[2] Department of Cognitive, Linguistic, and Psychological Sciences, Brown University, Providence, Rhode Island, United States of America

*E-mail: andersen@ucr.edu (GJA)

Note the hypotheses for Study 1 were not discussed in detail in Chapter 1. Hypotheses relevant to Chapter 1 will be discussed in the General Discussion.

Abstract

The present study examined the role of exogenous and endogenous attention in task relevant visual perceptual learning (TR-VPL). VPL performance was assessed by examining the learning to a trained stimulus feature and transfer of learning to an untrained stimulus feature. To assess the differential role of attention in VPL, two types of attentional cues were manipulated; exogenous and endogenous. In order to assess the effectiveness of the attentional cue, the two types of attentional cues were further divided into three cue-validity conditions. Participants were trained, on a novel task, to detect the presence of a complex gabor patch embedded in fixed Gaussian contrast noise while contrast thresholds were varied. The results showed initial differences were found prior to training, and so the magnitude of learning was assessed. Exogenous and endogenous attention were both found to facilitate learning and feature transfer when investigating pre-test and post-test thresholds. However, examination of training data indicate attentional differences; with endogenous attention showing consistently lower contrast thresholds as compared to exogenous attention suggesting greater impact of training with endogenous attention. We conclude that several factors, including the use of stimuli that resulted in rapid learning, may have contributed to the generalization of learning found in the present study.

Introduction

Through repeated exposure or training of visual stimuli, improvements in performance can result in enhanced visual processing known as visual perceptual learning (VPL). These perceptual improvements have been found to be long-lasting [1-3] and can result in changes in neural processing, known as neural plasticity [4, 5]. VPL research has been focused not only on understanding learning in visual processing but also identifying fundamental principles common to learning in general. In addition, many aspects of early visual processing decline with normal aging. These declines include decreased performance in spatial vision, contrast sensitivity, orientation, and motion—all of which are important for higher-level visual tasks such as driving [6]. Additionally, those suffering from visual deficits, such as macular degeneration [7], presbyopia [8, 9], or amblyopia [10-13], might benefit from VPL protocols. Thus, elucidating the mechanisms that underlie learning has important implications for the development and application of VPL in clinical and practical settings.

Research on VPL has revealed a diverse set of findings that have resulted in different theories of VPL. These findings have centered on whether aspects of VPL are specific or generalizable [14-17] as well as the changes in neural visual processing due to VPL [18-20]. Specificity is the failure for training-induced performance improvements to transfer, or generalize, to an untrained stimuli or task. VPL has been found to be dependent on many factors including the learned visual feature, the type of task, and exposure to a feature without a task [21]. Performance improvements from training have been found to be specific to early level attributes of a stimulus ranging from orientation

[22, 23] and spatial frequency [22,24] to motion [25, 26] and contrast [27- 29] (for detailed reviews of the extent of specificity in PL see [30] or [31]). This specificity has been taken to indicate that changes in processing occur at early cortical sites where primitive features are processed. Variations of the training task such as, task difficulty [14], high-precision stimuli [16], or long training sessions [32] could lead to some degree of learning specificity. VPL was reported to transfer across task [33], stimulus features [34], and retinal location [35] under different training conditions. This generalization suggests that the locus of learning might be at higher-level processing regions in which changes in reweighting of read-out connections or the level at which response decisions occur [36-40]. Generalization of VPL has also been found to occur for tasks that employ easy training [14,41], shorter training sessions [32], shorter training trials [42], or double-training [35].

Previous research on VPL has found two different types of VPL; task relevant VPL (TR-VPL) and task-irrelevant VPL (TI-VPL). TR-VPL is defined as VPL of a feature that is relevant to a given task during training. TI-VPL is defined as VPL of a feature that is irrelevant to a given task [43]. In TI-VPL, learning has been found to occur in the absence of attention suggesting an early-level mechanism that supports learning. It was found that mere exposure to a stimulus feature that is task-irrelevant and sub-threshold was sufficient to induce learning [44]. Although TI-VPL has been found to occur without focused attention, it is subject to attentional inhibition if the irrelevant signals compete with the relevant signals [45]. Failure to suppress weak task-irrelevant or sub-threshold signals allow the non-suppressed signals to be learned. Additionally, learning could occur for task-irrelevant or task-relevant supra-threshold stimuli [46]. Although transfer of learning for untrained features was found, most TI-VPL studies have found learning to be specific to the feature that is trained. It is likely, then, that learning occurs at multiple levels of the system and may be sub-served by different mechanisms.

Despite the ability of the visual system to adapt to its changing environment, constraints are needed to protect the system from continued modification and change. Acquisition or gating of learning has been found to occur in one of two ways---through reinforcement or via attention. With reinforcement, learning occurs through spatially diffuse signals that enhance incoming sensory signals irrespective of whether the feature is task-relevant or task-irrelevant [43]. This form of passive learning, in which mere exposure to a stimulus within the visual field, facilitates both TR-VPL or TI-VPL. By comparison, attention selects what is behaviorally relevant and thus what is learned on a task. Attention can flexibly modulate cells involved in learning. For instance, monkeys performed a task at fixation while surrounded by previously trained stimuli [3]. The cells that responded when the previously trained stimuli were task-relevant were now being suppressed. This was thought to reflect that the previously trained stimuli were actively competing with the task-relevant stimuli now being presented at fixation. With regard to the necessity of attention in visual processing, it is important to note that the vast amount of information in the environment can overwhelm the brain's limited processing capacity. One view of attention is that it is a selective mechanism by which aspects of information is prioritized over others thereby guiding learning and behavior. Two types of attention may be relevant for VPL---exogenous and endogenous attention.

Exogenous, or bottom-up, attention is a passive, transient, automatic, stimulus-driven process. Peripheral cues, presented near or at target stimuli, used to guide exogenous attention could be automatically captured by salient stimuli. With exogenous attention, feed-forward signals propagate from lower sensory areas to higher cognitive processing areas. Exogenous attention is driven by properties of a stimulus- such as color, orientation, luminance, can inadvertently go against the intentions of an observer [47-49], is deployed when salient novel stimuli are presented [50, 51] and is often difficult to ignore [52]. It can be triggered reflexively by a salient sensory event, such as a flash in the periphery. It works via signal enhancement of relevant signals [53, 54]. The time course of the shift of attention to an exogenous cue is approximately 100-120ms [55-57].

Endogenous, or top-down, attention is a voluntary, sustained, goal-driven process. Information that aligns with an observer's behavioral goals are internally selected for further processing. It involves a more effortful process such as being instructed to orient attention to a particular location. The capture of attention is contingent upon top-down attentional control, a phenomenon known as contingent capture [58]. Posner [59] demonstrated an endogenous cueing paradigm in which participants *willfully* directed attention to a particular spatial location. A centrally presented symbolic cue, an arrow, would indicate the possible location of a subsequently presented target. The endogenous cue could point to the location of the target (valid trial), point away from the location (invalid trial), or give no indication to the location of the target (neutral trial). Performance is typically faster, more accurate, or both, for valid trials than for invalid trials and neutral trials. The source of endogenous attention is proposed to be through recurrent feedback connections that descend from higher cortical processing areas to lower sensory processing areas. Endogenous attention operates via signal enhancement of relevant signals and external noise reduction of irrelevant signals [53]. The time course of the shift of attention to an endogenous cue is approximately 300ms [60].

Although both types of attention share common perceptual effects [61,62], each is capable of affecting information processing in distinct ways (for extensive list of unique perceptual effects see [60]). These two types of attention may differentially modulate perceptual processes. As a result, the effect on performance is likely to vary in accordance with the type of attention that is engaged. For instance, the benefits and costs in discriminability and processing speed differ between exogenous and endogenous attention [63]. For endogenous attention, benefits and costs increased with cue-validity whereas for exogenous attention, benefits and costs were constant across cue-validity. Unlike exogenous attention, endogenous attention can optimize performance according to task demands. For instance, endogenous attention was found to improve performance at all eccentricities by flexibly modulating resolution at attended locations [64]. In contrast, exogenous attention, regardless of the effect on performance, was found to automatically increase resolution at attended locations [65]. As a result, exogenous attention was found to improve performance at locations with low resolution but impair performance at locations with high resolution. In conditions of external noise, exogenous attention enhances contrast sensitivity under both low- and high- noise conditions whereas endogenous attention works under high-noise conditions [53-54]. Whereas endogenous attention is susceptible to interference and requires more cognitive resources, exogenous attention does not [52,66-67]. The earliest stage of visual cortical processing is enhanced by exogenous attention whereas endogenous attention impacts later stages of processing [68]. Furthermore, endogenous attention may be maintained at a location for extended periods. On the other hand, exogenous attention exhibits inhibition of return, such that there is delay in responding from exogenous orienting after initial facilitation at same cued location [69].

Attention has often been argued as an important component of VPL. However, few studies have experimentally manipulated attention to examine its effects on VPL (see [70-71,21]). One study assessed varying effects of exogenous and endogenous attention on TR-VPL [72]. Both attentional cues were found to increase accuracy, but only exogenous attention was found to result in lower thresholds. Although this finding might suggest that the type of attention modulates VPL via distinct mechanisms, attentional cues were not systematically varied as participants were exposed to all validity cues, attended, divided-attended, and neutral, and thus make it difficult to assess the effect of attention. One such study did experimentally isolate the effect of exogenous attention on PL [33]. Learning was found when participants were trained with exogenous attentional cues as compared to neutral cues. Additionally, transfer of training was assessed for an untrained task and untrained feature and the findings indicated that learning only transferred to an untrained task. For location transfer, training with exogenous attentional cues facilitated transfer to untrained locations within and across visual hemifields whereas training with neutral cues exhibited location specificity [73]. A subsequent study, but with endogenous attention, also found transfer to untrained locations within and across visual hemifields whereas training with neutral cues exhibited location specificity [74]. Specifically, the study investigated whether, like exogenous attention, endogenous attention facilitates learning and location transfer in an orientation discrimination task. Notably, performance improvements as a result of training with attention carried over to untrained locations despite the effect of attention being local to the target location.

Despite similar performance improvements across both studies, distinct mechanisms underlie facilitation of location transfer with exogenous attention operating via response gain [73] and with endogenous attention operating via contrast gain [74]. Performance changes in response to changes in stimulus intensity is characterized by the psychometric function. Changes in the psychometric function via contrast or response gain are thought to reflect neuronal activity as a function of stimulus contrast, which creates a contrast response function [75]. Attentional modulation via contrast gain leads to an increase in contrast sensitivity with no change in the relative firing rate. Contrast gain may be reflected in the psychometric function as a left-ward shift in the psychometric function. Whereas, response gain leads to a multiplicative increase in firing rate across the contrast response function with no change in threshold. Response gain may be reflected behaviorally as improved accuracy across stimulus intensity with pronounced effects as higher stimulus intensities. Another study investigated the role of exogenous attention in the transfer of learning across location in two different acuity tasks; Landolt acuity and Vernier acuity [76]. In the Landolt acuity task, training with exogenous cues resulted in location transfer whereas, training with neutral cues resulted in location specificity. However, in the Vernier acuity task, training with both exogenous and neutral cues resulted in location specificity. This suggests that even after training with exogenous attention, learning on certain tasks may not be amenable to transfer across locations. Altogether, these findings demonstrate the effect of the type of attention, albeit complicated, on learning and specificity.

The extensive literature on PL has resulted in several different models that consider the role of attention. These models differ in terms of several different factors that include what cortical area is activated, the degree of specificity of VPL, and the type of VPL. For the purpose of the present study, VPL models that explicitly incorporate attention will be discussed. The Reverse Hierarchy Theory [14, 77] assumes learning is a top-down attention-guided process. According to this model, the locus of learning are higher processing areas that allow for learning on tasks that involve coarse discrimination. Learning, then, cascades to lower processing areas for tasks that require fine discrimination. Specificity arises with continued training allowing access to lower level processing sites. This model assumes that top-down attention is required for the occurrence of VPL and thus does not account for findings regarding TI-VPL.

A more recent theory, the Dual-Plasticity model, posits learning can occur in the presence of or absence of attention [30, 78]. This theory proposes two types of plasticity; task-based plasticity and feature-based plasticity. Feature-based plasticity is defined as changes in the representation of features. Task-based plasticity is defined as changes in processing related to a trained task. Feature-based plasticity results from mere exposure to a feature during training irrespective of whether the feature is task-relevant or task-irrelevant and is specific to the exposed feature. On the other hand, task-based plasticity stems from involvement on a trained task, occurs only in TR-VPL, and is specific to the trained task. According to this model, changes associated with feature-based plasticity should be observed as changes in neural responses to the trained feature (in the corresponding visual areas in association with TR-VPL) as opposed to task-based plasticity which will be associated with changes in high-level cognitive areas or connectivity between visual and cognitive areas. Evidence for two types of plasticity, that occur in different cortical regions, has been found suggesting that, to some degree, separate mechanisms exist [79].

The purpose of the current study was to examine the role of different types of attention in TR-VPL. Specifically, the present study investigated the role of exogenous and endogenous attention on TR-VPL. Within the framework of the dual-plasticity model, it was hypothesized that endogenous attention is important for TR-VPL and exogenous attention is not important for TR-VPL. This suggests that in the present study, learning will be enhanced when endogenous attention, as compared to exogenous attention, is engaged. Furthermore, learning will be impacted by cue-validity with greater learning for higher cue-validity conditions as opposed to lower cue-validity conditions when endogenous attention is engaged. Finally, the issue of transfer of learning to an untrained stimulus was examined. If transfer of training occurs, then transfer should be greater for endogenous attention conditions as compared to exogenous attention conditions because of the greater role of endogenous attention in TR-VPL.

Methods

Participants

60 college-aged adults (mean age = 19 years, SD = 2.35) from the University of California, Riverside (35 male and 35 female) participated in the study. All participants were compensated for their participation at a rate of $15 per hour. The Institutional Review Board of University of California, Riverside approved this study. Participants gave their written informed consent for their participation and participants were debriefed on the purpose of the study after their participation. All participants had normal or corrected-to-normal visual acuity and were naive to the purpose of the study. Participants' near visual acuity was screened using a LogMAR chart (*M* = -0.05, *SD* = 0.08). All participants were screened for eye diseases through self-report. Corrective lenses normally worn by the participants were allowed during the experiment. Participants with extreme initial contrast thresholds prior to training -/+1.5 SD were excluded from the study. Seven participants were excluded from the study due to consistently high thresholds indicating that they could not perform the task.

Apparatus

Stimuli were presented on a 49.53-cm CRT monitor Viewsonic PF817 at a resolution of 1,024 × 768 pixels; the monitor had a refresh rate of 75 Hz non-interlaced and a mean luminance value of 42.7 cd/m_2. Stimuli were generated on an Alienware AREA_51 PC equipped with an Intel Core i7 960 processor using the Windows 7 Ultimate 2009 operating system. A NVIDIA GeForce GTX 480 graphics card was used along with a Bits++ system (Cambridge Research Systems, Rochester, Kent, United

Kingdom) to achieve 14-bit gray scale (16,384 gray-scale levels). Custom experimental software was written in MATLAB (The MathWorks, Natick, MA); Psychophysics Toolbox extensions (Brainard, 1997; Pelli 1997; Kleiner, Brainard & Pelli, 2007). The EyeLink 1000 Tower Mount (SR Research, Ottawa, Ontario, Canada) was used to monitor participants' eye movements as well as stabilize head position. The monitor was calibrated using a ColorCal 2 colorimeter (Cambridge Research Systems).

Participants' far acuity was measured using the 2000 Series Revised ETDRS Chart 2 (Precision Vision, La Salle, IL) at a distance of 3 m. Participants' near acuity was measured using the 2000 series New ETDRS Chart 3 at a distance of 40 cm. Contrast sensitivity was measured using the Pelli-Robson Contrast Sensitivity Chart (Precision Vision).

Stimuli and Procedure

The stimulus was a gabor patch defined by a sine wave at a spatial frequency of 0.5 cycles/degree of visual angle and the target was the gabor patch but with the presence of an additional sinewave at a spatial frequency of 1.5 cycles/degree [22, 80]. Contrast of the 0.5 cycle/degree sinusoid is denoted as c_1 and the contrast of the 1.5 cycles/degree sinusoid, c_2. Gabor stimuli were embedded in fixed additive Gaussian noise with a standard deviation set at 0.33 throughout the experiment. The phase of the stimuli was randomized ±180° on each trial. Luminance was matched across trials using root-mean-square luminance [81]. Contrast thresholds were derived.

Stimuli were presented at one of two locations; left or right 7.5 degree of visual angle from center. Presentation of the gabor patch at one location was always accompanied by its corresponding distractor stimulus at the opposite location. The distractor stimulus was the same gabor patch presented during the trial but each pixel at each location that composed the gabor patch was randomized to a new location. This allowed for constant luminance on each trial. All stimuli were enveloped by a Gaussian mask with a standard deviation of 2.2 degrees of visual angle.

To remove any edge cues, all stimuli were viewed through a black circular aperture with a radius of 2.4 degrees of visual angle and aperture thickness of .4 degrees. In order to assess transfer, stimuli were presented at two orientations; 20 degrees and 110 degrees.

The task was a Yes/No detection task in which participants were to determine the presence or absence of an additional sinewave component in the gabor patch. Participants were to respond on the numeric keypad with '1' if the additional 1.5 cycle/degree sine-wave was present or '2' if additional 1.5 cycle/degree sine-wave was not present. A fixation point was a bulls-eye target with a radius of .8 degrees of visual angle presented in the center of the screen. Participants were to maintain fixation on the center bulls-eye target throughout the experiment. The eye tracker was utilized to ensure participants were fixated on the center. Given the temporal nature of endogenous cues and that ~200-250ms are needed for goal-directed saccades, stimulus onset asynchrony (SOA) for the endogenous cue may allow participants to make an eye movement [82]. To control for this, trials would restart if participants were not fixated on the center.

The experiment was administered over 2 consecutive days with 1 hour each day. Each day consisted of 2 sessions: on day 1, contrast threshold measurements were obtained prior to training then one training session with attentional cues while on day 2, one training session with attentional cues then contrast threshold measurements were obtained after training. Stimuli were viewed binocularly on a monitor at a distance of 95.25 cm. The experiment was run in a darkened room; the only light source was the monitor. Refer to fig 1 for the time course of the experiment.

Practice

Before the start of the experiment and at the start of day 1, all participants were given 4 blocks of 20 trials to familiarize them to the task. Orientation of the stimuli was alternated across each block. At the start of each trial, participants saw a fixation point in the center of the screen for 1000-ms followed by a 1000-ms presentation of the stimuli (simultaneous presentation of gabor stimuli and noise stimuli). Following the presentation of the stimuli, a uniform mid-gray background was presented to indicate that subjects should respond. After the response cue, feedback was given based on their response. Stimuli were presented for 1000-ms for the first two blocks and then for 53-ms for the last two blocks. For practice trials, contrast values were fixed at $c_1 = 0.6$ and $c_2 = 0.4$; values that were well above threshold.

Testing

Contrast thresholds of c_2 were assessed for trained and untrained orientations at the beginning of day 1 and the end of the day 2 of the experiment. c_1 was set at a fixed value of 0.4. The QUEST procedure was used to measure contrast thresholds of contrast c_2 of the gabor patch [83]. QUEST was initialized with a criterion level of 0.75 ($\beta = 1.3$, $\delta = 0.10$, $\gamma = 0.5$). This β value is based on a preliminary study designed to find the optimal β value for the task. Participants completed 60 trials/block for 4 blocks. The first two blocks were presented at one orientation and the last two blocks were presented at another orientation. 60 trials were collected at each orientation for contrast c_2 of the 1.5 cycles/degree sine-wave in the gabor patch. From preliminary data, 60 trials for each stimulus orientation was sufficient for QUEST to converge at a stable threshold estimate.

A fixation point was presented for 53-ms followed by a 53-ms presentation of the stimuli (simultaneous presentation of gabor patch and noise stimuli). Then, the response cue followed by feedback based on their response. Testing order of the orientations were counterbalanced across participants. Participants were given a one-minute break after each block. During testing, stimuli were presented without cues.

Training

Training occurred on day 1 after testing and on day 2 prior to testing with a 5-minute break between testing session and training session. Using the same stimuli and a similar procedure as in the testing phase- with the key difference being that participants were trained on only one orientation instead of the two they saw during testing sessions. During training, all subjects completed six blocks with 60 trials each block. Subjects were given a one-minute break after each block.

During each training session, the QUEST procedure was run using the same parameters as during the testing sessions, but with one modification. The contrast threshold estimate for QUEST for each subject used the threshold derived on the prior session as the initial estimate. Subsequent trials used the current threshold, taking into account each trial during the training sessions. Using this method, subjects were trained at their threshold (75% correct) across all training trials. Of the 720 trials administered over the course of the training sessions, only 360 trials were inputted into QUEST to derive contrast thresholds.

To assess the effectiveness of attention on PL, participants were divided and trained in one of three cue-validity conditions; 100% valid in which the cue always specified the location of the target, 80% valid in which the cue specified the location of the target 80% of the time with the other 20% invalid in which the cue specified the location of the distractor, and a neutral condition in which the cue specified both locations. For the training sessions, the attentional cues preceded the simultaneous presentation of the gabor and noise stimuli. Following Posner's [59] original experiment, the neutral cue condition of the endogenous group displayed a fixation cross rather than a double-ended arrow.

To assess possible differential effects of the type of attention on PL, one group was trained with an exogenous attentional cue (n=30) and another group was trained with an endogenous attentional cue (n=30). From the type of attention, these participants were further divided into the three cue-validity conditions with 10 participants in each condition. The exogenous attentional cue was a visually salient cue (white square-shaped frame) presented at either one of the two locations (100% or 80% valid) or both locations (neutral) [48]. The endogenous cue was a black arrow presented in the center of the screen that could point to one of two locations (100% or 80% valid) or both locations (neutral) (adapted from [59]). In regard to both types of cues, participants were instructed that the presence of the cues, either a 'white-square outline' for the exogenous cue or ‘black-arrow’ for the endogenous cue, prior to the presentation of the stimuli may or may not indicate the location of the target pattern.

The time course for a training trial was as follows: a fixation point was presented for 1000-ms followed by either one of two attentional cues (67-ms for an exogenous cue and 305-ms for an endogenous cue). The endogenous cue was a black arrow (2 degrees for length of the arrow and .5 degrees for the arrow hands) presented near the center of the fixation point. The exogenous cue was a white square outline (10 degrees in length for each side of the square) presented near the stimuli. Next, an inter-stimulus interval (ISI) was presented for 53-ms followed by the training stimuli (simultaneous presentation of the gabor and noise stimuli) which was presented for 53-ms. After the stimuli disappeared, a response cue indicated to participants to make a judgment followed by feedback. Refer to fig 2 for attentional cues used during training.

Results

Contrast thresholds prior to training were examined using a 2 (attention: exogenous, endogenous) x 3 (cue-validity: 100%, 80%, neutral) x 2 (feature orientation: trained, untrained) mixed–design analysis of variance (ANOVA). Attention type and cue-validity were between-subject factors. Orientation was a within-subjects factor. Analyses were conducted using IBM SPSS Statistics software Version 24. The first analysis conducted was to assess whether there were any differences between the exogenous and endogenous attention groups prior to training. This was assessed by examining the type of attention and thresholds for the trained and untrained orientation prior to training.

Differences prior to training were found across attention and cue-validity conditions for both trained orientation, and untrained orientation, $F(1,54)= 4.716$, $p=.034$ $\eta_{p2}= .080$ with higher thresholds for trained orientation (*M*=.292, *SE*=.016) as compared to untrained orientation (*M*= .261, *SE*=.016). Refer to figure 3 for contrast thresholds at pre-test and post-test.

Magnitude of Learning

As indicated above, given differences in initial performance, and in order to compare performance across attention type, a magnitude of learning score was calculated for trained and untrained orientation by calculating the difference between pre-test threshold from post-test threshold and then divided by the pre-test threshold.

$$\text{Magnitude of learning} = \frac{\text{PostTest Threshold} - \text{PreTest Threshold}}{\text{PreTest Threshold}}$$

By doing so, this allows for an examination of any changes in performance given an individual participant's initial performance level. Using this metric, it was found that there was a significant difference between trained and untrained orientation, $F(1,54) = 15.627$, $p <.001$, $\eta_{p2}= .224$ with greater magnitude of learning for trained orientation (*M* = -.352, *SE*= .023) as compared to the untrained orientation (*M*= -.201, *SE*= .039). There was a non-significant trend for the effect of cue-validity, $F(2,54) = 2.590$, $p =.084$, $\eta_{p2}= .088$.

To assess whether magnitude of learning differs by attention type and cue-validity, a 2 (attention: endogenous, exogenous) x 3 (cue-validity: 100% valid, 80% valid, neutral) factorial ANOVA was conducted. No interaction between attention and cue-validity on magnitude of learning for trained orientation was found, $F(2,54)=2.080$, *p*

= .135, η_{p2}=.072. The results for magnitude of learning across attention groups is shown in fig 4. Subsequent analyses were conducted separately by attention type.

Exogenous Attention

A cue-validity (100%, 80%, neutral) x feature orientation (trained, untrained) x test day (pre-test, post-test) mixed-design ANOVA was conducted on correct response times (RT). Test day was a within-subjects factor. There was an effect of test day such that participants were faster following training from pre-test (*M*= .728, *SE* = .041) to post-test (*M*=.602, *SE* = .017), $F(1,27)$= 16.555, p <.001, η_{p2}= .380. Thresholds prior to training reveal performance was comparable across cue-validity conditions, $F(1,27)$= 1.951, p=.174, η_{p2}= .067. A 2 (feature orientation: trained, untrained) x 3 (cue-validity: 100%, 80%, neutral) x 2 (test day: pre-test, post-test) mixed–design ANOVA was conducted. There was a main effect of test day, $F(1,27)$= 32.210, p <.001, η_{p2}= .544 such that post-test thresholds (*M*=.192, *SE*= .011) were significantly lower than pre-test thresholds (*M*= .287, *SE*= .020). There was no main effect of orientation, $F(1,27)$= .265, p =.611, η_{p2}= .010 suggesting that there were no differences between trained and untrained orientation.

There was also a non-significant trend of an interaction between orientation and test day, $F(1,27)$= 3.514, p=.072 η_{p2}= .115, such that training improved thresholds (trained orientation: post-test threshold, *M*= .184, *SE* = .011; pre-test threshold, *M*=.300, *SE* = .021) as opposed to the untrained thresholds (untrained orientation: post-threshold, *M*= .200, *SE* = .014; pre-test threshold, *M* = .273, *SE*= .023). Consistent with our hypothesis, there was no effect of cue-validity, $F(1,27)$= .265, p=.776, η_{p2}= .019.

Endogenous Attention

A cue-validity (100%, 80%, neutral) x feature orientation (trained, untrained) x test day (pre-test, post-test) mixed-design ANOVA was conducted on correct response times (RT). There was an effect of test day such that participants were faster following training from pre-test (*M*= .762, *SE* = .083) to post-test (*M*= .575, *SE* = .015), $F(1,27)$= 5.800, p =.023, η_{p2}= .177. Thresholds prior to training reveal performance was comparable across cue-validity conditions, $F(1,27)$ = 2.778, p = .107, η_{p2}= .093. A 2 (feature orientation threshold: trained, untrained) x 3 (cue-validity: 100%, 80%, neutral) x 2 (test day: pre-test, post-test) mixed–design ANOVA was conducted. There was a main effect of test day, $F(1,27)$= 29.401, p<.001, η_{p2}= .521 such that post-test thresholds (*M*= .173 , *SE*= .009) were lower than pre-test thresholds (*M*= .267, *SE*= .020). There was an interaction of trained orientation x test day, $F(1,27)$= 4.931, p=.035, η_{p2}= .154 such that thresholds improved from pre-test (*M*= .283, *SE* = .023) to post-test (*M*= .167, *SE* = .011) of the trained orientation as compared to the pre-test (*M*= .249, *SE* = .021) and post-test of the untrained orientation (*M*= .179, *SE* = .009). There was no effect of orientation, $F(1,27)$= .860, p=.362, η_{p2}= .031. Contrary to our hypothesis, there was no effect of cue-validity, $F(2,27)$= .495, p=.615, η_{p2}= .035.

Training Sessions

If any attentional differences exist, then such differences may be present as a function of training sessions. To investigate whether any differences occurred during training, contrast thresholds were obtained at the end of each training day. Contrast thresholds were examined using a 2 (attention type: exogenous, endogenous) x 3 (cue-validity: 100%, 80%, neutral) x 2 (training day: day 1, day 2) mixed–design ANOVA. Training day was a within-subjects factor. An effect of attention was found such that contrast thresholds of those in the endogenous attention conditions had significantly lower thresholds (M=.161, SE=.010) for both training days as compared to the exogenous attention condition (M=.193, SE=.010), F(1,54)= 4.880, p=.031, $\eta_p 2$= .083. Fig 5 shows training data as a function of different attention groups. These results suggest overall enhanced learning when endogenous attention, as compared to exogenous attention, is engaged during training. This may stem from learning-induced changes in both sensory feature representations and task-related processing. There was an effect of training day such that the second day of training (M=.156, SE=.007) had significantly lower thresholds than the first day of training (M=.199, SE= .008), F(1,54) = 131.11, p < .001, $\eta_p 2$= .708. Not only does it appear that training facilitated learning but sleep after a session of training appears to enhance learning, which suggests memory consolidation. Specifically, there is a noticeable decrease in thresholds from training day 1 to training day 2. As shown in Fig 6, this effect can be seen when examining the first block of the last training session (day 2, training block 7) and the last block of the first training session (day 1, training block 6). An analysis on the last block of the first training session (M=.199, SE= .008) and first block of the last training (M=.179, SE=.010) session reveal a significant decrease in threshold, F(1, 54) = 8.232, p =.006, $\eta_p 2$ = .132.

d' (sensitivity)

For each participant, a d' (measure of sensitivity/detection) was calculated. One participant did not produce a valid d' measure due to high correct rejection rate and so a correction was applied to the participant's data to obtain a valid d' measure [84]. To investigate whether there were any baseline group-level differences in sensitivity (d'), prior to training, between trained and untrained orientation, a 2(attention type: exogenous, endogenous) x 3(cue-validity: 100%, 80%, neutral) x 2(feature orientation: trained, untrained) mixed design ANOVA was conducted on d' measures. There was no effect of feature orientation, $F(1,54) = 2.619$, $p = .111$, $\eta_{p2}=.046$. Additionally, no 3-way interaction was observed, $F(2,54) = .201$, $p = .818$, $\eta_{p2}=.007$. This suggests no differences in sensitivity prior to training between trained and untrained orientations across all conditions.

Subsequent analyses allowed for comparisons across all groups (attention type (exogenous, endogenous) x cue validity (100% valid, 80% valid, neutral)). Changes in sensitivity across testing day was conducted using 2 (attention type: exogenous, endogenous) x 3 (cue-validity: 100%, 80%, neutral) x 2 (feature orientation: trained, untrained) x 2 (test-day: pre-test, post-test) mixed design ANOVA. There was an effect of orientation with greater sensitivity for trained orientation ($M = 1.721$, $SE =.056$) as compared to untrained orientation ($M = 1.595$, $SE = .058$), $F(1,54) = 4.152$, $p = .046$, $\eta_{p2}=.071$.

Discussion

The current study was concerned with investigating differential effects of exogenous and endogenous attention on TR-VPL on a novel yes/no detection task that involves determining the presence or absence of an additional sine-wave component in the gabor stimulus. We used this type of discrimination task because previous research has found rapid improvement with practice for this type of stimuli [23]. Analyses on pre-test contrast thresholds for trained and untrained orientation across cue-validity condition and attention type show that participants were not at similar levels of performance prior to training. High inter-observer variability is commonly found in the field of PL [16, 85-88]. In fact, not only are individual differences in initial performance levels common in the field of PL but also the rate of learning is variable among participants.

An analyses of attention x cue-validity x test day was problematic because of different baseline performances between the groups prior to training. For example, a group that performed well, prior to training, may already be at asymptotic performance with minimal range for improvement. In contrast, a group with very poor thresholds is likely to have a greater range for improvement. As a result, separate analyses were conducted based on the attention condition. For exogenous attention, there was an overall improvement of thresholds following training. When analyses were conducted separately by cue-validity condition, learning was observed across all cue-validity conditions for the trained orientation but these improvements did not transfer to the untrained orientation. This suggests that learning was specific to the trained feature when trained with exogenous cues, regardless of cue-validity. For the endogenous condition, different patterns of performance were observed between the cue-validity conditions. For the 100% cue-validity, learning was specific to the trained orientation. For the 80% cue-validity condition, learning was not observed for the trained orientation but performance improvements were observed for the untrained orientation. For the neutral condition, both learning and transfer was observed.

An alternative approach was to evaluate the magnitude of learning. Thus, any changes in performance could be evaluated with respect to an individual participant's initial performance level. There was a significant difference in the magnitude of learning between trained and untrained orientation. Improved thresholds following training were found across exogenous and endogenous attention regardless of cue-validity conditions. Moreover, the magnitude of improvement between exogenous and endogenous attention was comparable. This is consistent with previous studies that found both exogenous and endogenous attention facilitated both learning and transfer but evaluated in the context of learning across locations in an orientation discrimination task [73, 74]. The current study failed to find behavioral differences between exogenous and endogenous attention. It is possible that both forms of attention may lead to similar levels of improvement at the behavioral level. But the dissociation between endogenous and exogenous attention may stem from different mechanisms involved to achieve changes in performance. Previous studies demonstrated that training with either valid exogenous [73] or valid endogenous cues [74] both facilitated learning and location transfer. Despite similar performance improvements, distinct neural signatures underlie exogenous and endogenous attention with performance improvements for exogenous attention achieved via response gain [73] and for endogenous attention was achieved via contrast gain [74]. Threshold measurements employed in the current study may not estimate changes in performance to the same degree as accuracy measurements typically employed in PL studies. Previous research evaluating contrast thresholds and accuracy did not find any correlation between the behavioral changes observed during training and improvements in contrast sensitivity [72]. This study provides additional evidence that threshold measurements may be qualitatively different from accuracy measurements in the context of PL.

Cue-Validity

It was predicted that greater learning would occur for higher cue-validity conditions when endogenous attention was engaged. We did not find an interaction between attention and cue-validity on the magnitude of learning. Performance was comparable across attention type and cue-validity condition. This suggests that magnitude of learning does not vary with cue-validity when endogenous attention is engaged, which is at odds with previous findings [63]. The failure to find an effect could be due to the type of stimulus training. We utilized a task in which participants were presented with complex sine wave patterns. This task was used because it results in rapid learning. The current study trained participants over the course of 2 days for several hundred trials. This differs from a majority of PL studies that often train participants for several sessions and thousands of trials in order to produce training-related learning. However, few studies have employed fewer training sessions and were able to produce learning [22-24, or see 31, for a review]. Particularly relevant to the current study is that learning has been observed following a few hundred trials of training for complex grating patterns [22-23]. Studies that have examined the time course of learning have shown at least two different learning processes; rapid and slow learning [89]. Rapid learning occurs over a few hundred trials, affects higher-level processing, exhibits generalized learning, and may involve top-down processing by improving the link between task-dependent processing and sensory units while selecting optimal units for the task [2]. In contrast, slow learning is thought to be a slower process that occurs over several hundred trials or more, exhibits stimulus specific learning, and may involve lower-level processing by modulating primary sensory areas. It is possible that the failure to find a training difference based on the type of attention was due to the use of stimulus conditions that result in rapid learning as compared to slow learning. An important question will be to examine this question in future research.

Feature Transfer

Contrary to our hypothesis that feature transfer of training would occur via endogenous attention only, the results indicate feature transfer occurred for both exogenous and endogenous attention. This is not necessarily at odds with the Dual-Plasticity model [30, 78]. According to the Dual-Plasticity model, task-related processing involves both feature and task-based plasticity whereas feature-related processing involves feature-based plasticity. Given that both endogenous and exogenous attention may involve feature-based plasticity, transfer to an untrained feature may have occurred for both forms of attention. And so, any performance differences may not have been apparent because both attention types may have engaged similar mechanisms on the feature transfer task. Future research should focus on learning and transfer across different tasks between exogenous and endogenous attention and whether there is a differential effect of attention on transfer to an untrained task.

A caveat to this study is that it cannot rule out that feature transfer may be due to the novel paradigm employed. Generally, in the field of PL, performance improvements tend to be specific to the trained feature with performance improvements lost when stimulus feature or stimulus location has changed. Exceptions to this finding are studies that employ the double-training or training-plus-exposure technique [35, 90-92] or introducing variability in stimulus location or stimulus set, or exposure to an untrained location (see [31], for a review).

To account for conditions under which transfer occurs, the integrated reweighting theory posits that transfer to new retinal positions/locations is fundamentally different from transfer over stimulus features [40]. Location transfer is proposed to be mediated by location-independent representations whereas feature transfer reflects the compatibility of the weight structures between location-specific and location-independent representations. According to this framework, transfer is predicted when the same stimulus feature is presented in a new location and specificity is predicted when a new stimulus feature is presented to the same trained location. The study by Dosher and colleagues [40] examined the extent of transfer by training observers on an orientation discrimination task and subsequently randomly assigned participants to one of three conditions. Participants were either randomly assigned to continue training either in a condition in which the same stimulus feature was presented in a new location/position (P), a new stimulus feature was presented (O), or both a new orientation and new location was presented (OP). Greater transfer was found when the same stimulus feature was presented in a new location (P) than a new stimulus feature presented in the same location (O) [40].

But there was partial transfer when both a new stimulus feature and new location was presented. In the current study, the location of the target stimulus varied by trial and exposure to the untrained orientation in combination with rapid learning for the type of stimuli used may have enabled transfer of learning to the untrained orientation. Finding of generalization across untrained feature is more compatible with the view that learning occurs at a higher level of neuronal plasticity.

How might these findings fit within the broader context of attention and PL? The results of the present study suggest that the utility of attention in PL may depend on a variety of factors. For instance, the task configuration was optimal for targeting the early component processes involved in rapid learning. In studies involving rapid learning, the findings of specificity or transfer may well depend on the neural structures involved in the training task. With rapid learning, training of simple visual discriminations was found to be specific [31, 23] but training with visual search, which presumably involves neural structures further along the visual hierarchy, was found to transfer [94]. Additionally, the rapid improvements found in the current study may reflect an early component learning process that have been shown to exhibit generalized learning. Previous findings reported generalized learning in an early phase of training followed by specificity of learning [32, 42]. These studies are consistent with two qualitatively distinct component processes of learning; rapid and slow learning. This has important implications for training studies involving some marked visual dysfunction such as those with amblyopia. The source of dysfunction in amblyopes is loss of critical information in early visual processing. Thus, any effective intervention should restrict the site of training to target those neural structures, be broad enough to generalize learning, require little intervention yet maximal benefit, as well as minimal effort from the individual.

Whether specifically manipulating attention further enhances learning may require a closer look at the type of task utilized. It seems whether attention is distributed (as in the neutral cue-validity condition) or directed (as in the 100% or 80% cue-validity conditions), learning and transfer was observed. And so, learning was found across all conditions suggesting that, as least in this context, attention was sufficient for learning to occur. The type of transfer- feature transfer, location transfer or task transfer- may be constrained by the type of attention. Although, common mechanisms may activate both forms of attention which allow for the occurrence of feature transfer. However, other forms of transfer may depend on the type of attention. Despite inter-individual variability at initial levels of performance, all participants were at comparable levels following training. This finding suggests that attention may indeed reduce any individual differences in learning. Previous research found that individuals consistently exhibited transfer when trained with exogenous attentional cues [73].

Several factors of this study may have allowed for generalized learning to occur making it difficult to assess the effect of attention. However, this study does contribute to the growing literature that demonstrates specificity is not the only defining characteristic of PL. A complete characterization of PL also includes generalized learning and the factors involved. An increasing number of more recent papers suggest that it is unlikely that any one process or mechanism is responsible for PL. Instead, multiple components of learning likely work together to produce changes in performance [95]. Complete characterization of PL involves viewing PL as a distributed process by which degree of learning and transfer are mediated by attributes of the task and stimuli used and moderated by characteristics of the individual. By extension, the exact role of attention may vary based on the configuration of the stimulus and the task. Attention may contribute to generalized learning but the nature of the training improvements and type of transfer may well depend on the type of attention.

In summary, the present findings observed learning and feature transfer across both types of attention regardless of cue-validity. Given the time-course of the study, rapid improvements were found in a few hundred trials which may reflect an early component of the learning process. This rapid learning may partly account for the finding of learning and feature transfer across conditions. Rapid learning may be qualitatively distinct from the type of learning observed in most PL studies that employ longer training trials and sessions. Thus, it is possible that employing another task that utilizes more extensive training could result in different patterns of learning and transfer. The findings here suggest that the effect of exogenous or endogenous may depend on the speed of learning.

Figures & Tables

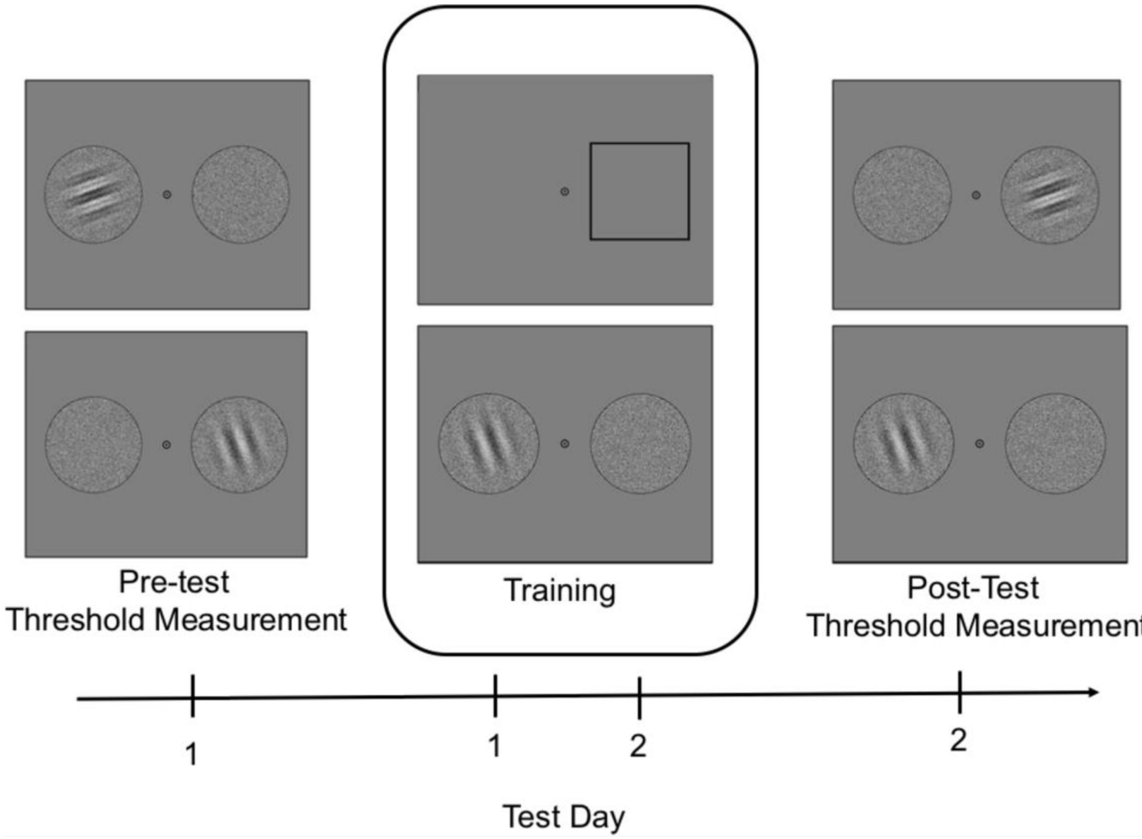

Figure 1.1. Time course of the experiment. Contrast thresholds for trained and untrained orientation were obtained at 75% correct. Training sessions occurred on day 1 and day 2 after pre-test and prior to post-test. Attention (exogenous, endogenous) and cue-validity (100%, 80%, neutral) were manipulated at training.

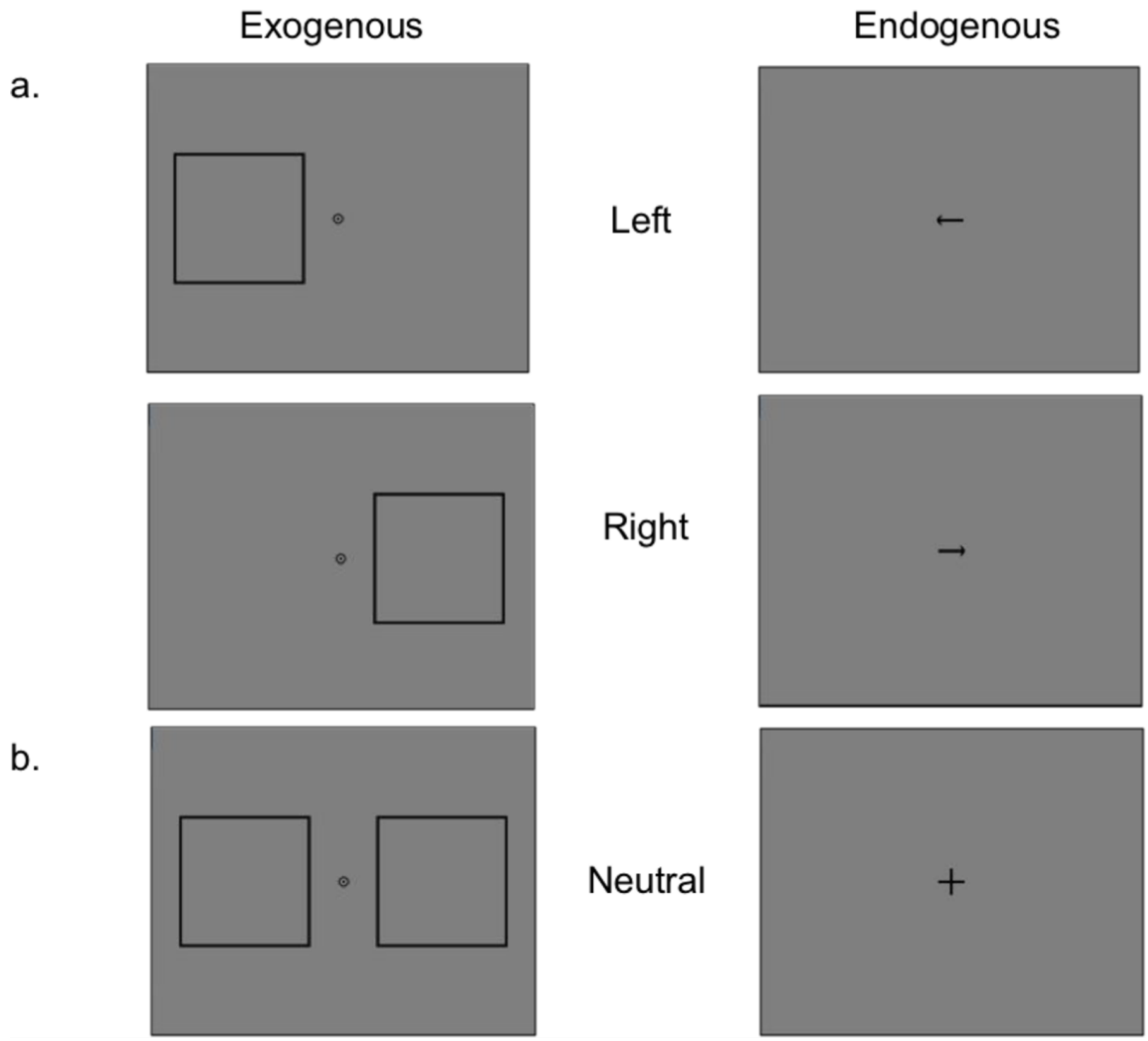

Figure 1.2. Attention cues (exogenous, endogenous) used during training. Left column shows exogenous cues, which were presented for 67ms. Right column shows endogenous cues, which were presented for 305ms. (a) left indicating (top-row) and right indicating (bottom-row) cues for either valid/invalid trials presented for 100% and 80% cue-validity condition. (b) neutral cues were presented only for the neutral cue-validity condition.

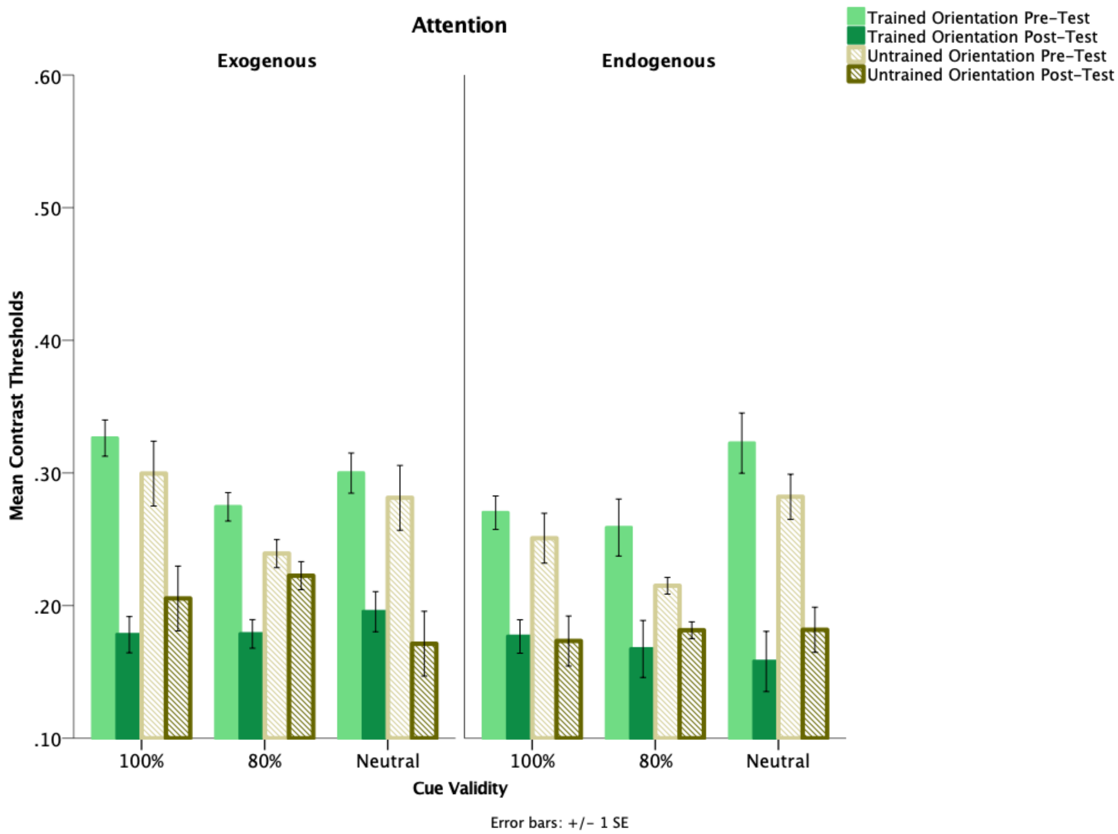

Figure 1.3. Changes contrast thresholds measured at pre-test and post-test. Contrast thresholds measured at pre-test and post-test for both trained and untrained orientation as a function of attention and cue-validity. Error bars indicate +/- 1 within-subjects standard error.

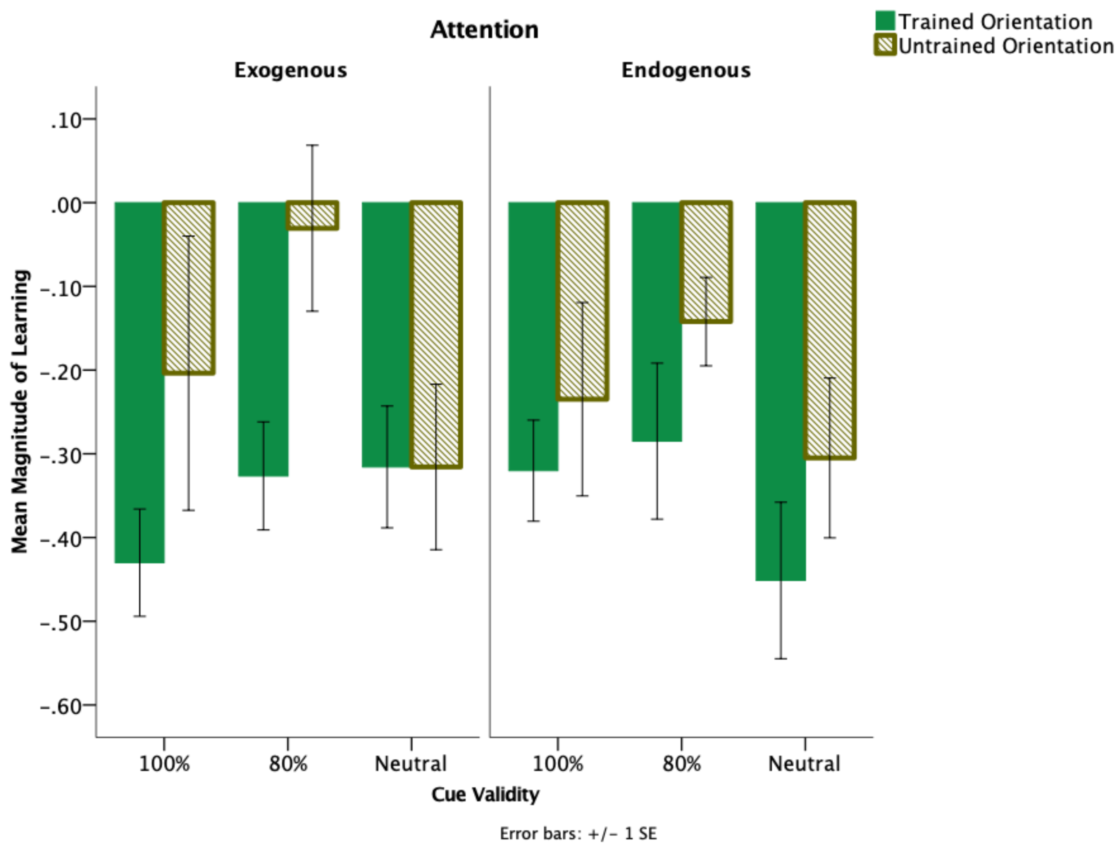

Figure 1.4. Magnitude of learning as a function of cue-validity and attention. Larger negative values indicate greater learning. Error bars indicate +/- 1 within-subjects standard error.

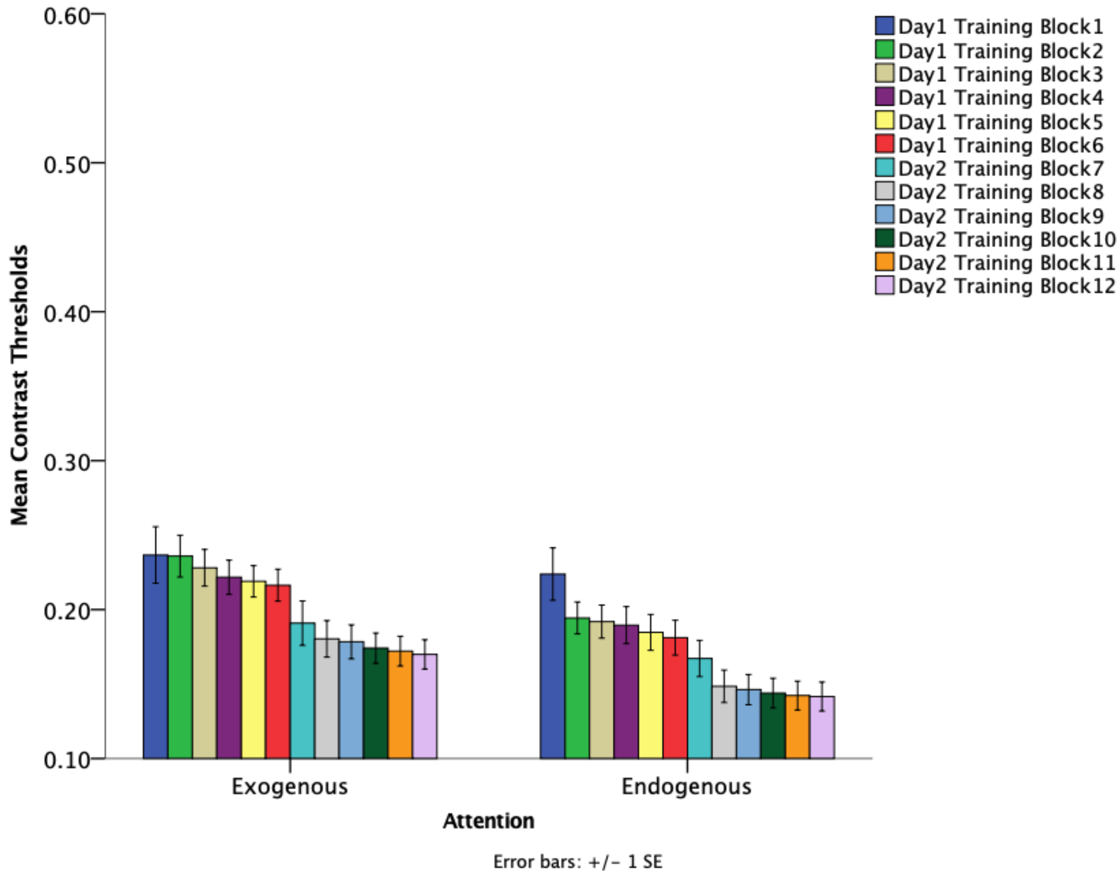

Figure 1.5. Mean contrast thresholds for training data as a function of Attention. Blocks 1-6 were on training day 1 and blocks 7-12 were on training day 2. Error bars indicate +/- 1 standard error.

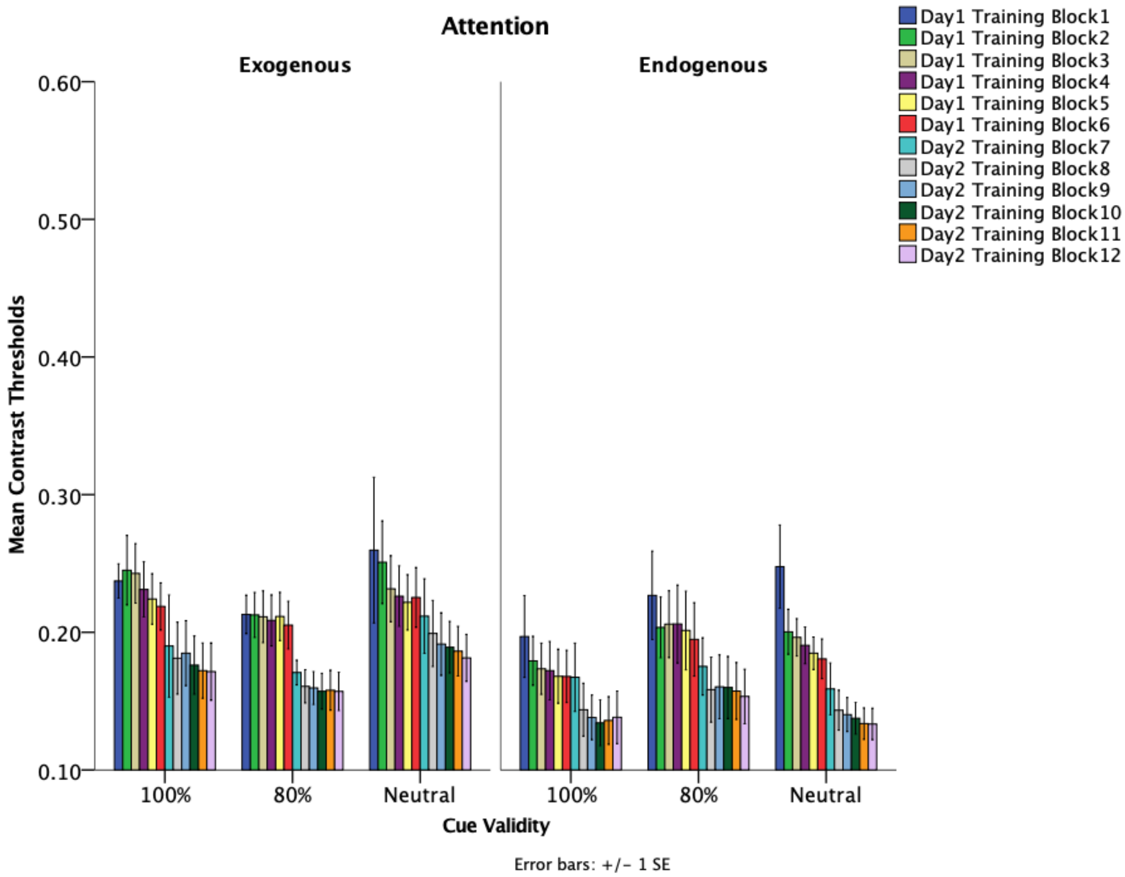

Figure 1.6. Mean contrast thresholds for training data as a function of Cue-Validity and Attention. Blocks 1-6 were on training day 1 and blocks 7-12 were on training day 2. Error bars indicate +/- 1 standard error.

References

1. Ball, K., & Sekuler, R. (1981). Adaptive processing of visual motion. *J. Exp. Psychol. Hum. Percept. Perform*. 7, 780–794. doi: 10.1037/0096-1523.7.4.780.

2. Sagi, D. & Tanne, D. (1994) Perceptual-learning – learning to see. *Current Opinion in Neurobiology*, *4*(2),195–199.

3. Crist R.E., Li W, & Gilbert C.D. (2001). Learning to see: experience and attention in primary visual cortex. *Nat. Neurosci., 4*, 519–25.

4. Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience, 27*, 11401–11411.

5. Yotsumoto Y., Watanabe T., & Sasaki Y. (2008) Different dynamics of performance and brain activation in the time course of perceptual learning. *Neuron*, 57, 827–33.

6. Andersen G.J. (2012). Aging and vision: changes in function and performance from optics to perception. *Wiley Interdiscip. Rev. Cogn. Sci., 3*, 403–10.

7. Baker, C. I., Peli, E., Knouf, N., & Kanwisher, N. G. (2005). Reorganization of visual processing in macular degeneration. *J. Neurosci., 25*, 614–618. doi: 10.1523/JNEUROSCI.3476-04.2005.

8. Polat, U. (2009) Making perceptual learning practical to improve visual functions. *Vision Research, 49*, 2566–2573.

9. Polat, U., Schor, C., Tong, J.-L., Zomet, A., Lev, M., Yehezkel, O. Sterkin, A., & Levi, D. M. (2012). Training the brain to overcome the effect of aging on the human eye. *Scientific Reports*, *2*, 278. http://doi.org/10.1038/srep00278.

10. Levi, D.M. (2005) Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Dev Psychobiol, 46,* 222–232.

11. Levi, D. M., & Li, R. W. (2009). Improving the performance of the amblyopic visual system. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 364(*1515), 399–407.

12. Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences of the United States of America, 93*(13), 6830–6834.

13. Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences of the United States of America, 101*(17), 6692–6697.

14. Ahissar, M., & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature, 387*, 401–6.

15. Liu, Z., & Weinshall, D. (2000). Mechanisms of generalization in perceptual learning. *Vision Research*, *40*(1), 97–109.

16. Jeter, P. E., Dosher, B. A., Petrov, A., & Lu, Z. L. (2009). Task precision at transfer determines specificity of perceptual learning. *Journal of Vision, 9*(3), 1–13.

17. Wang, R., Zhang, J. Y., Klein, S. A., Levi, D. M., & Yu C. (2012). Task relevancy and demand modulate double-training enabled transfer of perceptual learning. *Vision Research*, *61,* 33–38.

18. Yotsumoto, Y., Chang, L. H., Ni, R., Salat, D., Andersen, G., Watanabe, T., & Sasaki, Y. (2010). Perceptual learning and changes in white matter in aged brain revealed by difusion-tensor imaging (DTI). *Journal of Vision, 10*(7), 912.

19. Yotsumoto, Y., Chang, L.H., Ni, R., Pierce, R., Andersen, G.J., Watanabe, T., & Sasaki, Y. (2014). White matter in the older brain is more plastic than in the younger brain. *Nature Communications*, *5*, 5504.

20. Shibata, K., Watanabe, T., Sasaki, Y. & Kawato, M.(2011) Perceptual learning incepted by decoded fMRI neurofeedback without stimulus presentation. *Science*, *334*(6061), 1413-1415.

21. Yotsumoto, Y. & Watanabe, T. (2008). Defining a link between perceptual learning and Attention. *PLoS Biology, 6*(8), e221.

22. Fiorentini A, Berardi N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature, 287*, 43–44.

23. Fiorentini, A., & Berardi, N. (1981) Learning in grating wave form discrimination: specificity for orientation and spatial frequency. *Vision Research*, *21*, 1149–1158.

24. Poggio, T., Fahle, M., & Edelman, S. (1992) Fast perceptual learning in visual hyperacuity. *Science. 256*, 1018–1021.

25. Ball, K., & Sekuler, R. (1982). A specific and enduring improvement in visual motion discrimination. *Science*, *218,* 697–698.

26. Ball, K., & Sekuler, R. (1987). Direction-specific improvement in motion discrimination. *Vision Research, 27*, 953–65.

27. Adini, Y., Sagi, D., & Tsodyks, M. (2002). Context-enabled learning in the human visual system. *Nature*, *415*,790–93.

28. Yu, C., Klein, S. A., & Levi, D. M. (2004). Perceptual learning in contrast discrimination and the (minimal) role of context. *Journal of Vision, 4*(3), 169–182.

29. Hua, T., Bao, P., Huang, C.B., Wang, Z., Xu, J., Zhou, Y., & Lu, Z.L. (2010). Perceptual learning improves contrast sensitivity of V1 neurons in cats. *Current Biology, 20*, 887–94.

30. Watanabe, T., & Sasaki, Y., (2015). Perceptual Learning: toward a comprehensive theory. Annu. Rev. Psychol. http://dx.doi.org/10.1146/annurev-psych-010814-015214.

31. Sagi, D. (2011) Perceptual learning in vision research. *Vision Research, 51*, 1552-1566.

32. Jeter, P. E., Dosher, B. A., Liu, S. H., & Lu, Z. L. (2010). Specificity of perceptual learning increases with increased training. *Vision Research, 50*(19), 1928–1940.

33. Szpiro, S. F. A., & Carrasco, M. (2015). Exogenous attention enables visual perceptual learning. *Psychological Science, 27(4), 592.* https://doi.org/10.1177/0956797616636342

34. Liu, Z. (1999). Perceptual learning in motion discrimination that generalizes across motion directions. *Proc. Natl. Acad. Sci.* USA, *96*, 14085–87.

35. Xiao, L.Q., Zhang, J.Y., Wang, R., Klein, S.A., Levi, D.M., & Yu, C. (2008) Complete transfer of perceptual learning across retinal locations enabled by double training. *Current biology, 18,* 1922–6.

36. Dosher, B.A., & Lu, Z.L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proc. Natl. Acad. Sci.* USA, *95*, 13988–93.

37. Dosher, B.A., & Lu, Z.L. (1999). Mechanisms of perceptual learning. *Vision Research*, 39, 3197–221.

38. Liu, J., Lu, Z.L., & Dosher, B.A. (2010). Augmented Hebbian reweighting: interactions between feedback and training accuracy in perceptual learning. *Journal of Vision, 10*, 29.

39. Petrov, A.A., Dosher, B.A., & Lu, Z.L. (2005). The dynamics of perceptual learning: an incremental reweighting model. *Psychol. Rev., 112*, 715–43.

40. Dosher, B.A., Jeter, P., Liu, J., & Lu, Z.L. (2013). An integrated reweighting theory of perceptual learning. *Proc. Natl. Acad. Sci.* USA, *110*, 13678–83.

41. Ahissar, M., & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences, 8*, 457–464.

42. Aberg, K. C., Tartaglia, E. M., & Herzog, M. H. (2009). Perceptual learning with Chevrons requires a minimal number of trials, transfers to untrained directions, but does not require sleep. *Vision Research, 49*(16), 2087–2094.

43. Seitz, A., & Watanabe, T. (2005). A unified model for perceptual learning. *Trends Cogn. Sci.* 9:329–34.

44. Watanabe, T., Nanez, J.E., & Sasaki, Y. (2001). Perceptual learning without perception. *Nature, 413*, 844–48.

45. Seitz, A. R., & Watanabe, T. (2009). The phenomenon of task-irrelevant perceptual learning. *Vision Research, 49*, 2604–2610.

46. Gutnisky, D.A., Hansen, B.J., Iliescu, B.F., & Dragoi, V. (2009). Attention alters visual plasticity during exposure-based learning. *Current Biology*, 19, 555–60.

47. Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 121−134.

48. Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(5),601-21.

49. Jonides J. & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43*, 346-354.

50. Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 95−107.

51. Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 676−681.

52. Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In: Long, JB.; Baddeley, AD., editors. Attention & performance IX. Erlbaum; Hillsdale, NJ: 187-203.

53. Lu, Z.L., & Dosher, B.A. (2000) Spatial attention: Different mechanisms for central and peripheral temporal precues?, *Journal of Experimental Psychology: Human Perception and Human Performance*, *26*(5), 1534-1548.

54. Lu, Z.L., & Dosher, B.A. (1998) External noise distinguishes attention mechanisms. *Vision Research, 38*,1183–1198.

55. Theeuwes J. (2010) Top-down and bottom-up control of visual selection. *Acta Psychologica, 135*(2), 77-99.

56. Cheal M., Lyon D. (1991) Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*. *43*(4), 859–880.

57. Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*(11), 1631–1647.

58. Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*(4), 1030−1044.

59. Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

60. Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research, 51*, 1484–1525.

61. Suzuki, S., & Cavanagh, P. (1997). Focused attention distorts visual space: An attentional repulsion effect. *Journal of Experimental Psychology: Human Perception and Performance*, 23(2), 443–463.

62. Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research*, 33(9), 1219–1240.

63. Giordano, A. M., McElree, B., & Carrasco, M. (2009). On the automaticity and flexibility of covert attention: A speed-accuracy trade-off analysis. *Journal of Vision, 9*(3), 10–31.

64. Yeshurun, Y., Montagna, B., & Carrasco, M. (2008). On the flexibility of sustained attention and its effects on a texture segmentation task. *Vision Research, 48*(1), 80–95.

65. Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution, *Nature, 396* (6706), 72–75.

66. Muller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(2), 315–330.

67. Posner M.I., Nissen, M.J., & Ogden, W.C. (1978). Attended and unattended processing modes: The role of set for spatial location. J.H.I. Pick, E. Saltzman (Eds.), *Modes of perceiving and processing information* (pp.137-157). Erlbaum, Hillsdale, NJ, 137-157.

68. Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage, 31*(2), 774–789.

69. Posner, M.I. & Cohen, Y. (1984) Components of Visual Orienting. In: Bouma, H. and Bouwhuis, D.G., Eds., Attention and Performance X: Control of Language Processes, Erlbaum, Hillsdale, 531-556.

70. Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

71. Tsushima, Y., & Watanabe, T. (2009). Roles of attention in perceptual learning from perspectives of psychophysics and animal learning. *Learn. Behav., 37,* 126–32.

72. Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-test target thresholds. *Journal of Vision, 11*(1), Article 25. doi:10.1167/11.1.125.

73. Donovan, I., Szpiro, S., & Carrasco, M. (2015). Exogenous attention facilitates perceptual learning transfer within and across visual hemifields. *Journal of Vision*, *15*(10), Article 11. doi:10.1167/15.10.11.

74. Donovan, I., & Carrasco, M. (2018). Endogenous spatial attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7,1-16. https://doi.org/10.1167/18.11.7.

75. Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168–185.

76. Donovan, I., Shen, A., Barbot, A., & Carrasco, M. (2019, May). Does exogenous spatial attention facilitate perceptual learning transfer in acuity and hyperacuity tasks? *Journal of Vision*, *19*(10):26d. doi: https://doi.org/10.1167/19.10.26d.

77. Hochstein, S., & Ahissar, M. (2002). View from the top: hierarchies and reverse hierarchies in the visual system. *Neuron, 36,* 791–804.

78. Shibata, K., Sagi, D., & Watanabe, T. (2014) Two stage model of perceptual learning, *the Year in Cognitive Neuroscience, Annual Review of New York Academy of Sciences, 1316*, 18-28.

79. Shibata, K., Sasaki, Y., Kawato, M., & Watanabe, T. (2016) Neuroimaging evidence for two types of plasticity in association with visual perceptual learning. *Cerebral Cortex*, 26 (9), 3681-3689.

80. Shibata, K., Yamagishi, N., Ishii, S., & Kawato, M. (2009). Boosting perceptual learning by fake feedback. *Vision Research, 49*, 2574–2585.

81. Peli, E. (1990). Contrast in complex images. *J. Opt. Soc. Am. A., 7*(10), 2032-2040.

82. Mayfrank, L., Kimmig, H., & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. In J. K. O'Reganm & A. Levy-Schoen (Eds.), Eye movements: From physiology to cognition (pp. 37–45). NY: North-Holland.

83. Watson, A. A. B., & Pelli, D. G. D. (1983). QUEST: A Bayesian adaptive psychometric method. *Attention, Perception, & Psychophysics, 33*, 113–120.

84. Hautus, M.J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d'. *Behavior Research, Methods, Instruments & Computers, 27*, 46-51. https://doi.org/10.3758/BF03203619.

85. Fahle, M., & Henke-Fahle, S. (1996) Interobserver variance in perceptual performance and learning. *Investigative Ophthalmology & Visual Science, 37*, 869–877.

86. Fine, I., & Jacobs, R.A. (2002). Comparing perceptual learning tasks: a review. *Journal of Vision, 2*(2), 190-203.

87. Kumar, T., & Glaser, D. A. (1993). Initial performance, learning and observer variability for hyperacuity tasks. *Vision Research, 33*, 2287–2300.

88. Fahle, M., & Edelman, S., (1993), Long-term learning in vernier acuity: Effects of stimulus orientation, range and of feedback. *Vision Research, 33*(3), 397-412.

89. Karni, A., & Sagi, D. (1993). The time course of learning a visual skill. *Nature, 365*, 250–52.

90. Zhang, T., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Decoupling location specificity from perceptual learning of orientation discrimination. *Vision Research, 50*(4), 368–374, https://doi.org/10. 1016/j.visres.2009.08.024.

91. Zhang J. Y. & Yang Y. X. (2014). Perception learning of motion direction discrimination transfers to an opposite direction with TPE training. *Vision Research*, *99*, 93–98.

92. Wang R., Zhang J. Y., Klein S. A., Levi D. M., Yu C. (2014). Vernier perceptual learning transfers to completely untrained retinal locations after double training: A "piggybacking" effect. *Journal of Vision*, 14 (13): 12, 1–12, doi:10.1167/14.13.12.

93. Fahle, M., Edelman, S., & Poggio, T. (1995). Fast perceptual learning in hyperacuity. *Vision Research, 35,* 3003–13.

94. Sireteanu, R., & Rettenbach, R. (2000). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research*, 40(21), 2925-2949.

95. Maniglia & Seitz (2017), "Towards a whole brain model of Perceptual Learning ", *Current Opinion in Behavioral Sciences*, *20*, 47-55. doi: 10.1016/j.cobeha.2017.10.004.

Chapter 2

Aging, endogenous attention and perceptual learning

Kieu Ngoc Nguyen[1] & George John Andersen[1]

Author Affiliations:

[1] Department of Psychology, University of California, Riverside, Riverside, California, United States of America

Abstract

Recent research has been focused on characterizing the role of attention in perceptual learning (PL) and specificity in college-aged adults. However, few studies have examined how attention and learning may be affected by aging. Given the reported age-related declines in types of visual function and attention, an important question is whether and how older adults benefit from PL training with attention and whether PL training improves attentional processing. The present study examined the role of endogenous attention in PL in the context of aging. Forty-eight older and younger adults were randomly assigned to one of two endogenous attention conditions; a valid cue or a neutral cue. All participants were trained on an orientation discrimination task for three days and performance was evaluated prior to and following the training days. To assess whether there were any changes in attention as a result of training, UFOV scores were administered prior to and after training days. Different patterns of performance were found for the age groups. Endogenous attention facilitated learning for both age groups. Furthermore, these performance improvements transferred to untrained locations for both age groups but were potentially achieved via different processes. Transfer was achieved via contrast thresholds for younger adults when trained with valid cues. For older adults, transfer via asymptote occurred irrespective of the type of cue presented. These findings indicate that older adults benefit from attention-induced PL but the optimal type of training protocol may differ between older and younger adults.

Introduction

Multiple types of visual processing decline with age. These declines could impact the health and well-being of an older population – ages 65 years or older. Changes in visual function has been implicated as a contributing factor to the incidence of falls among the elderly (Lord, Dayhew & Howland, 2002), increased vehicle accident risk (Evans, 2004; Owsley, Ball, Sloane, Roenker & Bruni, 1991) and decreased mobility (Menz, Morris & Lord, 2005; Wahl, Schilling, Oswald & Heyl, 1999). Although there is evidence of age-related changes in the optics of the eye, these changes alone do not account for age-related changes in sensory and perceptual processing (see, Andersen, 2012, for a review). According to Andersen (2012), research has demonstrated age-related declines in the contrast sensitivity function dependent on spatial frequency particularly for intermediate to higher spatial frequencies (Sekuler, Owsley & Hutman, 1982). Additionally, age-related declines in motion have been found to be selective. For instance, it was reported that older adults have difficulty with both 2D motion and 3D shape from motion but that performance on both tasks were uncorrelated (Atchley & Andersen, 1995). This suggests that age-related declines in 2D and 3D motion may be mediated by different mechanisms. If declines were due to optics alone, then declines in visual processing should be uniform (Andersen, 2012). However, the idiosyncratic changes across different types of visual input suggest that declines may not stem from changes in optics alone.

What interventions are possible to address these declines? Declines in visual function could, to some degree, be ameliorated with practice. Perceptual learning is practice or training on a perceptual task that can result in perceptual improvement (Gibson, 1953). These perceptual improvements can be long-lasting (Crist, Li, & Gilbert, 2001; Sagi & Tanne, 1994; Ball & Sekuler, 1981) and could modify neural processes, known as neural plasticity (Yotsumoto, Watanabe, & Sasaki, 2008; Mukai, Kim, Fukunaga, Japee, Marrett & Ungerleidger, 2007). It is well-documented in the literature in college-aged adults that PL can improve visual function for a wide variety of visual tasks such as texture (Karni & Sagi, 1991) contrast (Adini, Sagi, Tsodyks, 2002; Yu, Klein & Levi, 2004), motion (Ball & Sekuler, 1986), orientation (Fiorentini & Berardi, 1980;1981), divided attention (Richards, Bennett, & Sekuler, 2006), collision detection (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss, & Andersen, 2017), and action video game play (Belchior, Marsiske, Sisco, Yam, Bavelier, Ball & Mann, 2013).

Research on aging and PL have demonstrated that older adults, like younger adults, can benefit from PL training. For example, one study demonstrated that contrast sensitivity of older adults could be improved with PL and that these improvements were similar to performance of untrained younger adults (Deloss, Watanabe, & Andersen, 2014). In addition, improvements were found in near acuity in older adults but improved far acuity in younger adults. Given that both age groups benefit from PL, an important question is whether similar processes underlie PL improvement in both younger and older adults? One study investigated the underlying neural systems that are modified by PL in both older and younger adults (Yotsumoto, Chang, Ni, Pierce, Andersen, Watanabe, & Sasaki, 2014). Using diffusion tensor imaging, changes in white matter were evaluated before and after 3 days of behavioral training. An index commonly derived from DTI is fractional anisotropy (FA). FA is sensitive to changes in the properties of white matter microstructure. Although the magnitude of the behavioral improvements due to training was comparable, the nature of the underlying improvements differed between both age groups. Increases in FA were found for underlying areas of V3 cortex in older adults but not younger adults. This suggests that the underlying mechanism for PL may differ between younger and older adults.

In addition to age-related declines in vision, there is also evidence of specific declines in visual attention. Let us review this evidence in detail. Attention has been identified as involving two distinct processes; exogenous and endogenous attention. Exogenous attention is a relatively automatic, reflexive process and is deployed approximately 100-120ms after the onset of a cue (Theeuwes, 2010; Cheal, Lyon & Hubbard, 1991; Nakayama & Mackeben, 1989). This type of attention is driven by salient or novel properties of a scene or stimuli - such as color, orientation, luminance (Yantis & Hillstrom, 1994; Yantis, 1993). Studies have found that exogenous attention is a reflexive process that occurs automatically (Yantis & Jonides, 1990; 1984; Jonides & Yantis; 1988), and is difficult to ignore (Jonides, 1981). Mechanisms of exogenous attention may occur via feed-forward signals propagated from lower sensory areas to higher cognitive processing areas. Cues, presented in the periphery near or at target stimuli, are commonly employed to elicit exogenous attention.

On the other hand, endogenous attention is a voluntary, intentional, goal-driven process. With this type of attention, resources are directed to processing information that is relevant to the observer. A common paradigm to assess the effect of endogenous spatial attention on visual perceptual processing is to present a cue, at or near the fovea, to participants prior to the stimulus presentation (Posner, 1980). A centrally presented symbolic cue, such as an arrow, would indicate the possible location of a subsequently presented target. This type of cue, thought to engage endogenous attention, requires processing of the cue to determine the location of the target. Studies have found that this type of attention is deployed approximately 300 msec after the onset of a cue (Jonides, 1981; Muller & Rabbitt, 1989, Carrasco, 2011). The endogenous cue could indicate a correct location (valid trial), an incorrect location (invalid trial), or give no indication to the location of the target (neutral trial). Performance for valid cues has been found to be faster and/or more accurate, as compared to performance for invalid trials or neutral trials (Posner, Nissen and Ogden, 1978; Jonides, 1981). The mechanism of endogenous attention has been proposed to involve recurrent feedback connections that descend from higher cortical processing areas to lower sensory processing areas (Desimone & Duncan, 1995; Corbetta & Shulman, 2002).

Research suggests that endogenous and exogenous attention may involve separate neutral substrates as well as common neutral substrates to allow for interactions of the two systems (Chica, Bartolomeo, & Lupiáñez, 2013; Reuter-Lorenz & Fendrich, 1992; Rohenkohl, Coull & Nobre, 2011; Rosen, Rao, Caffarra, Scaglioni, Bobholz, Woodley, Hammeke, Cunningham, Prieto, & Binder, (1999). Neuroimaging has yielded evidence of activation in intraparietal and superior frontal cortex area when endogenous attention is engaged (Corbetta & Shulman, 2002). Exogenous attention has been associated with activation in the temporoparietal cortex and inferior frontal cortex (Corbetta & Shulman, 2002). In the context of aging and cognition, exogenous and endogenous attention may be differentially affected by aging. Sensory declines in early levels of processing may contribute to age-related differences in performance. Declines in sensory processing at the behavioral and neural level likely impact the ability to perform any early-level perceptual task when attention is engaged. However, age-related attentional declines cannot be attributed to sensory declines alone when controlling for sensory factors. Of particular interest are age-related declines due to spatial endogenous attention. In general, older adults are less efficient, or slower, to process the meaning of an endogenous cue yet show no deficit in shifting attention in response to endogenous cues (Brodeur & Enns, 1997; Folk & Hoyer, 1992; Hartley & Kieley, 1995; Iarocci, Enns, Randolph & Burack, 2009; Lien, Gemperle, & Ruthruff, 2011).

A task that has been extensively studied to assess age-related differences in sensory and attentional processing is the useful field of view task (UFOV). UFOV is a measure of the spatial extent of attention which is the spatial region of the visual field from which an observer can extract visual information (Sekuler & Ball, 1986; Ball, Beard, Roenker, Miller, & Griggs, 1988; Scialfa, Kline, & Lyman, 1987). The UFOV assesses three different attentional abilities: processing speed, divided attention, and selective attention. Processing speed is the amount of time an observer needs to accurately discriminate visual information. In UFOV, processing speed is obtained by deriving threshold performance for centrally-presented stimuli. Divided attention involves the ability to simultaneously discriminate multiple presented stimuli. UFOV assesses divided attention by obtaining a threshold for both centrally and peripherally-presented stimuli. Selective attention is the ability to process multiple stimuli in the presence of irrelevant distractors. This is similar to the divided attention task in the UFOV but with the addition of distractors. Declines in performance on the divided-attention component of the UFOV are particularly pronounced in older adults (Sekuler, Bennett, & Mamelak 2000; Sekuler & Ball, 1986). Declines in spatial extent of attention were evident in early adulthood (approximately 20 years of age) and decade-by-decade, steadily becomes pronounced with increasing age (Sekuler, Bennett & Mamelak, 2000).

Previous studies have employed PL as an intervention to improve attentional processing and counteract age-related attentional declines in older adults as assessed by the UFOV task (Richards, Bennett, & Sekuler, 2006; Belchior et al., 2013). PL training with UFOV resulted in improved performance in divided attention for older observers. The spatial extent of the UFOV increased (indicating greater function of divided attention) for older adults following 4 days of training and the improvement was retained for up to 3 months. These performance improvements transferred to untrained peripheral locations in both older adults and younger adults (Richards, Bennett, & Sekuler, 2006). PL training with action video games- a complex perceptual task- has been found to improve many aspects of attention (refer to Green & Bavelier, 2012), and could lead to changes in UFOV in college-aged adults (Green & Bavelier, 2006; 2003; Achtman, Green, & Bavelier, 2008) as well as older adults (Belchior et al., 2014). Training may optimize the effectiveness of top-down attention control (see Byers & Serences, 2012). According to Byers and Serences (2012), improving attentional control via training could induce plasticity in local connections so that top-down attentional modulations can be minimized. Results consistent with this hypothesis has demonstrated a reduction in the magnitude of activation, following training, in areas of the frontoparietal cortex commonly thought to mediate attentional control (Mukai et al., 2007; Sigman, Pan, Yang, Stern, Silbersweig, & Gilbert, 2005). This suggests that, initially, top-down attentional control is recruited but through the course of training its effect becomes minimized. This may explain why video game players, who score high on various attentional measures, exhibit greater rates of learning on novel tasks as compared to non-video game players (Green & Bavelier, 2012).

Evidence of top-down processing assessed using a cued spatial-attention task indicated additional recruitment of the frontal-parietal network (Madden, Spaniol, Whiting, Bucur, Provenzale, Cabeza, White, & Huettel, 2007). This suggests that older adults may engage top-down processes to compensate for declines in bottom-up processes in order to retain performance. Even under conditions that do not lead to a pronounced age-related decline in occipital activation, older adults show greater activation than younger adults in top-down attentional mechanisms. Greater reliance on frontal and parietal regions as compensation for bottom-up deficits may be counterproductive as these regions are more susceptible to age-related declines (Madden 2007; Madden, et al., 2007; Raz, Lindenberger, Rodrigue, Kennedy, Head, Williamson, Dahle, Gerstorf, & Acker, 2005; Salat, Tuch, Hevelone, Fischl, Corkin, Rosas & Dale, 2005). One explanation as to why older adults show over-utilization of top-down processes may stem from decreased cortical inhibition. Previous research found decreased selectivity and increased excitability of cells in older monkeys consistent with an age-related degeneration of intra-cortical inhibition (Schmolesky, Wang, Pu, & Leventhal, 2000). The increased activation in top-down attentional processes may thus reflect declines in cortical inhibition. For example, older adults exhibit difficulty in inhibiting/ignoring irrelevant information known as attentional inhibition. This deficit in attentional inhibition have led older adults to be more susceptible to the distracting effects of irrelevant and interfering stimuli (Sekuler & Ball, 1986).

One outcome of a decline in inhibiting irrelevant information is that observers may be prone to learning irrelevant stimuli. Previous studies have investigated whether older adults would learn unimportant or irrelevant information that would otherwise be suppressed or ignored and thus not learned in younger adults (Chang, Shibata, Andersen, Sasaki, & Watanabe, 2014). Learning was observed after repeated exposure to a task-irrelevant and sub-threshold stimulus feature and has been referred to as task-irrelevant PL (TIPL) (Watanabe, Nanez & Sasaki, 2001). With TIPL, failure to suppress weak task-irrelevant or sub-threshold signals allow the non-suppressed signals to be learned. However, irrelevant signals are subject to attentional inhibition if it competes with the relevant signals (Seitz & Watanabe, 2009). Thus, task-irrelevant stimuli that is supra-threshold and thus engages the attentional system would be subsequently suppressed and not induce PL (Tsushima, Seitz & Watanabe, 2008). However, older adults learned task-irrelevant features that younger adults did not learn (Chang, Shibata, Andersen, Sasaki, & Watanabe, 2014). Older adults learned both the features that were sufficiently strong for younger adults to suppress as well as the features that were too weak for younger adults to learn. Given that the older adults, as compared to younger adults, showed significant task-relevant PL these findings were interpreted as a decline in stability rather than plasticity. Stability refers to stable representations in response to incoming visual information so that important information can be retained. Plasticity is defined as experience-dependent processing that can result in long-lasting neural structural changes in order to support behavior. In regard to stability and plasticity, an older adults' visual system can continue to change with learning but the ability to prevent unimportant or irrelevant information from being learned may be compromised.

If plasticity is retained in older adults but stability compromised, what consequence does this have on PL training? In addition, could the effect of PL transfer to untrained perceptual attributes in older adults? A ubiquitous property of PL is specificity. Specificity occurs when performance improvements as a result of PL is specific to the trained feature/task/location but the performance benefits fail to transfer to novel feature/task/location. Specificity is commonly found in PL studies although some studies have found generalized learning by modifying attributes of the task (Ahissar & Hochstein, 1997, 2004; Jeter, Dosher, Liu & Lu, 2010; Aberg, Tartagla, & Herzog, 2009), employing specific training procedures as in double-training (Xiao, Zhang, Wang, Klein, Levi & Yu, 2008), training-plus-exposure (Zhang, Zhang, Xiao, Klein, Levi, Yu, 2010) and utilizing attention (Donovan & Carrasco, 2018; Donovan, Szpiro & Carrasco, 2015; Szpiro & Carrasco, 2015). It may be worthwhile to consider specificity and generalization as representing extremes along a continuum, either of which could theoretically be the ideal learning solution depending on the training conditions (Green & Bavelier, 2012).

Attention is often postulated as important for training to improve perceptual performance (Ahissar & Hochstein, 1993, 2004; Crist, Li & Gilbert, 2001; Gilbert, Sigman & Crist, 2001; Tartaglia, Bamert, Mast & Herzog, 2009). At a minimum, attention is sufficient for learning to occur (Bartolucci & Smith, 2011; Mukai, Bahadur, Kesavabhotla & Ungerleider, 2011; Szpiro & Carrasco, 2015). Many theories have proposed a specific process for the role of attention in PL. For example, one theory is that attention may serve as a gating mechanism to enable PL (Tsushima & Watanabe, 2009). Attention may provide the important contextual information to enable learning of relevant information and the prevention of learning irrelevant unwanted information.

The present study is focused on determining the role of attention in PL and location transfer in the context of aging. Given the results of previous research, the present research examined a number of important questions. First, how does performance change in PL for older adults when deploying an endogenous cue? Several key findings motivate this first question. It may be that initial performance level may influence the magnitude of learning (Yehezkel, Sterkin, Lev, Levi, & Polat, 2016). The initial baseline differences in visual acuity were found to be predictive of the magnitude of learning (Yehezkel et al., 2016). Specifically, individuals with lower acuity values exhibited the greatest performance improvements and greater transfer in reading speed. Participants with the poorest performance have the most capacity to improve whereas those with best initial performance may already be closest to the limit of their performance on a task. Baseline differences are also apparent between younger and older participants possibly due to age-related sensory declines (Andersen, Bower & Watanabe, 2010). Thus, it is possible that older adults may benefit most from PL training. Therefore, the first hypothesis is that the ability to learn increases with age. If this is correct, older adults should learn at greater magnitude than younger adults. In addition, irrespective of cue presented, neutral and valid, performance of older adults will improve at a greater magnitude than younger adults. However, age-related declines in the efficiency with which endogenous cues are processed has been reported (Folk & Hoyer, 1992). If PL depends on the degree to which attention is allocated to the task, then older adults' difficulty with processing an attentional cue may be hindered, resulting in decrease learning.

Second, how is performance for older adults affected by endogenous cues and specificity? The finding of transfer, or generalization, to an untrained location is important for the development of training regimens. A desirable training regimen should focus on optimizing learning by exhibiting the broadest benefits but with minimal amount of training. Studies with college-aged students often exhibit learning specific to the trained stimulus attribute including stimuli presented at a specific location. This specificity limits the feasibility of training interventions if training is laborious and effortful, especially if laborious training is presented to older adults. Training with attentional cues, however, have generalized learning and improvements to an untrained task (Szpiro & Carrasco, 2015) and untrained location (Donovan, Szpiro & Carrasco, 2015; Donovan & Carrasco, 2018) have been found. PL training with older adults often finds partial or complete transfer (Bower & Andersen, 2012; Bower, Watanabe, & Andersen, 2013; Deloss, Watanabe, & Andersen, 2014) with the exception of one study that found complete specificity to an untrained location (Andersen, Ni, Bower, & Watanabe, 2010). This may be partly attributed to age-related declines in stability which may allow older adults to exhibit generalized learning and thus exhibit learning to an untrained location. Thus, a second hypothesis is that older adults as compared to younger adults exhibit generalized learning. Specifically, irrespective of the endogenous cue, improvements in learning will transfer to an untrained location.

Finally, does PL training generally improve attentional processing especially for older adults? Improvements may not only be constrained to improved visual processing but may also improve older adults' ability to allocate attention. Following PL training, improvements were associated with more efficient deployment of attention (Bays, Visscher, Le Dantec & Seitz, 2015). Activation of cortical regions thought to be associated with attention were thought to initially be recruited during PL training (Mukai et al., 2007; Sigman et al., 2005). This reduction in activation following training may suggest better functional connectivity between attentional networks and visual areas engaged during PL (Mukai et al., 2007). Common mechanisms of PL and attention have been reported (see Byers & Serences, 2012, for a review). For instance, PL and attention improve perceptual performance via exclusion of external noise (Dosher & Lu, 2000; Dosher & Lu, 1999), and both can increase the signal to noise ratio of sensory signals (Desimone & Duncan, 1995; Martinez-Trujillo & Treue, 2004; Moran & Desimone, 1985; Schoups, Vogels, Qian & Orban, 2001). Thus, a third hypothesis is that PL training with attention cues improves attentional processing. If this is correct, then UFOV scores should improve as a result of PL for both younger and older adults. However, the magnitude of improvement should be greater for older adults than younger adults.

The current study was concerned with determining whether similar patterns of learning and location-transfer and the underlying processes will occur for older adults as a result of training with endogenous attention. The current study was administered over a 6-day period, which included a practice session, pre-test and post-test assessments on separate days with three intervening training days. Within each age group, participants were assigned to be trained with one of two endogenous cues---an valid cue or a neutral cue. Both older and younger adults were tested on an orientation discrimination task prior to and after training with neutral cues. Learning and location transfer were assessed by measuring changes in performance at pre-test and post-test. Changes in attentional processing was assessed by measuring UFOV scores at pre-test and post-test.

Methods

Participants

24 younger adults (12 female, 12 male) age 18-30 (*M* = 20.38 , *SD* = 1.21) from the University of California, Riverside and 24 older adults (12 female, 12 male) over the age of 65 (*M* = 75.54, *SD* = 3.78) from the surrounding Riverside County participated in the study over the course of six days. All participants were compensated for their participation at a rate of $15 per hour. All participants had normal or corrected-to-normal visual acuity and were naive to the purpose of the study. Participants' near visual acuity were screened using a LogMAR chart (older adults: *M* = .25, *SD* = .16; younger adults: *M*

= -.07, *SD* = .08). Participants' contrast sensitivity was screened using the Pelli-Robson Contrast Sensitivity Chart (Precision Vision) (older adults: *M* = 1.30, *SD* = .95; younger adults: *M* = 1.38, *SD* = .06 missing 3 participants' scores). All participants were screened for eye diseases through self-report. Corrective lenses normally worn by the participants were allowed during the experiment. Four other participants (1 younger adult, 3 older adults) were dropped from the study due to consistently low accuracy across all contrast levels indicating inability to perform the task.

Apparatus

Stimuli were presented on a 49.53-cm CRT monitor Viewsonic PF817 at a resolution of 1,024 × 768 pixels; the monitor has a refresh rate of 75 Hz non-interlaced and a mean luminance value of 42.7 cd/m^2. Stimuli were generated on an Alienware AREA_51 PC equipped with an Intel Core i7 960 processor using the Windows 7 Ultimate 2009 operating system. A NVIDIA GeForce GTX 480 graphics card was used along with a Bits++ system (Cambridge Research Systems, Rochester, Kent, United Kingdom) to achieve 14-bit gray scale (16,384 gray-scale levels). Custom experimental software was written in MATLAB (The MathWorks, Natick, MA); Psychophysics Toolbox extensions. The EyeLink 1000 Tower Mount (SR Research, Ottawa, Ontario, Canada) was used to monitor participants' eye movements as well as stabilize head position.

Participants' far acuity was measured using the 2000 Series Revised ETDRS Chart 2 (Precision Vision, La Salle, IL) at a distance of 3 m. Participants' near acuity was measured using the 2000 series New ETDRS Chart 3 at a distance of 40 cm. Contrast sensitivity was measured using the Pelli-Robson Contrast Sensitivity Chart (Precision Vision).

Stimuli and Procedure

The following stimuli and procedure were adapted from the study by Donovan & Carrasco, (2018). Participants participated in the study over the course of 6 days. Participation in the study was to be completed within a two-week period from the start of the practice session. The practice session was administered a day prior to the first testing session. The experiment of testing or training sessions was administered over 5 sessions with one session per day. The task was an orientation discrimination task. Stimuli were presented on a uniform gray background. The time course of each trial was as follows: each trial started with the presentation of a white fixation cross (0.4° x 0.4°, degrees of visual angle [dva]) for 600ms. A pre-cue was then presented for 500ms. The pre-cue was either a neutral or a valid cue presented in the center. The neutral cue consisted of two 0.75°-long black lines, starting 0.65° from fixation and pointing toward the two possible target locations along one diagonal (i.e., the top-right and bottom-left quadrants or vice versa). The valid cue was one 0.75°-long black line, starting 0.65° from fixation and pointing toward the target location for that trial. A 400-ms inter-stimulus interval (ISI) was presented. One Gabor patch (4 cycles/degree sinusoidal grating in a Gaussian envelope; subtending 2°) was then presented, 5° from fixation, for 60-ms at one of four inter-cardinal (equidistant from horizontal and vertical meridian) iso-eccentric locations. The phase of the Gabor was randomized up to between 0 - 180 deg on each trial. A 300-ms ISI was then presented. Following the 300-ms ISI, a response cue (black line 0.75° in length and 0.65° from fixation) was presented for 300-ms indicating the location of target stimulus that had just been presented. The response cue was presented to eliminate location uncertainty. Following the presentation of the response cue, a uniform mid-gray background was presented to indicate that participants should report the target orientation; either clockwise or counterclockwise relative to vertical. Participants pressed the left arrow-key for counter-clockwise or the right arrow-key for clockwise. Auditory feedback was provided after each trial. Text feedback was provided at the end of each block informing participants of their percent correct on that block. Figure 2.1 illustrates the time course for a sample experimental trial.

Target contrast randomly varied across eight contrast levels (2%, 4%, 8%, 12%, 16%, 24%, 32%, and 64%) with each contrast presented an equal number of trials per block. Participants were to maintain fixation on the center throughout the experiment. The eye tracker was utilized to ensure participants were fixated on the center. If participants did not maintain fixation at any point during the trial, the trial ended immediately and a trial, with identical parameters (stimulus location, contrast level, and tilt), was added to the remainder of the unpresented trials of the block to ensure completion of all trials without eye fixation deviating from the center.

Practice

Prior to the practice session, participants were presented with demonstrations of what the stimuli looked like and how to respond. The practice session presented neutral pre-cues only. The practice session was administered on a day prior to the first test session. Participants completed 96 trials of the practice to familiarize them with the task.

Following the practice, the QUEST procedure (Watson & Pelli, 1983) was used to determine the orientation difference from vertical that would yield 75% accuracy at 64% contrast. Participants completed a total of 160 trials. QUEST was initialized with a criterion level of 0.75 ($\beta = 1.3$, $\delta = 0.10$, $\gamma = 0.5$). This β value was based on a preliminary study designed to find the optimal β value for the task.

Testing

Testing sessions were presented with only neutral pre-cues. The first session was the pre-test session, which was administered on another day following the practice session. The last session was the post-test session which was administered after completion of the training sessions. Testing sessions were 160 trials per block for four blocks. Within a single block, the target appeared at one of two locations located along the same diagonal (i.e., top-left and bottom-right in one block; top-right and bottom-left in the other block). The tested diagonal alternated each block. One set of the tested diagonal were designated as the trained locations, which were presented during testing and training sessions. The other set of the tested diagonal were the untrained locations which were only presented during the testing sessions. Presentation of the trained and untrained locations were counterbalanced by block during testing sessions. The designated trained and untrained locations were counter-balanced across participants. Breaks were given each quarter of a block (40 trials) and between each block. UFOV assessments were conducted on the testing days; prior to pre-test and after post-test.

Training

Training sessions were administered between pre-test and post-test days. For training sessions only, participants were either randomized into a neutral training group, in which the pre-cues were neutral-central on all trials of the training sessions, or in the attention training group, in which pre-cues were valid-central cues on all trials of the training sessions. The target stimulus always appeared at one of two locations along the same diagonal (i.e., top-left and bottom-right or top-right and bottom-left) for all training sessions. The locations along the same diagonal were designated as the trained locations. Training sessions contained 160 trials per block for four blocks. Breaks were given each quarter of a block and between each block.

Results

Between-subject variables were age group (2: younger adults, older adults) and endogenous cue condition (2: attention, neutral). Within-subject variables were location-type (2: trained locations, untrained locations) and test-day (2: pre-test, post-test). The following dependent variables were measured; overall accuracy, correct response times, d' (discrimination sensitivity), parameters of the psychometric function: α (contrast thresholds), asymptotic performance. Overall accuracy was aggregate performance across all contrast levels across the psychometric function.

A 2 (age-group) by 2 (condition) by 2 (location type) was conducted for overall accuracy to assess whether there were any differences in baseline performance. There was an effect of age group indicating that there were initial differences in overall accuracy prior to training between younger (*M*= 71.654, *SE*=1.243) and older adults (*M*= 61.165, *SE* = 1.243), $F(1,44) = 35.589$, $p < .001$, η_{p2}= .447. There was also an age-group x endogenous cue condition interaction, $F(1,44) = 4.133$, $p = .048$, η_{p2}= .086; younger adults (attention: *M* = 73.281, SE = 1.758; neutral: *M* = 70.026, *SE* = 1.758) and older adults (attention: *M* = 59.219, SE = 1.758; neutral: *M* = 63.112, *SE* = 1.758). These results indicate that overall accuracy of older adults was lower than that of younger adults. For younger adults those in the attention cue condition had higher accuracy than those in the neutral cue condition. However, the opposite pattern was observed with older adults. Older adults in the neutral cue condition had higher accuracy than the older adults in the attention cue condition. Further analyses separated by age group indicated that there were no differences in overall accuracy prior to training between the attention and neutral cue conditions in older adults, $F(1,22) = 2.191$, $p =.153$, η_{p2}= .091, or in the younger adults, $F(1,22) = 1.946$, $p =.177$, η_{p2}= .081. Given differences in baseline performance, analyses were first conducted separately by age group. Results are first reported for older adults followed by the results for the younger adults. Subsequent analyses were then conducted to compare age groups using magnitude of learning. Magnitude of learning is defined as the amount of improvement in performance between initial baseline performance from pre-test to post-test. Magnitude of learning was computed using the following formula:

$$\text{Magnitude of learning} = \frac{\text{PostTest} - \text{PreTest}}{\text{PreTest}}$$

Using this formula accounts for initial performance level by evaluating any changes in performance are with respect to each participant's initial performance level. This calculation was applied anytime baseline differences were found.

Older Adults

Overall Accuracy

An endogenous cue condition by location-type by test-day mixed-design ANOVA was conducted on overall accuracy. There was an interaction of location-type x test-day, $F(1,22) = 6.151$, $p = .021$, $\eta_{p2} = .218$ with greater rate of learning for trained locations (pre-test: $M = 61.094$, $SE = 1.438$; post-test: $M = 67.982$, SE = 1.273) than for untrained locations (pre-test: $M = 61.237$, $SE = 1.332$; post-test: $M = 65.052$, $SE = 1.505$). There was an effect of test-day $F(1,22) = 34.973$, $p < .001$, $\eta_{p2} = .614$, such that overall accuracy was greater for post-test ($M = 66.517$, $SE = 1.328$) as compared to pre-test ($M = 61.165$, $SE = 1.315$). For location-type, overall accuracy was significantly greater for the trained locations ($M = 64.538$, $SE = 1.210$) than the untrained locations ($M = 63.145$, $SE = 1.341$), $F(1,22) = 5.400$, $p = .030$, $\eta_{p2} = .197$. These differences in accuracy could not be attributed to differences in baseline performance given that no effect of location-type, $F(1,22) = .027$, $p = .872$, $\eta_{p2} = .001$, nor endogenous cue condition x location-type were found, $F(1,22) = 2.919$, $p = .102$, $\eta_{p2} = .117$. Figure 2.2 shows overall accuracy across testing and training days. When assessing magnitude of learning, there was significantly greater learning for trained locations ($M = .120$, $SE = .023$) than untrained locations ($M = .064$, *SE* = .016) which indicated that older adults benefitted from training, $F(1,22) = 6.260$, $p = .020$, $\eta_{p2} = .222$.

Speed-Accuracy Trade-offs

To rule out speed-accuracy trade-offs, RT data was analyzed as an endogenous cue condition by location-type by test-day mixed-design ANOVA. There was an effect of endogenous cue condition with those in the attention condition exhibiting significantly slower correct RT ($M = 1.021$, $SE = .100$) than those in the neutral condition ($M = .670$, $SE = .100$), $F(1,22) = 6.218$ $p = .021$, $\eta_{p2} = .220$**.** This may be attributed to initial correct RT differences prior to training, $F(1,22) = 4.442$ $p = .047$, $\eta_{p2} = .168$. However, an effect of test-day shows that correct RT was faster with test-day which indicates that overall there was no presence of speed-accuracy trade-offs, $F(1,22) = 30.483$ $p < .001$, $\eta_{p2} = .581$.

d' (discrimination sensitivity)

d' was calculated using an endogenous cue condition by location-type by test-day mixed-design ANOVA to assess whether any changes in performance is primarily due to discrimination and not due to a tendency to choose one orientation direction over another. There was a location-type x test-day interaction with greater rate of improvement in discrimination for trained locations (pre-test: $M = .412$, $SE = .054$; post-test: $M = .693$, $SE = .057$) as compared to untrained locations (pre-test: $M = .428$, $SE = .054$; post-test: $M = .601$, $SE = .062$), $F(1,22) = 4.882$, $p = .038$, $\eta_{p2} = .182$. There was a significant improvement from pre-test ($M = .420$, $SE = .051$) to post-test ($M = .647$, $SE = .057$), $F(1,22) = 36.042$, $p < .001$, $\eta_{p2} = .621$. This was not attributed to initial differences in sensitivity prior to training between location-type, $F(1,22) = .211$, $p = .651$, $\eta_{p2} = .009$ nor due to initial endogenous cue condition x location interaction, $F(1,22) = 2.434$, $p = .133$, $\eta_{p2} = .100$. The mean d' values for both younger and older adults are presented in Figure 2.3.

Parameters of the Psychometric Function

Changes in performance across the psychometric function was investigated following analytic procedures of Donovan, Carrasco (2018). However, slope was a fixed parameter in the current study and was obtained via preliminary data using QUEST and thus was not evaluated. Performance was evaluated as percent correct at each stimulus contrast. To model the psychometric data, data were fit to a Weibull function using the following formula:

$$y(x) = 0.5 + (1 - 0.5 - \lambda) \, x \, (1 - e^{-(\frac{x}{\alpha})^{\beta}})$$

using a maximum likelihood criterion fitting procedure. y represents performance as a function of stimulus contrast x. λ represents the lapse rate, calculated as 1- asymptotic performance of the stimulus contrast values. Asymptotic performance is the arc-sine square root transformation of the following formula $(1-\lambda)$ and represents the percent correct at stimulus contrast values of the psychometric function (Donovan & Carrasco, 2018; Donovan, Szpiro & Carrasco, 2015; Burnett, Close, d'Avossa, & Sapir, 2016; Sokal & Rohlf, 1981; White, Lunau, & Carrasco, 2014). α represents the threshold level which is evaluated as the stimulus contrast at which percent correct performance is 63.21% of the asymptotic performance. β represents the slope which was fixed at a value of 1.3 obtained from preliminary data.

An endogenous cue condition by location-type by test-day mixed–design ANOVA was conducted separately on each of the following parameters of the psychometric function: contrast thresholds (α) and asymptotic (transform). Figure 2.4a shows fitted data to psychometric function for endogenous cue condition, location-type, and test-day for older adults.

Contrast Thresholds (α). For α, there was a 3-way interaction of endogenous cue condition x location-type x test-day, $F(1,22) = 6.227$, $p = .021$, $\eta_{p2} = .221$. Also, there was a significant 2-way interaction of location-type x test-day, $F(1,22) = 11.938$, $p = .002$, $\eta_{p2} = .352$. Lastly, there was an effect of condition such that there was significantly lower contrast thresholds, indicating higher performance, for the neutral cue condition (M = 16.875, SE = 2.118) as compared to the attention cue condition (M = 24.708, SE = 2.118), $F(1,22) = 6.839$, $p = .016$, $\eta_{p2} = .237$. However, this seems to be due to initial contrast threshold differences prior to training between location-type for trained locations (M= 27.083, SE = 2.868) and untrained locations (M = 18.333, SE = 2.841), $F(1,22) = 6.240$, $p = .020$, $\eta_{p2} = .221$ and due to a 2-way interaction of endogenous cue condition x location-type, $F(1,22) = 7.227$, $p = .013$, $\eta_{p2} = .247$. There were higher initial contrast thresholds for trained locations (M = 35.667, SE = 4.056) as compared to untrained locations (M = 17.500, SE = 4.017) for the attention cue condition and similar contrast thresholds between trained (M =18.500 , SE = 4.056) and untrained locations (M = 19.167, SE = 4.017) for the neutral cue condition.

Analyses for contrast thresholds were subsequently conducted separately by endogenous cue condition. For the attention cue condition, there was a significant interaction of location-type x test-day with trained locations showing improved contrast thresholds from pre-test (M = 35.667, SE = 5.198) to post-test (M = 19, SE = 2.959) as opposed to untrained locations which shows worsening of thresholds from pre-test (M= 17.500, SE = 2.840) to post-test (M= 26.667 , SE = 5.599), $F(1,11) = 11.197$, p =.007, η_{p2}=.504. This interaction may be driven by significant differences between pre-test and post-test for trained locations, $t(11) = 2.425$, p =.034 but no differences found for untrained locations, $t(11) = -1.376$, p =.196. For the neutral cue condition, no 2-way interaction of location-type x test-day was found, $F(1,11) = 1.100$, p =.317, η_{p2}=.091, which suggests changes in performance were comparable across trained and untrained locations. A paired-samples t-test for the neutral cue condition indicated no significant learning from pre-test to post-test for trained locations, $t(11) = 1.802$, p= .099, nor untrained locations, $t(11) = .397$, p=.699. Figure 2.5 shows contrast threshold performance for pre-test and post-test for each condition.

Asymptote (transform). For asymptote (transform), there was an effect of test-day with a significant improvement from pre-test (M=1.117, SE =.028) to post-test (M = 1.274, SE = .031), $F(1,22)$ =37.675, p <.001, η_{p2}=.631. There was an effect of location-type with asymptote performance significantly greater in the trained locations (M = 1.224, SE = .027) as compared to the untrained locations (M = 1.167, SE = .030), $F(1,22)$ = 7.194, p =.014, η_{p2}=.246. However, this result may be attributed to initial differences prior to training in the interaction between endogenous cue condition x location-type, $F(1,22) = 6.920$, p =.015, η_{p2}=.239. Figure 2.6 shows the asymptotic performance for pre-test and post-test across condition and location type.

Subsequent analyses for asymptote performance were conducted separately by endogenous cue condition. For the attention condition, there was an effect of location-type with greater asymptotic performance for trained locations (M= 1.220, SE = .038) as compared to untrained locations (M = 1.120, SE = .034), $F(1,11) = 10.299$, p =.008, η_{p2}=.484. There was an effect of test-day with improvements in asymptotic performance from pre-test (M = 1.094, SE = .034) to post-test (M = 1.246, SE= .042), $F(1,11)$ = 13.743, p =.003, η_{p2}=.555. A paired-samples t-test indicate significant learning for trained locations, $t(11) = -3.199$, p = .008, and untrained locations, $t(11)$= -4.224, p = .001. This suggests significant learning and transfer for the attention cue condition. However, this seems to be attributed to significant differences between trained and untrained locations prior to training, $t(11) = 3.015$, p = .012. Magnitude of learning was then assessed between trained and untrained locations to assess changes in asymptote. There was no significant difference between trained and untrained locations which suggests that changes in asymptote were comparable, $t(11) = -.103$, p =.920.

For the neutral cue condition, there were no differences prior to training between trained and untrained locations, $t(11) = -.555$, p = .590, suggesting no differences in baseline performance between trained and untrained locations for the neutral cue condition. There was a significant effect of test-day, $F(1,11) = 28.279$, $p < .001$, η_{p2} = .720. Paired samples t-tests confirm that performance improvements were comparable for trained locations and untrained locations, respectively. There was significant improvement for trained locations, $t(11) = -5.390$, $p < .001$ and untrained locations, $t(11)$

= -3.235, p = .008, for the neutral cue condition suggesting improvements in asymptote from pre-test to post-test for both trained and untrained locations.

Magnitude of learning was also calculated for changes in asymptote so that comparisons could be made between endogenous cue conditions. A endogenous cue condition by location-type by test-day mixed-design ANOVA was conducted on magnitude of learning. From this, there was no effect of location-type, $F(1,22) = 1.098$, $p = .306$, $\eta_{p2}=.048$ nor endogenous cue condition x location-type interaction, $F(1,22) = 1.295$, $p = .267$, $\eta_{p2}=.056$. This suggests that changes in asymptote were comparable across all conditions for older adults.

UFOV

To assess whether attentional processing was improved with PL training, analyses was conducted using a endogenous cue condition by test day mixed-design ANOVA for the three different attentional abilities of the UFOV---processing speed, selective attention and divided attention. For processing speed, there was no effect of test-day, $F(1,22) = .000$, $p = .989$, $\eta_{p2}=.000$ nor endogenous cue condition x test-day, $F(1,22) = 1.663$, $p = .211$, $\eta_{p2}=.070$. For divided attention, there was no effect of test-day $F(1,22) = 1.500$, $p = .234$, $\eta_{p2}=.064$, nor endogenous cue condition x test-day, $F(1,22) = 2.436$, $p = .133$, $\eta_{p2}=.100$. For selective attention, there was no effect of test-day, $F(1,22) = .366$, $p = .551$, $\eta_{p2}=.016$, nor endogenous cue condition x test-day, $F(1,22) = 1.850$, $p = .188$, $\eta_{p2}=.078$. This suggests that there were no changes in attentional processing as measured by UFOV.

Younger Adults

Overall Accuracy

To assess whether there were any differences prior to training between trained and untrained locations an endogenous cue condition by location-type mixed-design ANOVA was conducted. There was no significant difference between trained and untrained locations prior to training, $F(1,22) = 4.071$, $p = .056$, $\eta_{p2} = .156$, nor endogenous cue condition x location-type interaction, $F(1,22) = .001$, $p = .978$, $\eta_{p2} = .000$. Overall accuracy prior to training was examined using a endogenous cue condition by location-type by test-day mixed–design ANOVA. There was an effect of test-day, $F(1,22) = 42.209$, $p < .001$, $\eta_{p2} = .657$, such that overall accuracy was greater for post-test ($M = 77.598$, $SE = 1.568$) as compared to pre-test ($M = 71.654$, $SE = 1.167$). There was an effect of location-type, $F(1,22) = 14.588$, $p = .001$, $\eta_{p2} = .399$, with overall accuracy significantly greater for trained locations ($M = 76.172$, $SE = 1.311$) as compared to untrained locations ($M = 73.079$, $SE = 1.418$). This suggests that accuracy was significantly higher for trained locations as compared to untrained locations.

Subsequent analyses were conducted on magnitude of learning. There was no reliable effect of trained and untrained locations in magnitude of learning which suggests that similar improvements in accuracy may have occurred for both trained and untrained locations, $F(1,22) = 2.746$, $p = .112$, $\eta_{p2} = .111$. Furthermore, there was no endogenous cue condition x location-type interaction which suggests that improvements were similar across trained and untrained locations for the attention and neutral cue condition, $F(1,22) = .017$, $p = .898$, $\eta_{p2} = .001$.

Speed-Accuracy Trade-Offs

Speed-accuracy trade-offs were analyzed using correct RT. There was an effect of test-day which shows that correct RT decreased, or faster correct responses, across testing days (pre-test: $M = .272$, $SE = .022$; post-test: $M = .178$, $SE = .010$), $F(1,22) = 27.337$, $p < .001$, $\eta_{p2} = .554$. The finding of faster correct RT accompanied with increased overall accuracy across test days suggests no speed-accuracy trade-offs was observed in the data.

d' (discrimination sensitivity)

An endogenous cue condition by location-type by test-day mixed design ANOVA was conducted on d'. There was an effect of location-type such that there was greater sensitivity, or better discrimination, for trained locations ($M = 1.067$, $SE = .063$) as compared to untrained locations ($M = .935$, $SE = .067$) , $F(1,22) = 15.455$, $p = .001$, $\eta_{p2} = .413$. This was not attributed to initial baseline differences between trained and untrained locations, $F(1,22) = 3.784$, $p = .065$, $\eta_{p2} = .147$. There was also an effect of test-day with an improvement in performance from pre-test ($M = .848$, $SE = .052$) to post-test ($M = 1.154$, $SE = .081$), $F(1,22) = 35.936$, $p < .001$, $\eta_{p2} = .620$. No 3-way interaction of endogenous cue condition x location-type x test-day was found, $F(1,22) = .069$, $p = .795$, $\eta_{p2} = .003$ nor a location x test-day, $F(1,22) = 3.855$, $p = .062$, $\eta_{p2} = .149$.

Parameters of the Psychometric Function

An endogenous cue condition by location-type by test-day mixed–design ANOVA was conducted separately on each of the following parameters of the psychometric function: α, asymptotic (transform).

Contrast Thresholds (α). For α, analyses were conducted on performance prior to training and no interaction of endogenous cue condition x location-type was found which suggests baseline performance were similar across groups, $F(1,22) = .206$, $p = .654$, $\eta_{p2} = .009$. Subsequently, a 3-way ANOVA of endogenous cue condition x location-type x test-day was conducted. No 3-way interaction was found suggesting no differences in contrast thresholds with training between endogenous cue conditions from pre-test to post-tests for both trained and untrained locations, $F(1,22) = .080$, $p = .780$, $\eta_{p2} = .004$.

Subsequent analyses were conducted separately for each attention cue condition. For the attention cue condition, a 2-way ANOVA (location-type x test-day) was conducted and an effect of test-day was found, $F(1,11) = 23.768$, $p < .001$, $\eta_{p2} = .684$. To assess whether the effect of test-day was robust, Bonferroni corrected post-hoc analyses indicated significant learning from pre-test to post-test for both trained and untrained locations, $p < .001$. This suggests improvements were similar across trained and untrained locations for the attention cue condition. There was no 2-way interaction of location-type x test-day for the attention cue condition, $F(1,11) = .057$, $p = .816$, $\eta_{p2} = .005$. For the neutral cue condition, no effect of test-day $F(1,11) = .105$, $p = .752$, $\eta_{p2} = .009$, and no 2-way interaction was found $F(1,11) = .216$, $p = .651$, $\eta_{p2} = .019$, which suggests no significant change in contrast thresholds were found for participants trained with neutral cues.

Asymptote (transform). For asymptotic transform performance, there was a significant interaction of location-type x test-day with trained locations showing a greater rate of improvement (pre-test; $M = 1.263$, $SE = .027$; post-test: $M = 1.413$, $SE = .033$) as compared to untrained locations (pre-test; *M* = 1.230 *SE* = .028 ; post-test: *M* = 1.293, *SE* = .030), $F(1,22) = 7.618$, $p = .011$, $\eta_{p2} = .257$. Subsequent analyses were conducted separately by endogenous cue condition. There was significant improvement for trained locations in both attention and neutral cue conditions, $t(11) = -3.176$, $p = .009$; $t(11) = -4.086$, $p = .002$, respectively. No reliable improvements were observed for untrained locations in both attention and neutral cue conditions, $t(11) = -1.791$, $p = .101$; $t(11) = -2.154$, $p = .054$, respectively. This suggest that there was learning for trained locations for both attention and neutral cue conditions, but that learning was specific to the trained locations.

There was a significant effect of location-type showing that asymptotic performance significantly improved for trained locations (*M* = 1.338, *SE* =.026) than for untrained locations (*M* = 1.262, *SE* = .026), $F(1,22) = 9.122$, $p = .006$, $\eta_{p2} = .293$. There was also an effect of test-day with improvements from pre-test (*M*= 1.246, *SE*=.024) to post-test (*M*=1.353, *SE*= .027), $F(1,22) = 26.386$, $p < .001$, $\eta_{p2} = .545$. An endogenous cue condition by location-type mixed-design ANOVA was conducted to confirm whether greater improvements in the trained locations were attributed to training days and not due to initial differences in asymptotic performance prior to training. There was no difference in initial asymptotic performance between trained and untrained locations suggesting that asymptote was comparable across location-type, $F(1,22) = 1.457$, $p = .240$, $\eta_{p2} = .062$. Figure 2.4b shows fitted data to psychometric function for endogenous cue condition, location-type, and test-day for younger adults.

UFOV

To assess whether attentional processing was improved with PL training, analyses were conducted using a endogenous cue condition by test-day mixed-design ANOVA for the three different attentional abilities of the UFOV. For processing speed, there was no effect of test-day, $F(1,22) = 1.724$, $p = .204$, η_{p2}=.073 nor endogenous cue condition x test-day, $F(1,22) = .276$, $p = .605$, η_{p2}=.012. For divided attention, there was no effect of test-day $F(1,22)$ =3.113, $p = .092$, η_{p2}=.124, nor endogenous cue condition x test-day, $F(1,22) = .878$, $p = .359$, η_{p2}=.038. For selective attention, there was no effect of test-day $F(1,22) = .315$, $p = .581$, η_{p2}=.014, nor endogenous cue condition x test-day, $F(1,22)$ = 1.046, $p = .318$, η_{p2}=.045 This suggests that there were no changes in attentional processing as measured by UFOV.

Discussion

In the present study three hypotheses were examined. With regard to the first hypothesis, it was proposed that the ability to learn increases with age. In addition, it was predicted that irrespective of cue presented, neutral or attention cue condition, performance of older adults would improve at a greater magnitude as compared to younger adults. The results of both age groups for magnitude of learning (overall accuracy) and contrast thresholds do not support this hypothesis. The present results indicated that the magnitude of learning in trained and untrained locations were similar across age-groups. Several studies have reported that the amount of learning could be predicted from initial performance level (Aberg & Herzog, 2009; Astle, Blighe, Webb &

Mcgraw, 2014; Fahle, 1997; Fahle & Henke-Fahle, 1996; Polat, Schor, Tong, Zomet, Lev, Yehezkel, Sterkin, & Levi, 2012; Yehezkel, et al., 2016). Those with lower initial baseline performances should exhibit greater magnitude of learning. Given the age-related declines in visual function, visual performance of older adults should be lower, as compared to younger adults, and thus have greater range for improvement. In contrast, visual performance of younger adults may be at optimal performance and thus smaller improvements would be expected. Indeed, participants with the lowest initial performance, as compared to participants with greater initial performance, have the largest amount to improve whereas those with the best initial performance may already be at near optimal performance on a task (Yehezkel et al., 2016).

Why were similar improvements between older and younger adults observed in the current study? No direct comparative analyses could be made given initial baseline differences between age groups. However, visual inspection of accuracy across sessions (see *figure* 2.2) for both older and younger adults reveal some interesting possibilities. For example, consider the performance for the training sessions. The performance of training sessions indicated that youngers adults in the attention cue condition consistently performed with greater accuracy than those in the neutral cue condition. This suggests greater performance with perhaps a greater allocation of attention for participants in the attention cue condition as compared to the neutral cue condition. However, training sessions for older adults reveal similar patterns of performance for both attention cue and neutral cue conditions. This may reflect older adults' inefficiency with engaging attention regardless of cue condition. There is well-documented evidence of age-related declines in a number of different aspects of visual and attentional function (see Andersen, 2012; Madden, 2007). The impaired ability in older adults to effectively allocate attention may explain similar patterns of performance between attention cue and neutral cue conditions and consequently why greater magnitude of learning was not found. Thus, the age-related decrement in allocating attention may explain why the patterns of learning between conditions do not seem to be well-delineated in older adults as in younger adults. This is consistent with the viewpoint of a role of attention in PL and the importance of focused attention in limiting plasticity (Ahissar & Hochstein, 1993, 2004; Byers & Serences, 2012). Furthermore, if learning is affected by the degree to which attention is allocated to the task for younger adults, then this explanation would be consistent with the finding of greater performance in the attention cue condition than the neutral cue condition.

Attention has often been implicated as a key factor in the variability of learning (Ahissar & Hochstein, 1993; Tsushima & Watanabe, 2009; Crist, Li, & Gilbert, 2001; Fahle, 2004; Li, Piech, & Gilbert, 2004; Shiu & Pashler, 1992). Evidence in support of this proposal can be found by visual examination of the data for older adults for overall accuracy at post-test. For post-test performance, there appears to be a decrease in performance for older adults in the attention cue condition following training but not for those in the neutral cue condition. It appears that older adults in the attention cue condition may be affected by the change to neutral cues, during post training assessment, after being trained with attention cues. Specifically, older adults in the attention cue condition were only presented with valid cues during training. However, during post-test, only neutral cues were presented. This switch, from valid to neutral cues, appears to have negatively impacted performance via decreased accuracy at post-test. This is consistent with research on age-related deficits in task-switching abilities (Wasyshyn, Verhaeghen, & Sliwinski, 2011; Zanto & Gazzaley, 2014). Perhaps, older adults in the attention cue condition have difficulty adjusting to a new task-set after being trained for several days with a different task-set. This difficulty may stem from updating their internal model to the new task set or maintaining the current task set after the task-switch. Future research may want to further evaluate this possibility.

According to the second hypothesis, older adults as compared to younger adults exhibit generalized learning. As a result, it was predicted that older adults will exhibit transfer irrespective of the type of cue presented, and improvements in performance would transfer to untrained locations. For younger adults, it was predicted that performance improvements would transfer to untrained locations when trained with the attention cue condition but not with the neutral cue condition. Transfer of training was assessed by investigating both contrast thresholds (α) and asymptote performance. For younger adults, contrast threshold (α) improvements generalized to untrained locations when trained with the attention cue condition but not in the neutral cue condition. This result indicates that training with valid cues, as indexed by the attention cue condition, produced both learning and transfer to untrained locations.

Performance improvements generalized to untrained locations, via contrast thresholds, in younger adults are consistent with a contrast gain mechanism. Previous research has investigated the possible underlying neural mechanism associated with the impact of endogenous attention on visual performance (Ling & Carrasco, 2006). The response behavior of sensory neurons, as a function of stimulus intensity, is known as the contrast response function (CRF) (Albrecht & Hamilton, 1982). Specifically, there is an increase neuronal firing as a function of stimulus intensity. This neural behavior may be related to the psychometric function. Attention can modulate activity of the neuronal firing in visual cortical areas in two ways; contrast gain or response gain (Reynolds & Heeger, 2009). First, attention can increase the contrast gain of neurons by shifting the most sensitive operating range of the system to lower stimulus intensities. This is depicted psychophysically as a leftward shift in the psychometric function. Attention can also increase the response gain of neurons which effectively increases the proportion of accurate responses across the psychometric function with pronounced effects at higher contrast levels. This is depicted in the psychometric function as an increase in performance at the asymptote (or higher contrast levels) of the psychometric function. Endogenous attention has been reported as operating via contrast gain to enhance visual performance (Ling & Carrasco, 2006; Donovan & Carrasco, 2018) or both contrast and response gain (Huang & Dobkins, 2005). Consistent with previous findings, training with valid cues in younger adults improves perceptual performance by decreasing contrast thresholds which resembles contrast gain.

Furthermore, asymptote improvements in younger adults did not generalize to the untrained locations when trained with the attention or neutral cue conditions. Learning via asymptote performance was found for the trained locations for both the attention and neutral cue condition. This result indicates that learning was specific to the trained locations when assessing performance via asymptotic performance.

For older adults, contrast thresholds did not transfer, or generalize, to untrained locations when trained with an attention cue or a neutral cue. In contrast, performance improvements evaluated via asymptote performance generalized to untrained locations irrespective of the endogenous cue condition. These improvements in asymptote performance are consistent with a response gain mechanism in older adults. Notably, different mechanisms may be engaged for the different age groups in order for training effects to generalize to untrained locations. Specifically, the mechanism of response gain in older adults and contrast gain in younger adults. Thus, performance benefits can transfer to untrained locations for both age groups but are carried out using different mechanisms between younger and older adults.

Why were contrast threshold improvements specific to trained locations in older adults? It is difficult to make a definitive conclusion about the training data for older adults in the attention cue condition. Baseline contrast thresholds (pre-test performance) were high for older adults in the attention cue condition as compared to thresholds for older adults in neutral cue condition as well as thresholds for younger adults in the attention and neural cue condition. Given that post-test contrast thresholds of older adults, in the attention cue condition, were comparable to the pre-test performance level of the other groups, it is possible that learning may not have occurred. If this is correct, then the results of the older adults in the attention cue condition could be explained by the presence of neutral cues in the post-test.

What might account for the lack of learning at post-test performance for older adults? A unique condition for the post-test assessment for the attention cue condition was that there was a switch in the cue type at post-test. The pre-cues changed from a valid cue to a neutral cue. This switch of cue type, from training sessions to post-test, was unique to the attention cue condition. Given that older adults have shown evidence of a cost in task-switching abilities (Wasylyshyn, Verhaeghen & Sliwinski, 2011), it is possible this may have interfered with learning. The reconfiguration in the task-set (see Monsell, 2003) from informative valid cues to uninformative neutral cues may have disrupted improvements on the task that may have otherwise been observed. As a result, the assessment of learning for the present conditions may be problematic. Performance may have been negatively affected by the presence of neutral cues at post-test after being trained with valid cues for the older adults in the attention cue condition. This is further supported by the finding of declines in contrast thresholds in the untrained locations for the older adults in the attention cue condition. Both these patterns of results for the trained and untrained locations for the attention cue condition of older adults may be attributed to an age-related performance cost of task-switching. This explanation is consistent with the hypothesis that learning is impacted by the degree of attention allocation. The degree of attentional allocation in an optimally functioning attentional system, like that of younger adults, appears to promote learning. Greater allocation of attention, as observed training with valid cues, produces learning as compared to no learning with distributed attention as a result of training with neutral cues. In contrast, a compromised attentional system in older adults may produce no learning or interfere with learning. There is evidence to suggest that plasticity seems to be preserved in older adults

(Chang et al., 2014) but the present results may suggest how deficiencies in a system that are important in learning, such as attention, could be detrimental to PL.

Another explanation is that the contrast gain mechanism may be compromised in older adults and thus the response gain mechanism was engaged in order to obtain performance benefits to untrained locations. Previous research has demonstrated that endogenous attention enhances visual performance via contrast gain (Ling & Carrasco, 2006; Donovan & Carrasco, 2018) or both response and contrast gain (Huang & Dobkins, 2005). However, exogenous attention facilitated visual performance via response gain (Donovan, Szpiro & Carrasco, 2015). There is no reported evidence for age-related declines in exogenous attention (see Madden 2007, for a review). If exogenous attention operates in accordance with response gain (in which no age-related declines have been reported), then perhaps the response gain process may be preserved with aging. In contrast, age-related declines in endogenous attention may reflect declines in the contrast gain mechanism. This suggests that the engagement of a response gain mechanism for older adults---to elicit location transfer---may be a compensatory process for the age-related declines in the contrast gain mechanism. Future research may want to investigate the effect of exogenous attention in older adults on learning and transfer and whether the same mechanism is engaged between younger and older adults. If the same mechanism is engaged, then this suggests that the mechanism is preserved.

According to the third hypothesis, PL training with attention cues improves attentional processing. If this hypothesis is correct, then UFOV scores should improve as a result of PL training for both younger and older adults. Given the age-related declines in attention, older adults may be better situated to show training-related benefits because their attentional abilities are lower, offering them greater range for improvement. Thus, the magnitude of improvement was predicted to be greater for older adults than younger adults. In contrast, younger adults might be more optimized in their attentional abilities and therefore may not have as much potential for improvement. The results for UFOV performance do not support this hypothesis. Rather, this evidence supports the view that attention may be primarily involved in facilitating learning but not necessarily modified with learning. Specifically, the source mechanism of attention and the corresponding areas are activated with PL but are not themselves modified with learning (see Watanabe & Sasaki, 2015).

Another explanation is that the attentional mechanism engaged during PL may not necessarily be the same mechanism engaged or is not entirely dependent on the same mechanism as that engaged in the UFOV task. Processing speed is a primary measure of the UFOV task. Processing speed has been proposed as a general mechanism involved in age-related declines in cognitive processing (Salthouse, 1996). But processing speed, as assessed by the UFOV, may be limited in explaining some aspects of cognitive decline. If improvements in learning and transfer were related to speed of processing, then changes in the processing speed of the UFOV task should be observed. However, this pattern of results was not found in the present study. It has been proposed that attentional control could be the single underlying source that contributes to variability in cognitive change, and that cognitive speed measures relate to cognitive capability and aging because they require focusing and maintaining attention (Horn & Blankson, 2005). But it is unclear as to the exact source of the attentional declines as attention has been implicated as being involved in multiple processes and its role in many task-related attention tasks.

With regard to the performance of younger adults, several important conclusions can be reached. For example, the current results for younger adults do not reliably replicate the results reported by Donovan & Carrasco, 2018. There was no reliable 3-way interaction of endogenous cue condition x location-type x test-day for change in contrast thresholds (α). However, when analyses were conducted independently by endogenous cue condition, learning and location transfer for those in the attention cue condition was found, which was consistent with previous reported findings (Donovan & Carrasco, 2018). For the neutral cue condition, there was no significant learning observed for trained and untrained locations. This suggests no learning or transfer was found when trained with neutral cues. This is inconsistent with previous findings that found learning when trained with neutral cues (Donovan & Carrasco, 2018). An explanation for this discrepancy is that training with neutral cues may produce variable learning and transfer. More specifically, distributed attention, due to training with neutral cues, may not reliably produce learning. In fact, PL training in which exogenous cues were manipulated demonstrated individual variability in learning for those trained in the neutral group (Donovan, Szpiro & Carrasco, 2015; Szpiro & Carrasco, 2015). Furthermore, it is not uncommon in PL studies to observe variability in the patterns of PL and the lack of reliability in producing PL (Jeter, Dosher, Petrov & Lu, 2009; Fahle & Henke-Fahle, 1996; Fine & Jacobs, 2002; Kumar & Glaser, 1993; Fahle & Edelman, 1993; Green & Bavelier, 2012). This variation in performance has been attributed to inherent differences in participants (Maniglia & Seitz, 2017). Moreover, individual differences in attentional processing may be predictive of the rate of PL (Yehezkel et al., 2016). Thus, the variability in learning may partly stem from distributed attention as indexed by neutral cues.

In addition, there appears to be conflicting conclusions between contrast thresholds and overall accuracy observed in the neutral cue condition. Learning or failure to find learning could depend on whether performance is assessed via overall accuracy or contrast thresholds. For overall accuracy, significant performance improvements for younger adults were observed for both trained and untrained locations. In contrast, no significant changes in contrast threshold were observed for either trained or untrained location. It could be that PL measured using thresholds may be quantitatively different than PL measured by accuracy. Contrast thresholds capture performance for a single value on the psychometric function. Overall accuracy captures performance across the entire psychometric function. As a result, it is likely that contrast thresholds may be less sensitive than overall accuracy to changes in performance because overall accuracy may mask learning effects at specific contrasts.

A mechanism that may account for PL transfer is the extent to which participants are able to focus attentional resources following PL training (Bays, Fisscher, Le Dantec & Seitz, 2014). PL research investigating changes in alpha-band electroencephalogram (EEG) for trained and untrained stimuli found desynchronization of alpha-band activity following training, which suggests that participants learned to more effectively allocate their resources as a result of training (Bays, Fisscher, Le Dantec & Seitz, 2014). Alpha-band activity has been proposed to be associated with the level of attention with greater synchronization of alpha-band activity correlated with greater effort. One explanation is that neutral cues may result in the distribution of attentional resources across the visual display and consequently produce costs in perceptual processing that lead to disparate learning effects. It could be that distributing attentional resources to two locations may not engage the target stimulus to a level that reliably produces enhanced learning. Specifically, valid cues in the attention cue condition may more effectively allocate attentional resources in order to produce more reliable learning effects. These results may be at odds with earlier findings as reported by Donovan & Carrasco (2018) but this failure to replicate learning in the neutral cue condition may be evidence of neutral cues producing variable learning effects.

Another explanation for the failure to replicate the trained location neutral cue condition for younger adults may be due to differences in some of the methods employed between the two studies. One explanation may be the fewer number of trials used in the current study. The current study used 160 trials per block whereas the previous study used 256 trials per block (Donovan & Carrasco, 2018). PL studies with college-aged adults often employ an extensive number of training trials in order to produce PL effects. Thousands of trials and several training sessions are typically employed in order to produce training-related improvements in performance. Thus, the failure to replicate the pattern of results for the neutral cue trained-location condition may be that insufficient trials were used to produce strong effects of learning. As a result, this may not have allowed for reliable learning effects to occur in the trained neutral condition.

However, this may not be a likely explanation given that the original study showed learning was relatively stable within training sessions (Donovan & Carrasco, 2018). The reason why fewer trials were employed in the present study was to avoid long periods of training that may fatigue older adults. Older adults may have difficulty with sustained attention although research on this topic is contentious (Zanto & Gazzaley, 2014) and so, training for potentially long periods of time may lead to fatigue.

In summary, the present study investigated the effect of endogenous attention in PL and location specificity in the context of aging. Specifically, the present study examined whether older adults exhibit similar patterns of learning and location transfer given reported age-related declines in vision and attention. The findings of the present study add to the growing body of literature in PL and aging. First, plasticity is preserved with age. Consistent with PL studies on aging (Yotsumoto et al., 2013; Chang et al., 2014), older adults are amenable to perceptual improvements with practice. Thus, PL is useful as a training intervention to improve visual function in older adults. However, understanding the factors involved in PL and how they may be mediated by age is important to consider when thinking about certain desired outcomes of PL training. Second, the role of attention and its impact on stability may decline with age. Specifically, age-related declines in attention may account for the different patterns of learning observed between older and younger adults. Attentional abilities of older adults may be compromised and thus learning may not be constrained by attention in the same way as in younger adults. Additionally, older adults may be more susceptible to disruptions in learning brought out by changes in the task configuration. Lastly, different mechanisms may be engaged when learning by age. Engagement of different mechanisms may reflect compensatory behavior to account for age-related declines in attention. The contrast gain mechanism that may have otherwise been engaged as in younger adults may have been compromised in older adults. As a result, the response gain mechanism, which may be preserved in older adults, may have been engaged to produce transfer to untrained locations.

The results reported here demonstrate that plasticity is preserved in older adults, which is useful as a potential intervention to age-related declines in vision. However, special considerations to the design of training procedures for older adults should be considered given the reported age-related declines in attention. An effective training procedure for older adults should utilize a paradigm in which improvements also translate to improvements in attention allocation or at a minimum utilize attention that minimizes any negative impact on performance.

Figures & Tables

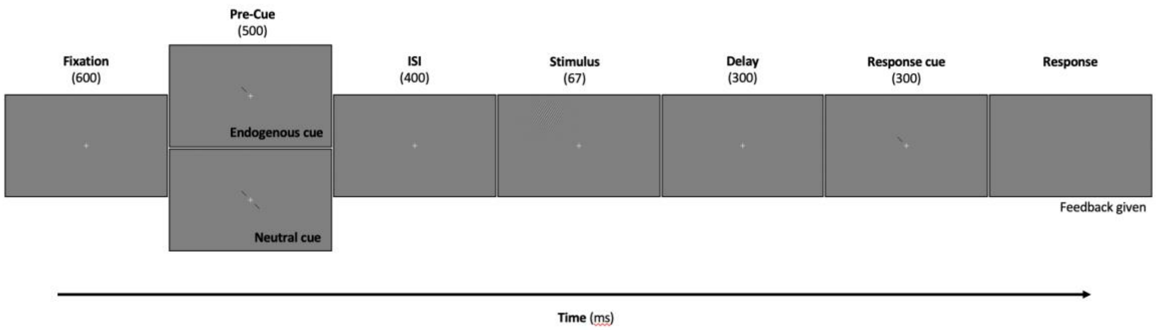

Figure 2.1. Sample depiction of an experimental trial. Neutral cues presented at pre-test and post-test. During training, participants were presented with either an endogenous valid cue or an endogenous neutral cue.

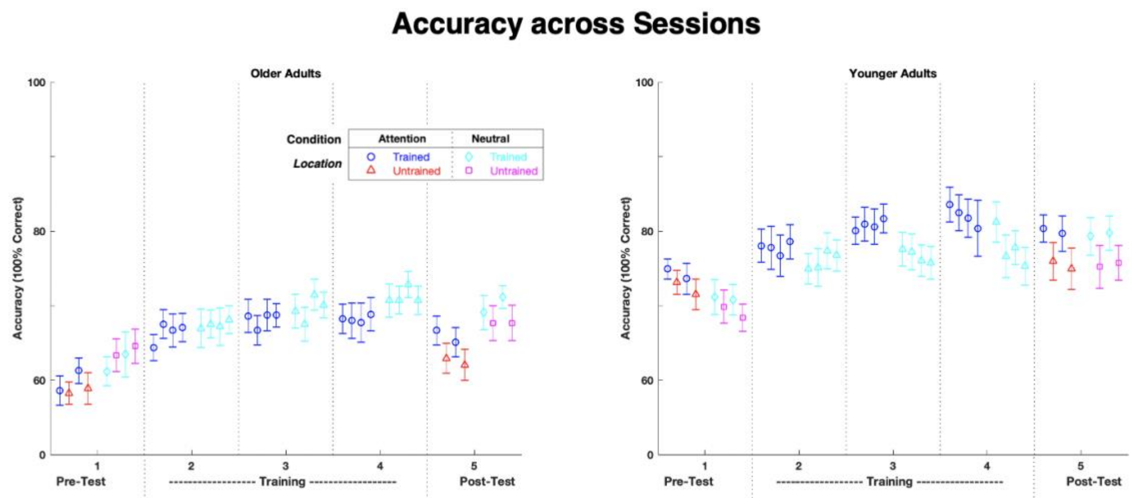

Figure 2.2. Overall accuracy (% correct averaged across all stimulus contrast) for both attention and neutral cue conditions and trained and untrained locations across testing and training days. Left graph depicts performance for older adults. Right graph depicts performance for younger adults.

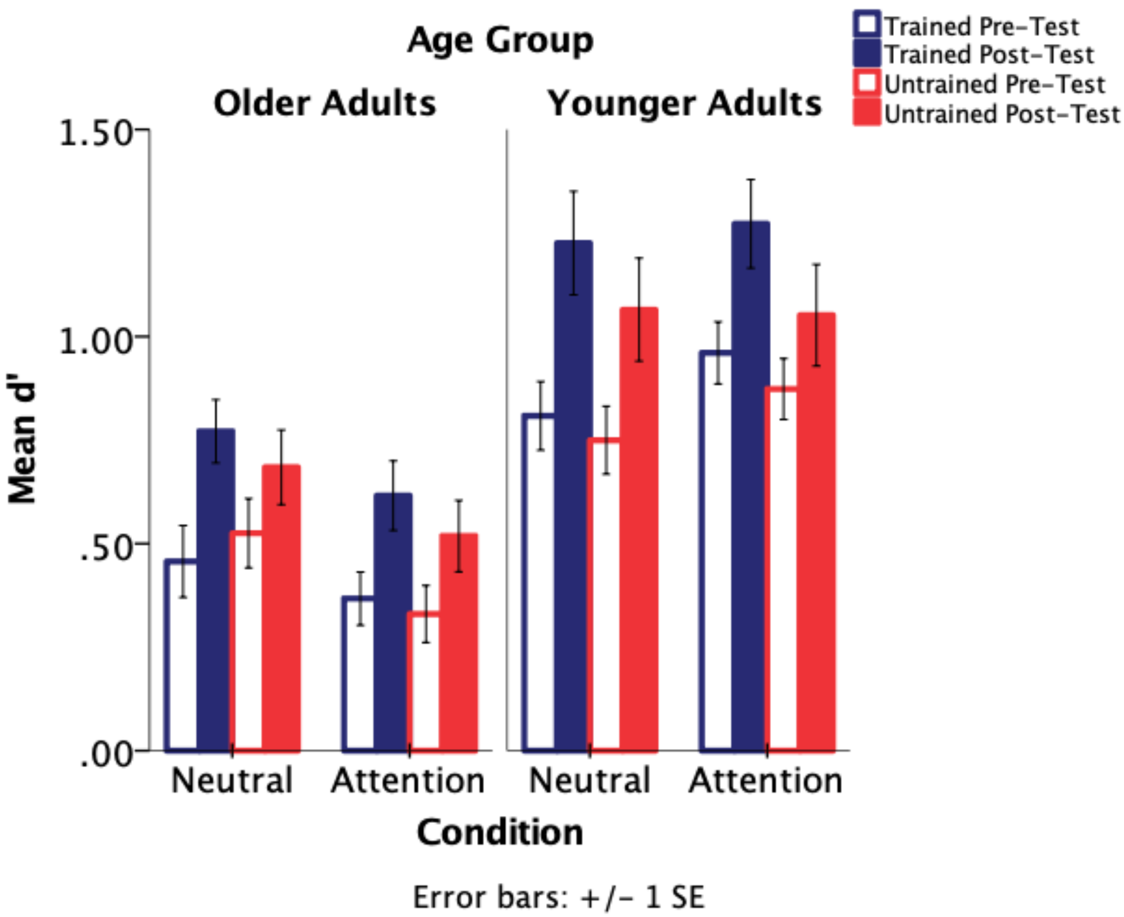

Figure 2.3. Mean d' (discrimination sensitivity) pre-test and post-test values for neutral and attention cue conditions for trained and untrained locations for older adults (left graph) and younger adults (right graph). Higher scores indicate greater sensitivity.

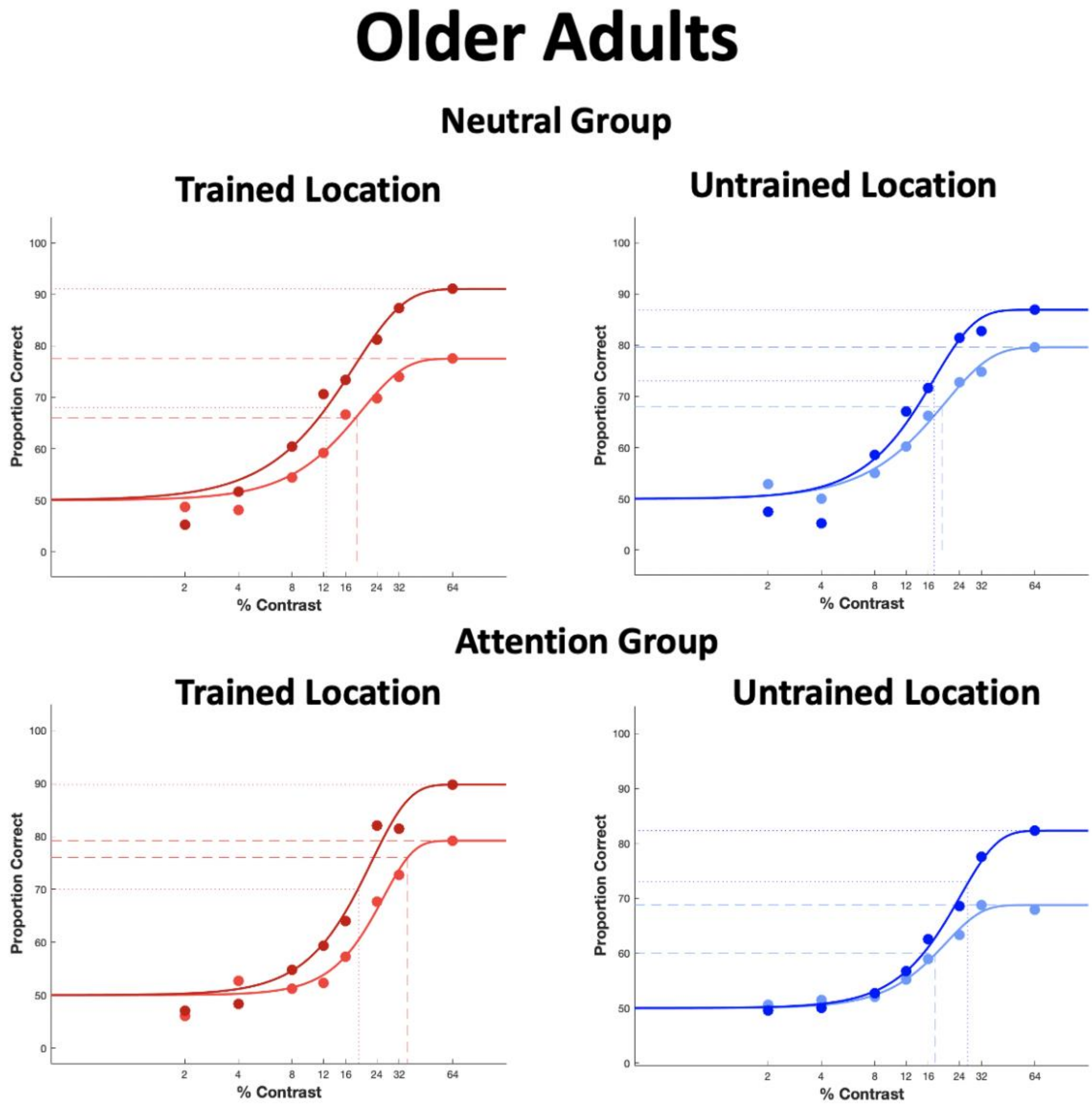

Figure 2.4 (a). Psychometric function depicts mean performance at each stimulus contrast for older adults.

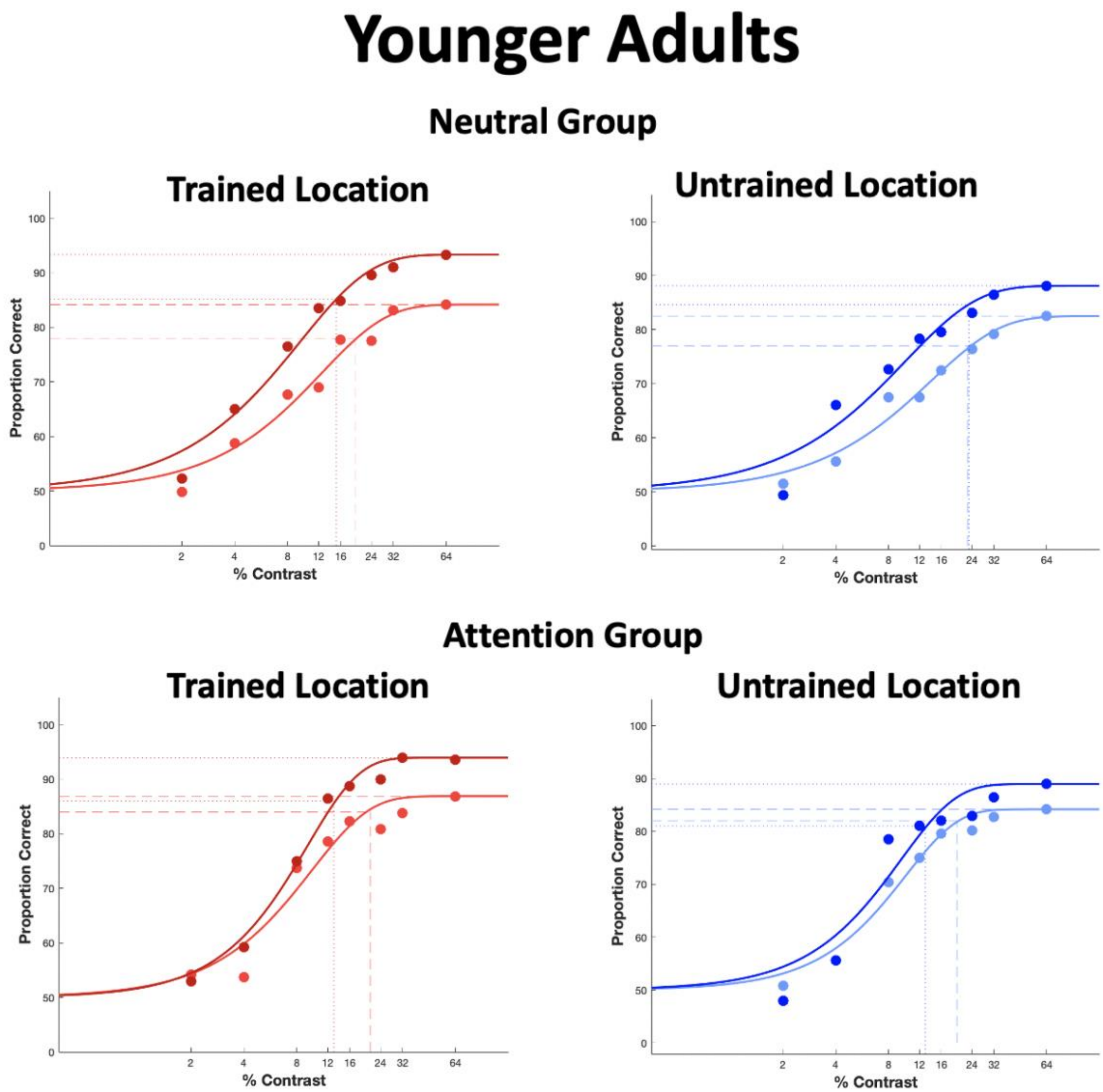

Figure 2.4 (b). Psychometric function depicts mean performance at each stimulus contrast for younger adults.

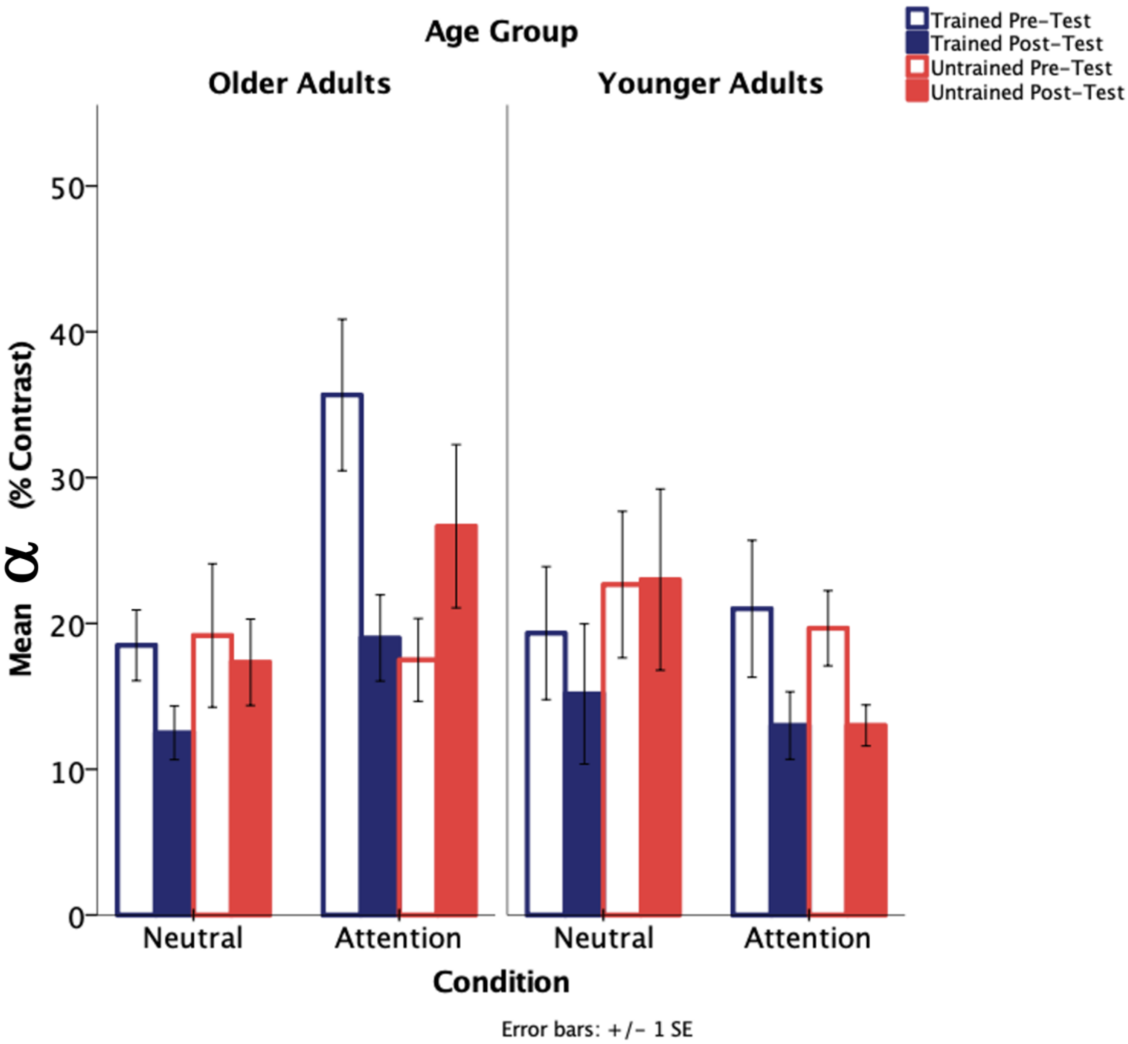

Figure 2.5. Contrast threshold (α) performance for pre-test and post-test for both trained and untrained locations by endogenous cue condition for older adults (left graph) and younger adults (right graph).

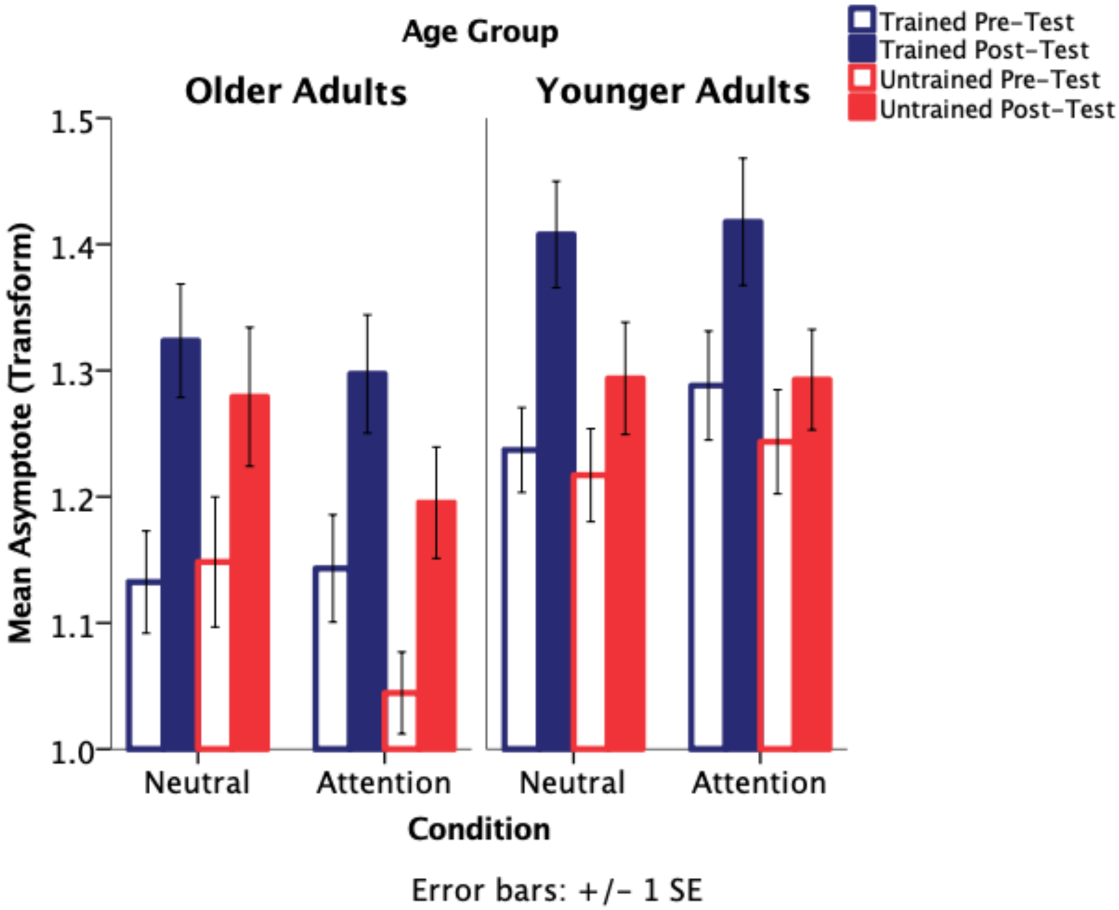

Figure 2.6. Asymptotic performance for pre-test and post-test for both trained and untrained locations by endogenous cue condition for older adults (left graph) and younger adults (right graph).

References

Aberg, K. C., & Herzog, M. H. (2009). Interleaving bisection stimuli—Randomly or in sequence—Does not disrupt perceptual learning, it just makes it more difficult. *Vision Research*, *49*(21), 2591–2598. https://doi.org/10.1016/j.visres.2009.07.006.

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience*, *26*(4–5), 435–446.

Adini, Y., Sagi, D., & Tsodyks, M. (2002). Context-enabled learning in the human visual system. *Nature*, *415*(6873), 790–793. https://doi.org/10.1038/415790a.

Ahissar, M, & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature*, *387*(6631), 401–406. https://doi.org/10.1038/387401a0.

Ahissar, Merav, & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences*, *8*(10), 457–464. https://doi.org/10.1016/j.tics.2004.08.011.

Albrecht, D.G. & Hamilton, D.B. (1982) Striate cortex of monkey and cat: contrast response function. Journal of Neurophysiology, 48(1), 217-237.

Andersen, G. J. (2012). Aging and vision: Changes in function and performance from optics to perception. *Wiley Interdisciplinary Reviews. Cognitive Science*, *3*(3), 403–410. https://doi.org/10.1002/wcs.1167.

Andersen G.J. & Atchley P. (1995). Age-related differences in the detection of three-dimensional surfaces from optic flow. *Psychology and Aging. 10*(4):650–658. doi:10.1037/0882-7974.10.4.650.

Andersen, G. J., Ni, R., Bower, J. D., & Watanabe, T. (2010). Perceptual learning, aging, and improved visual performance in early stages of visual processing. *Journal of vision*, *10*(13), 4. https://doi.org/10.1167/10.13.4.

Astle A.T., Blighe A.J., Webb B.S. & McGraw P.V. (2015) The effect of aging on crowded letter recognition in the peripheral visual field. Investig Ophthalmol Vision Science, 55, 5039-5045.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America. A, Optics and Image Science*, *5*(12), 2210–2219. https://doi.org/10.1364/josaa.5.002210.

Ball, K., & Sekuler, R. (1981). Adaptive processing of visual motion. *J. Exp. Psychol. Hum. Percept. Perform.* 7, 780–794. doi: 10.1037/0096-1523.7.4.780.

Ball, K., & Sekuler, R. (1986). Improving visual perception in older observers. *Journal of Gerontology, 41*(2), 176-182.

Bartolucci, M., & Smith, A. T. (2011). Attentional modulation in visual cortex is modified during perceptual learning. *Neuropsychologia*, *49*(14), 3898–3907. https://doi.org/10.1016/j.neuropsychologia.2011.10.007.

Bays, B. C., Visscher, K. M., Le Dantec, C. C., & Seitz, A. R. (2015). Alpha-band EEG activity in perceptual learning. *Journal of Vision*, *15*(10), 7–7. PubMed. https://doi.org/10.1167/15.10.7.

Belchior, P., Marsiske, M., Sisco, S. M., Yam, A., Bavelier, D., Ball, K., & Mann, W. C. (2013). Video game training to improve selective visual attention in older adults. *Computers in Human Behavior*, *29*(4), 1318–1324. PubMed. https://doi.org/10.1016/j.chb.2013.01.034.

Bower, J. D., Watanabe, T., & Andersen, G. J. (2013). Perceptual learning and aging: Improved performance for low-contrast motion discrimination. *Frontiers in Psychology, 4*, 1–7.

Bower, J. D., & Andersen, G. J. (2012). Aging, perceptual learning, and changes in efficiency of motion processing. *Vision Research, 61*, 144–156.

Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 51*(1), 20–35. https://doi.org/10.1037/1196-1961.51.1.20.

Burnett, K. E., Close, A. C., d'Avossa, G., & Sapir, A. (2016). Spatial attention can be biased towards an expected dimension. *Quarterly Journal of Experimental Psychology, 69*(11), 2218–2232, https://doi.org/10.1080/17470218.2015.1111916.

Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012.

Chang, L.-H., Shibata, K., Andersen, G. J., Sasaki, Y., & Watanabe, T. (2014). Age-related declines of stability in visual perceptual learning. *Current Biology : CB*, *24*(24), 2926–2929. https://doi.org/10.1016/j.cub.2014.10.04.

Cheal, M., Lyon, D. R., & Hubbard, D. C. (1991). Does attention have different effects on line orientation and line arrangement discrimination? *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *43*(4), 825–857. https://doi.org/10.1080/14640749108400959.

Chica, A. B., Bartolomeo, P., & Lupiáñez, J. (2013). Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behavioural Brain Research*, *237*, 107–123. https://doi.org/10.1016/j.bbr.2012.09.027.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755.

Craik, F. I. M., & Byrd, M. (1982a). Aging and Cognitive Deficits. In F. I. M. Craik & S. Trehub (Eds.), *Aging and Cognitive Processes* (pp. 191–211). Springer US. https://doi.org/10.1007/978-1-4684-4178-9_11.

Craik, Fergus I M, & Byrd, M. (1982b). *Aging and Cognitive Deficits BT - Aging and Cognitive Processes* (F I M Craik & S. Trehub, Eds.; pp. 191–211). Springer US. https://doi.org/10.1007/978-1-4684-4178-9_11.

Crist, R. E., Li, W., & Gilbert, C. D. (2001). Learning to see: Experience and attention in primary visual cortex. *Nature Neuroscience*, *4*(5), 519–525. https://doi.org/10.1038/87470.

Deloss, D. J., Bian, Z., Watanabe, T., & Andersen, G. J. (2015). Behavioral training to improve collision detection. *Journal of Vision*, *15*(10), 2–2. https://doi.org/10.1167/15.10.2

DeLoss, D. J., Watanabe, T., & Andersen, G. J. (2014). Optimization of perceptual learning: Effects of task difficulty and external noise in older adults. *Vision Research*, *99*, 37–45. https://doi.org/10.1016/j.visres.2013.11.003.

Desimone R. & Duncan J. (1995) Neural mechanisms of selective visual attention. Annual Review of Neuroscience,18:193–222.

Donovan, I. & Carrasco, M. (2018). Endogenous attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7, 1-16.

Donovan, I., Szpiro, S., & Carrasco, M. (2015). Exogenous attention facilitates perceptual learning transfer within and across visual hemifields. *Journal of Vision*, *15*(10), Article 11. doi:10.1167/15.10.11.

Dosher, B A, & Lu, Z. L. (1999). Mechanisms of perceptual learning. *Vision Research*, *39*(19), 3197–3221. https://doi.org/10.1016/s0042-6989(99)00059-0.

Dosher, B A, & Lu, Z. L. (2000). Noise exclusion in spatial attention. *Psychological Science*, *11*(2), 139–146. https://doi.org/10.1111/1467-9280.00229.

Dosher, B.A., & Lu, Z.-L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proceedings of the National Academy of Sciences*, *95*(23), 13988. https://doi.org/10.1073/pnas.95.23.13988.

Evans, L. (2004). Overview of traffic fatalities. In Traffic safety (pp. 36–62). Bloomfield Hills, MI: Science Serving Society.

Fahle, M. (1997). Specificity of learning curvature, orientation, and vernier discriminations. *Vision Research*, *37*(14), 1885–1895. https://doi.org/10.1016/s0042-6989(96)00308-2

Fahle, M, & Edelman, S. (1993). Long-term learning in vernier acuity: Effects of stimulus orientation, range and of feedback. *Vision Research*, *33*(3), 397–412. https://doi.org/10.1016/0042-6989(93)90094-d.

Fahle, M., & Henke-Fahle, S. (1996). Interobserver variance in perceptual performance and learning. *Investigative Ophthalmology & Visual Science*, 37 (5), 869– 877.

Fahle, M. (2004). Perceptual learning: A case for early selection. *Journal of Vision*, *4*(10), 879–890. https://doi.org/10.1167/4.10.4.

Fine, I., & Jacobs, R. A. (2002). Comparing perceptual learning tasks: A review. *Journal of Vision*, *2*(2), 190–203. https://doi.org/10.1167/2.2.5.

Fiorentini, A., & Berardi, N. (1981). Learning in grating waveform discrimination: Specificity for orientation and spatial frequency. *Vision Research*, *21*(7), 1149–1158. https://doi.org/10.1016/0042-6989(81)90017-1.

Fiorentini A., & Berardi N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature, 287*, 43–44.

Folk, C. L., & Hoyer, W. J. (1992). Aging and shifts of visual spatial attention. *Psychology and aging*, *7*(3), 453–465. https://doi.org/10.1037//0882-7974.7.3.453.

Gibson E. J. (1953). Improvements in perceptual judgement as a function of controlled practice of training. Psychological Bulletin, 50, 402-431.

Gilbert, C. D., Sigman, M., & Crist, R. E. (2001). The neural basis of perceptual learning. *Neuron*, *31*(5), 681–697. https://doi.org/10.1016/s0896-6273(01)00424-x.

Green, C.S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current Biology: CB*, *22*(6), R197–R206. PubMed. https://doi.org/10.1016/j.cub.2012.02.012.

Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–537. https://doi.org/10.1038/nature01647.

Green, C Shawn, & Bavelier, D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(6), 1465–1478. PubMed. https://doi.org/10.1037/0096-1523.32.6.1465.

Hartley, A. A., & Kieley, J. M. (1995). Adult age differences in the inhibition of return of visual attention. *Psychology and Aging, 10*(4), 670–683. https://doi.org/10.1037/0882-7974.10.4.670.

Horn, J. L., & Blankson, N. (2005). *Foundations for Better Understanding of Cognitive Abilities.* In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (p. 41–68). The Guilford Press.

Huang, L., & Dobkins, K. R. (2005). Attentional effects on contrast discrimination in humans: Evidence for both contrast gain and response gain. *Vision Research*, *45*(9), 1201–1212. https://doi.org/10.1016/j.visres.2004.10.024.

Iarocci, G., Enns, J. T., Randolph, B., & Burack, J. A. (2009). The modulation of visual orienting reflexes across the lifespan. *Developmental Science, 12*(5), 715–724. https://doi.org/10.1111/j.1467-7687.2009.00810.x.

Jeter, P. E., Dosher, B. A., Liu, S.-H., & Lu, Z.-L. (2010). Specificity of perceptual learning increases with increased training. *Vision Research*, *50*(19), 1928–1940. PubMed. https://doi.org/10.1016/j.visres.2010.06.016.

Jeter, P. E., Dosher, B. A., Petrov, A., & Lu, Z.-L. (2009). Task precision at transfer determines specificity of perceptual learning. *Journal of Vision*, *9*(3), 1–1. https://doi.org/10.1167/9.3.1.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In: Long, JB.; Baddeley, AD., editors. Attention & performance IX. Erlbaum; Hillsdale, NJ: 187-203.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, *43*(4), 346–354. https://doi.org/10.3758/bf03208805

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Sciences of the United States of America*, *88*(11), 4966–4970. https://doi.org/10.1073/pnas.88.11.4966.

Kumar, T., & Glaser, D. A. (1993). Initial performance, learning and observer variability for hyperacuity tasks. *Vision research*, *33*(16), 2287–2300. https://doi.org/10.1016/0042-6989(93)90106-7.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2017). Training to improve collision detection in older adults. *Driving Assessment Conference.* DOI: 10.17077/drivingassessment.1651.

Li, W., Piëch, V., & Gilbert, C. D. (2004). Perceptual learning and top-down influences in primary visual cortex. *Nature Neuroscience*, *7*(6), 651–657. https://doi.org/10.1038/nn1255.

Lien, M. C., Gemperle, A., & Ruthruff, E. (2011). Aging and involuntary attention capture: electrophysiological evidence for preserved attentional control with advanced age. *Psychology and aging*, *26*(1), 188–202. https://doi.org/10.1037/a0021073.

Ling, S., & Carrasco, M. (2006). Sustained and transient covert attention enhance the signal via different contrast response functions. *Vision Research, 46*(8-9), 1210–1220. https://doi.org/10.1016/j.visres.2005.05.008.

Lord S.R., Dayhew J. & Howland A. (2002). Multifocal glasses impair edge-contrast sensitivity and depth perception and increase the risk of falls in older people. *J Am Geriatr Society* 50(11):1760–1766. doi:10.1046/j.1532-5415.2002.50502.x. [PubMed: 12410892].

Madden, D. J. (2007). Aging and Visual Attention. *Current Directions in Psychological Science*, *16*(2), 70–74. PubMed. https://doi.org/10.1111/j.1467-8721.2007.00478.x.

Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., White, L. E., & Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging*, *28*(3), 459–476. https://doi.org/10.1016/j.neurobiolaging.2006.01.005.

Maniglia, M., & Seitz, A. R. (2017). Towards a whole brain model of Perceptual Learning. *Current Opinion in Behavioral Sciences*, *20*, 47–55. https://doi.org/10.1016/j.cobeha.2017.10.004.

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology: CB*, *14*(9), 744–751. https://doi.org/10.1016/j.cub.2004.04.028.

Menz, H. B., Morris, M. E., & Lord, S. R. (2005). Foot and ankle characteristics associated with impaired balance and functional ability in older people. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *60*(12), 1546–1552. https://doi.org/10.1093/gerona/60.12.1546.

Monsell S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134–140. https://doi.org/10.1016/s1364-6613(03)00028-7.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science (New York, N.Y.)*, *229*(4715), 782–784. https://doi.org/10.1126/science.4023713.

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision*, *11*(1), 10.1167/11.1.25 25. PubMed. https://doi.org/10.1167/11.1.25.

Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience*, 27, 11401–11411.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*(11), 1631–1647. https://doi.org/10.1016/0042-6989(89)90144-2.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, *6*(3), 403–415. https://doi.org/10.1037//0882-7974.6.3.403.

Polat, U., Schor, C., Tong, J.-L., Zomet, A., Lev, M., Yehezkel, O., Sterkin, A. & Levi, D. M. (2012). Training the brain to overcome the effect of aging on the human eye. *Scientific Reports*, 2: 278.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., & Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex (New York, N.Y. : 1991)*, *15*(11), 1676–1689. https://doi.org/10.1093/cercor/bhi044.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168–185. https://doi.org/10.1016/j.neuron.2009.01.002.

Reuter-Lorenz, P. A., & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral precues. *Perception & Psychophysics, 52*(3), 336–344. https://doi.org/10.3758/BF03209150.

Richards E, Bennett P., & Sekuler A. (2006) Age related differences in learning with the useful field of view. *Vision Research, 46* (25), 4217–4231. doi:10.1016/j.visres.2006.08.011.

Rohenkohl, G., Coull, J. T., & Nobre, A. C. (2011). Behavioural Dissociation between Exogenous and Endogenous Temporal Orienting of Attention. *PLOS ONE*, *6*(1), e14620. https://doi.org/10.1371/journal.pone.0014620.

Rosen, A. C., Rao, S. M., Caffarra, P., Scaglioni, A., Bobholz, J. A., Woodley, S. J., Hammeke, T. A., Cunningham, J. M., Prieto, T. E., & Binder, J. R. (1999). Neural basis of endogenous and exogenous spatial orienting. A functional MRI study. *Journal of Cognitive Neuroscience*, *11*(2), 135–152. https://doi.org/10.1162/089892999563283.

Sagi, D., & Tanne, D. (1994). Perceptual learning: Learning to see. *Current Opinion in Neurobiology*, *4*(2), 195–199. https://doi.org/10.1016/0959-4388(94)90072-8.

Salat, D. H., Tuch, D. S., Hevelone, N. D., Fischl, B., Corkin, S., Rosas, H. D., & Dale, A. M. (2005). Age-related changes in prefrontal white matter measured by diffusion tensor imaging. *Annals of the New York Academy of Sciences*, *1064*, 37–49. https://doi.org/10.1196/annals.1340.009.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition. *Psychol. Rev. 103*, 403–428.

Schmolesky, M. T., Wang, Y., Pu, M., & Leventhal, A. G. (2000). Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, *3*(4), 384–390. https://doi.org/10.1038/73957.

Schoups, A., Vogels, R., Qian, N., & Orban, G. (2001). Practising orientation identification improves orientation coding in V1 neurons. *Nature*, *412*(6846), 549–553. https://doi.org/10.1038/35087601.

Scialfa, C. T., Kline, D. W., & Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging*, *2*(1), 14–19. https://doi.org/10.1037//0882-7974.2.1.14.

Seitz, A. R., & Watanabe, T. (2009). The phenomenon of task-irrelevant perceptual learning. *Vision Research, 49*, 2604–2610.

Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America. A, Optics and image science*, *3*(6), 864–867. https://doi.org/10.1364/josaa.3.000864.

Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research*, *26*(2), 103–120. https://doi.org/10.1080/036107300243588.

Sekuler, R., Owsley, C., & Hutman, L. (1982). Assessing spatial vision of older people. *American Journal of Optometry and Physiological Optics*, *59*(12), 961–968. https://doi.org/10.1097/00006324-198212000-00005.

Shiu, L., Pashler, H. (1992) Improvement in line orientation discrimination is retinally local but dependent on cognitive set. *Perception & Psychophysics 52*, 582–588. https://doi.org/10.3758/BF03206720.

Sigman, M., Pan, H., Yang, Y., Stern, E., Silbersweig, D., & Gilbert, C. D. (2005). Top-down reorganization of activity in the visual pathway after learning a shape identification task. *Neuron*, *46*(5), 823–835. https://doi.org/10.1016/j.neuron.2005.05.014.

Sokal, R. R., & Rohlf, J. F. (1981). Biometry: The principles and practice of statistics in biological research (2nd ed.). San Francisco: W.H. Freeman.

Szpiro, S. F., & Carrasco, M. (2015). Exogenous Attention Enables Perceptual Learning. *Psychological science*, *26*(12), 1854–1862. https://doi.org/10.1177/0956797615598976.

Tartaglia, E. M., Bamert, L., Mast, F. W., & Herzog, M. H. (2009). Human perceptual learning by mental imagery. *Current Biology: CB*, *19*(24), 2081–2085. https://doi.org/10.1016/j.cub.2009.10.060.

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006.

Tsushima, Y., Seitz, A. R., & Watanabe, T. (2008). Task-irrelevant learning occurs only when the irrelevant feature is weak. *Current Biology: CB*, *18*(12), R516–R517. PubMed. https://doi.org/10.1016/j.cub.2008.04.029.

Tsushima, Y., & Watanabe, T. (2009). Roles of attention in perceptual learning from perspectives of psychophysics and animal learning. *Learning & Behavior*, *37*(2), 126–132. https://doi.org/10.3758/LB.37.2.126.

Wahl H.W., Schilling O., Oswald F., & Heyl V. (1999) Psychosocial consequences of age-related visual impairment: comparison with mobility-impaired older adults and long-term outcome. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 54*(5): P304–316.

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching: a meta-analysis. *Psychology and aging*, *26*(1), 15–20. https://doi.org/10.1037/a0020912.

Watanabe, T., Nanez, J.E., & Sasaki, Y. (2001). Perceptual learning without perception. *Nature, 413*, 844–48.

Watanabe, T., & Sasaki, Y. (2015). Perceptual learning: toward a comprehensive theory. *Annual review of psychology*, *66*, 197–221. https://doi.org/10.1146/annurev-psych-010814-015214.

Watson, A. A. B., & Pelli, D. G. D. (1983). QUEST: A Bayesian adaptive psychometric method. Attention, *Perception, & Psychophysics, 33*(2), 113–120.

White, A. L., Lunau, R., & Carrasco, M. (2014). The attentional effects of single cues and color singletons on visual sensitivity. *Journal of Experimental Psychology: Human Perception and Performance, 40*(2), 639–652, https://doi.org/10.1037/a0033775.

Xiao, L. Q., Zhang, J. Y., Wang, R., Klein, S. A., Levi, D. M., & Yu, C. (2008). Complete transfer of perceptual learning across retinal locations enabled by double training. *Current biology: CB*, *18*(24), 1922–1926. https://doi.org/10.1016/j.cub.2008.10.030.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 676−681.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 95−107.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 121−134.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10*(5):601-21.

Yehezkel, O., Sterkin, A., Lev, M., Levi, D. M., & Polat, U. (2016). Gains following perceptual learning are closely linked to the initial visual acuity. *Scientific Reports*, 6, 25188.

Yotsumoto Y., Chang L., Ni R., Pierce R., Andersen G.J., Watanabe T., Sasaki Y. (2014) White matter in the older brain is more plastic than in the younger brain. *Nature Comm.*

Yotsumoto, Y. & Watanabe, T. (2008). Defining a link between perceptual learning and Attention. *PLoS Biology,* 6(8), e221.

Yu C., Klein S.A., Levi D.M. (2004) Perceptual learning in contrast discrimination and the (minimal) role of context. *J. Vis. 4*:169–182.

Zanto T.P. & Gazzaley A. (2014) Attention and ageing. In: Nobre AC, Kastner S, editors. The Oxford Handbook of Attention. Oxford University Press, 927–971.

Zhang, J. Y., Zhang, G. L., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *The Journal of neuroscience: the official journal of the Society for Neuroscience*, *30*(37), 12323–12328. https://doi.org/10.1523/JNEUROSCI.0704-10.2010.

Chapter 3

Aging, perceptual learning and attention on driving performance

Kieu Ngoc Nguyen[1] & George John Andersen[1]

Author Affiliations:

[1] Department of Psychology, University of California, Riverside, Riverside, California, United States of America

Abstract

The incidence of automotive crashes is particularly high among drivers under the age of 25 (Evans, 2004; Williams & Carsten, 1989) and over the age of 65 (Tefft, 2008; Evans, 2004). An important issue for driving safety is identifying potential ways to reduce crash risk by examining drivers' ability to detect impending collisions. Perceptual learning (PL)---improvements on a perceptual task as a result of repeated exposure---has been shown to improve collision detection in both older and younger adults (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss & Andersen, 2017). An important component of PL training is attention, which has been found to improve performance for a variety of perceptual tasks (see Byers & Serences, 2012). The present study investigated the effect of attention and PL on collision detection for both older and younger drivers in a dual-task driving paradigm. Drivers were presented with a computer-simulated roadway scene and maintained within-lane vehicle steering while also identifying which object among a number of objects (number of objects; 2,4,8) will collide with the driver. During training, drivers were trained over several days in which the number of objects were varied (2, 4, or 8). Drivers were either presented with an endogenous valid cue (identifying the visual field location of the collision object) or an endogenous neutral cue. The results indicated an overall decrease in detection performance (lower accuracy and greater RT) with an increase in the number of objects. PL resulted in improved collision detection performance for both older and younger drivers. In addition, greater accuracy and RT were found when an endogenous valid cue

was presented during training with improved performance for both younger and older drivers. These results indicate the benefits of training and attention in collision detection.

Introduction

Vehicle crashes are a major global health concern accounting for more than 1.25 million deaths worldwide per year with millions of drivers sustaining serious injuries (World Health Organization, 2015). Drivers at greatest risk of vehicle motor crashes are those in the younger and older population. Research has consistently shown that younger and older adults are at greater risk of fatal and non-fatal collisions than those in the middle-aged population (Lam, 2002, Ma & Yan, 2014, McAndrews Beyer, Guse, & Layde, 2013; Williams & Shabanova, 2003; World Health Organization, 2015). Consistent with these studies, the relation between crash involvement and driver age is a U-shaped function---with greater crash rates for older and younger drivers (Sanders & McCormick, 1993; Son & Suh, 2011). By the year 2050, the 65-and-older population is expected to more than double the present number of persons (US Census, 2014). With the increase of persons in the older population, it follows that the number of older drivers on the road is likely to increase as well, resulting in an increase in crashes due to the greater number of older drivers.

Driving is a complex skill that requires the driver to concurrently perform multiple tasks. Of these multiple tasks, an important perceptual skill in driving is the ability to detect and avoid an impending collision. There are a variety of different scenarios that could result in a collision event. A collision event can occur when the observer is moving and the collision object is stationary, when an object is moving and the observer is static, or when both the observer and object are moving (Andersen & Sauer, 2004). Under these scenarios, there are a number of different conditions that can lead to collision; the trajectory of the object/observer can be linear or curved and the speed of object/observer motion can be constant or variable speed. The current study involves investigating both observer motion and object motion under linear trajectory at a constant speed. Under these conditions a collision event is defined by two sources of information; (1) optical expansion of the object; and (2) the bearing of the object. Optical expansion refers to an increase in the projected size of an object when an object approaches (Koenderink, 1986; Gibson, 1947). For an object on a linear trajectory and constant speed, constant bearing refers to an object maintaining an angular direction or fixed position in the optic flow field (Kaiser & Mowafy, 1993). For a linear and constant trajectory for both object and observer, collision objects will have a constant bearing whereas non-collision objects will change in bearing overtime.

Recent research has reported factors that impact one's ability to detect impending collisions. For example, increased speed can decrease the ability to the detect impending collisions (Andersen & Enriquez, 2006). Younger and older observers were presented with an approaching object and were asked to determine whether or not the object was on a collision path towards the observer. Both younger and older adults experienced decrements in sensitivity with increased observer speed. But this decline in sensitivity was particularly pronounced in older adults despite conditions in which older adults were given more time to observe the scene.

Decrements in detecting collision objects at high speeds are also apparent under conditions of deceleration (Andersen, Cisneros, Saidpour & Atchley, 2000). Detection of collision events during deceleration declines with increased speed. Not only were the declines in collision detection more pronounced for older adults, but older adults were more likely to report a collision under conditions in which no collision was present. Older adults have more difficulty than younger adults in judging relative speed of objects (Schiff, Oldak, & Shah, 1992), which may give them less time to react to a given situation. Older adults were more likely to report collisions sooner than simulated, which is likely a compensatory response to allocate time to react to a given situation.

What about more complex scenarios similar to that of real-world cluttered driving scenes? Previous research has found that the presence of multiple objects can impact one's ability to detect collisions (Andersen & Kim, 2001). The presence of multiple objects can increase the attentional demands of the driver and consequently reduce one's ability to detect a collision. Specifically, collision detection is limited by the number of objects in a scene, with a decrease in detection with increased number of objects in the scene. This can be further exacerbated by the presence of a distracting object. For example, Ni and Andersen (2006) examined collision detection in a dual-task driving paradigm. Older drivers were instructed to both maintain steering control and detect the presence of a collision object among a number of objects. The presence of a uniquely textured non-collision object, which distracted the driver's attention, was found to increase the steering control error of older drivers (Ni & Andersen, 2006). This finding indicates that older adults are negatively impacted by the presence of distracting non-relevant objects in a driving scene. Consistent with this result, older adults exhibit greater steering control error as compared to younger adults (Ni, Bian, & Andersen, 2009). Taken together, these results indicate that a number of factors can decrease a driver's ability to detect and avoid collisions, but that older adults may be particular vulnerable to these factors and thus at increased risk for vehicle accidents.

The high incidence of crashes among the elderly population could be partly attributed to age-related declines in vision and cognition. A number of age-related declines in visual function has been linked to increases in motor-vehicle crashes (Owsley, Ball, Sloan, Roenker & Bruni, 1991). For instance, contrast sensitivity was found to correlate with recent crash history (Owsley, Ball, Sloan, Roenker & Bruni, 1991). It is well-documented in the literature for age-related declines in spatial vision, which is the ability to detect and resolve spatially defined visual information. Assessment of spatial vision is a pre-requisite screening tool to obtaining a driver's license. Declines in spatial vision is also one of the contributors to increased risk of falls in the older population (Lord & Dayhew, 2001). Numerous studies have found that older adults experience age-related declines in vision (see Andersen, 2012, for a review). For instance, age-related changes have been reported in the optics of the eye, sensory processing, and perceptual processing. Age-related declines in sensory processing has been reported for tasks such as orientation discrimination (Betts, Sekuler, & Bennett, 2007) and contrast sensitivity (Richards, 1977; Owsley, Sekuler, & Siemsen, 1983). For perceptual processing, age-related declines include motion (Andersen & Atchley, 1995, Betts, Taylor, Sekuler, Bennett, 2005; Bennett, Sekuler, & Sekuler, 2007), form perception (Roudaia, Bennett, & Sekuler, 2008), and optic flow (Atchley & Andersen, 1998; Andersen, Cisneros, Atchley & Saipour, 1999). These types of declines in visual function have implications for driving safety as these age-related declines can affect the detection of impending collisions.

Given that driving occurs in a dynamic environment, older adults need more time to observe motion to perceive it (Ball & Sekuler 1986). This may reduce the time needed to respond to given situations. This may also impact an older adult's ability to accurately detect and judge relative speed of objects. Furthermore, age-related perceptual declines may affect an older adults' ability to perceive information under degraded driving conditions (i.e. inclement weather such as rain, fog or snow).

Increased crash risk is not limited to age-related declines in visual function. Age-related declines in cognition such as attention (see Madden, 2007, for a review) could account for increased accident risk among older drivers. For instance, age-related declines in attention include declines for both focused (Folk & Hoyer, 1992; Kramer et al., 1999) and divided attention tasks (Hartley & Little, 1999). One task that is known to be predictive of vehicle crash risk is the useful field of view task (UFOV). The UFOV is a measure of the spatial extent of attention which is the spatial region of the visual field from which an observer can extract visual information (Sekuler & Ball, 1986; Ball, Beard, Roenker, Miller, & Griggs, 1988; Scialfa, Kline, & Lyman, 1987). Three different attentional abilities are assessed in the UFOV: processing speed, divided attention, and selective attention. Processing speed is the amount of time an observer needs to accurately discriminate visual information. Processing speed, as assessed in the UFOV, is obtained by deriving threshold performance for centrally presented stimuli. Divided attention is the ability to simultaneously discriminate multiple presented stimuli. Divided attention, as assessed by UFOV, obtains a threshold for both centrally and peripherally presented stimuli. Lastly, selective attention is the ability to process multiple stimuli in the presence of irrelevant distractors. Selective attention is similar to the divided attention task in the UFOV but with the additional presence of distractors.

Considerable research with older adults utilizing the UFOV task has been informative for understanding the basis for the types of difficulties older adults encounter in everyday activities. Specifically, the age-related deficits observed in everyday activities that require time-sensitive responses, such as identification or detection of visual stimuli or dividing attention during driving, may be attributed to slowed processing speed or generalized slowing of information processing (Salthouse, 1991;1995). In fact, older adults that exhibit slowed processing speed as measured by the UFOV, take longer to complete visual tasks typical of everyday life. (Owsley, 2013). Additionally, declines in spatial extent of visual attention are evident in early adulthood (Sekuler, Bennett & Mamelak, 2000). These declines can start at approximately 20 years of age and decade-by-decade the decline becomes pronounced. Older adults exhibit declines in performance on the divided-attention component of the UFOV (Sekuler, Bennett, & Mamelak 2000; Sekuler & Ball, 1986). These declines in performance are further exacerbated in older adults when irrelevant, distracting stimuli were presented (Sekuler & Ball, 1986). Older adults seem to be particularly susceptible to the distracting effects of irrelevant or interfering visual stimuli. These findings of poorer performance on UFOV tasks for older adults is correlated with a myriad of difficulties in visual tasks of everyday life. For example, lower performance on the UFOV task has been linked to mobility problems (Owsley & Mcgwin, 2004), increased risk of falls (Sims, et al., 1998), and increased risk of motor collisions (Ball, Owsley, Sloane, Roenker & Bruni, 1993; Owsley, Ball, Sloane, Roenker & Bruni, 1991).

Given these age-related declines, recent work has been dedicated to developing interventions aimed at ameliorating age-related declines in vision. Perceptual learning (PL) refers to perceptual improvements as a result of repeated exposure or training on a perceptual task. Much of the research on PL has focused on low-level visual tasks such as orientation (Fiorentini & Berardi, 1980;1981), spatial frequency (Fiorentini & Berardi, 1980, 1981), contrast (Adini, Sagi & Tsodyks, 2002), motion (Ball & Sekuler, 1982,1987), texture (Karni & Sagi, 1991), with college-age adults. Relatively few studies have focused on age-related declines in PL. PL studies with older adults has focused on targeting visual functions known to decline with age. Specifically, older adults have benefitted from PL training with texture discrimination (Andersen, Ni, Bower, & Watanabe, 2010; Yotsumoto et al., 2014; Chang et al., 2014), contrast sensitivity (Deloss et al., 2015), orientation (Deloss, Watanabe, & Andersen, 2014), and motion (Bower, Watanabe & Andersen, 2013; Bower & Andersen, 2012).

A defining characteristic of PL with younger adults is that training tends be specific to the stimulus or task configuration. Specificity is when training-induced improvements on stimuli/task are specific, or fail to generalize, to untrained stimuli/task. For example, younger adults were trained on a texture discrimination task in the peripheral visual field and a letter discrimination task in central vision. Although significant improvement, as a result of training, was observed on that task, learning was specific to the trained location (Karni & Sagi, 1991). This finding of specificity, observed with younger populations, can also be specific to the trained feature including orientation (Fiorentini & Berardi, 1981), motion direction (Ball & Sekuler, 1987) as well as the trained eye (Karni & Sagi, 1991). However, certain variations in the task/stimuli or characteristics of the individual could lead to generalization or transfer. Characteristics of that task which include training with more complex stimuli tend to exhibit generalized learning (for review see Fahle, 2005). Meta-analysis of various PL studies at different levels of visual processing have observed greater learning with more complex visual stimuli (Fine & Jacobs, 2002). For example, training on action video games not only improved performance on the trained game but also generalized to different tasks that indexed attentional abilities. Additionally, PL training with collision detection produced improvements that transferred to faster observer speeds for both older (Lemon, Deloss & Andersen, 2017) and younger adults (Deloss, Bian, Watanabe & Andersen 2015). Given the importance of complex stimuli for generalization, an important issue is whether generalization is observed in complex tasks such as driving – a focus of the present study.

Characteristics of the individual such as age may impact learning and specificity. PL training with younger adults tend to exhibit specificity. In contrast, with the exception of one study (Andersen, Ni, Bower & Watanabe, 2010), learning has been found to be less specific in older individuals (Bower & Andersen, 2012; Bower, Watanabe & Andersen, 2013; Deloss, Watanabe & Andersen, 2014). Given decreased specificity found in older adults, what might be the basis for generalized learning observed in older individuals? Decrements in neural inhibition may be a contributing factor to age-related declines in vision and decreased specificity in PL with older adults. Decreased neuronal selectivity to orientation and direction as well as increased random neural firing may recruit a broader range of neurons when performing visual discriminations (Schmolesky et al., 2000; Leventhal et al., 2003; Hua et al., 2008). Thus, signals that would normally be ignored and subject to suppression would thus be learned. Consistent with this idea, previous research has investigated whether older adults would learn unimportant or irrelevant information that would otherwise be suppressed or ignored and thus not learned in younger adults (Chang, Shibata, Andersen, Sasaki, & Watanabe, 2014). Learning was observed after repeated exposure to a task-irrelevant and sub-threshold stimulus feature and has been referred to as task-irrelevant PL (TIPL) (Watanabe, Nanez & Sasaki, 2001). It was found that older adults learned task-irrelevant features that younger adults did not learn (Chang et al., 2014). Older adults learned the features that were both sufficiently strong for younger adults to suppress and too weak for younger adults to learn. Decreased neural selectivity in older adults may have enabled learning of stimuli that may have otherwise been suppressed. Thus, this decreased selectivity may allow for generalized learning.

Inhibition has several functions including modulation of selective attention. Selective attention has been conceptualized as processing of behaviorally-relevant information and ignoring processing of irrelevant information. Selective attention can be deployed in a voluntary, intentional, goal-driven manner called endogenous attention. Research on endogenous attention has found that an endogenous cue is maximally effective at approximately 300ms after the onset of a cue (Carrasco, 2011). This type of attention is an effortful process that includes processing of the cue (e.g., semantic meaning) in order to orient attention to a particular location. To assess the effectiveness of the cue, a centrally presented symbolic cue, such as an arrow, would indicate the possible location of a subsequently presented target. The valid cue indicates a correct location, an invalid cue indicates an incorrect location and a neutral cue could give no indication to the location of the target. Performance for valid cues tends to be faster and/or more accurate than performance for invalid trials or neutral trials (Posner, 1980). PL with endogenous cues may lead to greater learning for valid cues as compared to neutral cues and invalid cues (Mukai, 2011). In terms of transfer, performance improvements generalized to untrained locations when trained with valid cues but not when trained with neutral cues (Donovan & Carrasco, 2018). This suggests that greater allocation of attention to a trained task may induce PL and transfer. This is consistent with research that found training-induced improvements associated with efficient deployment of attention following PL (Bays et al., 2015).

Consequently, PL training may optimize the effectiveness of top-down attention control (see Byers & Serences, 2012). According to Byers and Serences (2012), training could induce plasticity in local connections so that intervention by top-down attentional modulations can be minimized. Consistent with this hypothesis, an associated reduction in the magnitude of activation in areas of the frontoparietal cortex commonly, thought to mediate attentional control, was found following training (Mukai et al., 2007; Sigman, Pan, Yang, Stern, Silbersweig, & Gilbert, 2005). This suggests that the magnitude of top-down attentional control is reduced through the course of training.

Given the review of the literature discussed above, the present study is concerned with investigating the effect of perceptual learning, aging and attention in a dual-task driving paradigm. The current study has three aims. The first aim was to evaluate the effect of aging and endogenous attention in PL in a dual-task driving paradigm. Given that aging results in declines in task performance, older adults may benefit to a greater degree than younger adults as a result of training on a collision detection task. Thus, the first hypothesis is that ability to learn increases with age. If this is correct, then magnitude of learning should increase with age. Research has found that lower baseline performance prior to training resulted in greater magnitude of learning (Yehezkel, Sterkin, Lev & Polat, 2015). Extending these findings, older adults may exhibit lower perceptual abilities as compared to younger adults and may have greater range for improvement with PL.

The second aim was to assess the effect of attention on learning. Previous research has reported that the type of cue can impact perceptual performance. Specifically, responses tend to be faster and/or more accurate with valid cues as compared to invalid cues or neutral cues (Posner, 1980). Furthermore, greater learning was found for valid cues as compared to neutral and invalid cues as a result of training with endogenous cues (Mukai, 2011). However, age-related declines in allocating attention has been observed in older adults. Previous research found that older adults had greater difficulty than younger adults in ignoring distracting objects in a scene (Cassavaugh, Kramer & Irwin, 2003). This difficulty in ignoring distracting objects may be a result of difficulty in disengaging attention to irrelevant information. And so, it is hypothesized that processing efficiency of endogenous attention declines with age.

Following this, it is likely that attention allocation declines with age. Thus, different predictions were made for older and younger adults. It was predicted that learning in older adults as a result of PL will not differ between those trained with valid or neutral cues. However, learning in younger adults as a result of PL will be greater for those trained with valid cues than those trained with neutral cues.

The third aim was to evaluate the effect of training on workload. Decrements in judgements of collision objects has been observed with increased number of objects in a driving scene (Andersen & Kim, 2001). Improved collision detection has been observed with PL for both older and younger adults (Lemon, Deloss & Andersen, 2017; Deloss, Bian, Watanabe & Andersen 2015). Given that PL training can improve task performance, both younger and older drivers should improve in collision detection, but performance will be affected by the number of objects in the scene. Specifically, it is hypothesized that performance declines with increased number of objects.

The last aim of the present study was to investigate whether training in PL with attentional cues will broadly generalize to visual attention. With regard to the last aim, it is hypothesized that PL training with attention cues improves attentional processing. Previous research has found training on action video game play, another type of high-level perceptual task, translated to improvements in UFOV (Green & Bavelier, 2003; 2006; Achtman, Green, & Bavelier, 2008; Belchior et al., 2014). If the UFOV task is predictive of driving performance, then improvements in driving performance should exemplified as improved scores in the UFOV task.

Both older and younger participants were trained on a collision detection task while simultaneously performing a steering control task. Drivers had to identify a collision object from among a number of objects (2, 4, or 8) while steering so that they were in the center of the lane by maintaining the yellow lane in the center. The study was administered over the course of 5 days. Testing sessions were administered the first and last day of the study. During testing sessions, performance was evaluated using only neutral cues for 2, 4 and 8 objects with 4.6 seconds display duration for the presented objects. Training sessions were administered between test days over the course of 3 days. During training days, both age groups were further divided to train in one of two attention conditions; endogenous auditory valid cues or endogenous auditory neutral cues. Each training sessions included multiple display durations (7.2s, 4.8s, 3.6s) for each number of objects with the number of objects (2,4,8) presented by day. Changes in performance was assessed by measuring changes in accuracy (percent correct), response times (RT), and steering control error.

Methods

Drivers

The drivers were 24 younger adults (12 female, 12 male) from the University of California, Riverside and 20 older adults (9 female, 11 male) over the age of 65 recruited in the surrounding Riverside county. All drivers were compensated for their participation and were naïve to the purpose of the experiment. Younger drivers had, on average, 3 years of driving experience and older drivers had, on average, 56 years of driving experience. All drivers had normal or corrected-to-normal vision. All drivers were screened for basic cognitive and perceptual assessments. Refer to table 3.1 for demographic information.

Design

Between-subject variables were age groups (older or younger drivers), type of endogenous attentional cues (valid cue or neutral cue). Within-subject variables were test-day (pre-test and post-test), number of objects (2,4,8), object-onset (pre-onset, post-onset) and display duration (7.2s, 4.8s, 3.6s). Dependent variables were accuracy (percent correct), correct RT, incorrect RT, and root-mean-square error (RMSE) for the secondary steering control task. Accuracy was derived from correctly identifying the collision object. Correct RT were measured from the initial presentation of a cue to the time a participant responds for only correct trials. Incorrect RT were measured from the initial presentation of a cue to the time a participant responds for only incorrect trials. Steering control was assessed by calculating root-mean-square error derived from the deviation between the simulated wind gusts and steering response of the driver to the simulated wind gusts. Two measures of RMSE was obtained labeled as object-onset; (1) pre-onset: 2 seconds prior to the presentation of the objects and (2) post-onset: 2 seconds following the presentation of the objects.

Apparatus

Stimuli were generated using software written using MATLAB (The Mathworks inc., Version 2018b) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The stimuli were presented on a 58-inch plasma display (Panasonic TH-58PF12UK). The display had a refresh rate of 60 Hz and a resolution of 1920 X 1080. A Dell precision T7500 equipped with dual Intel Xeon E5506 processors using Window 7 (Service Pack 1) operating system equipped with an NVIDIA Quadro FX 4800 graphics card was used. Google Cloud Speech-2-Text conversion was used for voice recognition for user responses.

Participants' far acuity was measured using the 2000 Series Revised ETDRS Chart 2 (Precision Vision, La Salle, IL) at a distance of 3 m. Participants' near acuity was measured using the 2000 series New ETDRS Chart 3 at a distance of 40 cm. Contrast sensitivity was measured using the Pelli-Robson Contrast Sensitivity Chart (Precision Vision). Cognitive assessments were the Weschler Adult Intelligence Scale III (Weschler, 1997) and Mini-Mental State Examination (Folstein, Folstein, & McHugh,1975).

Driving Simulator

A computer-generated 3D scene was of a 7.2m wide one-lane two-way road. Scene textures were derived from digital photographs of a roadway but were digitally altered and rescaled to realistically fit the simulation environment. The viewpoint was 1.2 m above the ground plane. The display was comparable to driving down a straight roadway with lateral wind gusts perturbing the driver's position on the roadway. The perturbation of the vehicle shifted the vehicle left and right away from the center of the lane. The perturbation of the vehicle was produced by a sum of sinusoid functions, whose frequencies were .08, .16, and .22 Hz respectively and amplitudes were .42, .22, .16 meters, respectively. Drivers were given two tasks: (1) steer to maintain horizontal position at the center of the lane despite simulated wind perturbations and (2) to quickly and accurately identify which object among 2,4,or 8 objects was on a collision path toward the driver by pressing a button on the steering wheel and then verbally identifying the number labeled on the object following the presentation of an endogenous attentional cue (valid or neutral). If the driver failed to steer for a few seconds, then the sound of a car horn was activated as a reminder. Figure 3.1 shows an example of the stimulus display for 4 objects.

The time course of a trial was as follows: the driver translated forward at a constant speed of 60 km/h along a linear path for two minutes. During the course of a trial, multiple iterations of the following occurred: An auditory endogenous attentional (valid or neutral) cue was presented, and subsequently multiple objects (either 2,4,8) translated at a fixed speed of 60 km/h opposite to the driver's moving direction (2.4 m diameter) along a linear trajectory. The valid cue was an auditory presentation of the word "left" or "right". The neutral cue was the word "both". An equal number of objects to the left and right of the roadway (i.e., if 2 objects, then 1 object on each side) was initially positioned at random along an arc (approx. 80º from the center of the display) at a fixed distance of 300 meters from the driver's viewpoint. Of the multiple objects, only one object was on a collision course towards the driver. The trajectory of the collision object intersected the simulated driver's viewpoint given the speed of the object and the speed of the driver motion. The display duration of the objects was either 7.2 seconds, 4.8 seconds or 3.6 seconds (Andersen & Kim, 2001) after which the objects disappeared from the display and the driver was to give a response. If the driver failed to respond, then the auditory word "respond" was presented as a reminder.

Procedure

The experiment was administered for 1.5-2 hours per day of testing or training over the course of 5 days. The first day was 2 hours, and subsequent days were 1.5 hours. The experiment took place in a darkened room, and the only source of light during the experiment was the display. Prior to participation in the study, drivers completed a preliminary questionnaire and phone screening to ensure drivers were eligible for the study. Participants were eligible for the study if they had no underlying visual diseases, no history of cognitive deficits, and were current drivers. The first day involved a series of practice trials for drivers to familiarize themselves with the task, UFOV task, and pre-test. Visual and cognitive assessments were administered. For the pre-test session, the following measures were derived; accuracy, correct RT, incorrect RT, RMSE for each number of objects (2,4,8). The display duration of the objects during testing sessions were presented for 4.8s. UFOV measurements were obtained during test days; prior to the pre-test and following the post-test. Training sessions were administered in between pre-test and post-test. During training sessions, accuracy, correct RT, incorrect RT, and RMSE was obtained for each number of objects (2,4,8) and for each display duration (3.6s, 4.8s, 7.2s). The last day (Day 5) was the post-test which is identical to pre-test but was administered following the training sessions.

Practice

There were 4 parts to the practice designed to build up to the main task. The first practice involved steering control in which drivers steered so that they were in the center of the lane by maintaining the yellow lane in the center for 3 trials with a 1-minute duration for each trial. The second practice session involved detection of a collision object. Prior to the second practice, drivers were shown sample demonstrations of a collision and non-collision trial. The second practice session trial was as follows; an object randomly appeared at a distance of 300 meters along an arc of 80 deg and appeared to move along a linear trajectory at a constant speed towards the driver. The driver responded with whether or not the object is a collision object. Drivers were required to obtain 80% accuracy or correctly respond to 8 out of 10 trials. Drivers were given 3 attempts to pass. Drivers were able to proceed to the next practice session once an accuracy of 80% or greater was obtained. Drivers that failed to achieve this level of performance were excluded from the experiment. For the third practice session, drivers had to identify the collision object. Four objects randomly appeared at a distance of 300 meters along an arc of 80 deg and translated along a linear trajectory at a constant speed towards the driver. To respond, the driver had to verbally identify which object the driver believed to be the collision object. For the fourth practice session, drivers had to both identify the collision object and maintain steering control. Drivers were to steer to maintain the yellow lane in the center and among 4 objects identify which was the collision object. Drivers identified the collision object by pressing a button to initiate a response and then verbally respond by identifying the number of the object that drivers believed to be the collision object.

Testing

Testing was on the first (day 1) and last day (day 5) of the study. The number of objects (2,4,8) were presented by block and counter-balanced across the drivers. Only the

4.8s display duration was presented for each number of objects (2,4, 8). For each trial, there were 8 iterations of the 4.8s display duration. In other words, the driver encountered and responded to 8 separate instances (or iterations) of a scene of objects while driving for the duration of a 2 minute-trial. These iterations appeared randomly within the 2-minute trial. There was a total of 18 trials with 6 trials per number of objects (2,4,8). Breaks were given between each trial. Auditory feedback was given.

Training

Training sessions occurred between testing days. The number of objects (2,4,8) were presented by training day and counter-balanced across the drivers. Each of the display durations (3.6s, 4.8s, 7.2s) were presented. For each trial, the order with which the display durations were presented was as follows: 3 iterations/7.2s display duration, 2 iterations/4.8s display duration, 3 iterations/3.6s display duration, respectively. These iterations appeared in the stated order at random times throughout the 2-minute trial. There was a total of 18 trials per number of objects (2,4,8). Breaks were given between each trial. Auditory feedback was given.

Results

The analytic method was a linear mixed-effects regression using the lme4 (version:1.1-23) (Maechler, & Bolker, 2013) package in R (R Foundation for Statistical Computing, 2013). Fixed effects were age group (older adults, younger adults), attention cues (valid cue or neutral cue), number of objects (2,4, or 8 objects), object-onset (pre-onset; post-onset) and test-day (pre-test and post-test). The random effect was driver (participant). Between-subject variables were age-group and attention cues. Within subject variables were object-onset, number of objects, and test-day.

Linear mixed-effects regression was conducted on accuracy measures at baseline prior to training (pre-test only). There was an effect of age-group [$F(2,40) = 26.2861$, $p < .0001$], an effect for the number of objects [$F(2,212) = 604.2775$, $p < .0001$] and an attention cues x number of objects interaction [$F(2,212) = 11.0169$, $p < .0001$]. This suggests that there was a difference in baseline accuracy, prior to training, between the performance of older and younger drivers, between the number of objects presented in the driving scene and an interaction of the type of attention cue presented and number of objects in the scene. Comparisons between older and younger drivers were originally intended in the study, but differences in baseline performance between age groups and number of objects prevented any direct comparative analyses. Thus, subsequent analyses were conducted separately by age-group. Analyses were first reported for older drivers for the following measures; accuracy (percent correct), correct RT, incorrect RT, RMSE, UFOV scores, and performance during training sessions. Next, the same analyses were reported for younger drivers. Analyses were then conducted for magnitude of learning with data combined for older and younger drivers.

Older Drivers

Accuracy

Analyses were conducted to assess whether changes in accuracy occurred as a result of training. Accuracy was calculated as proportion of correct responses to total number of responses expressed as percent correct for the 2, 4, and 8 object conditions between valid and neutral cues at pre-test and post-test. Analyses of percent correct in older drivers as a function of attention cues (valid cue, neutral cue), number of objects (2,4, or 8) and test-day (pre-test, post-test) was conducted.

Baseline accuracy between attention cue conditions. First, analyses were conducted on baseline percent correct (pre-test only) to assess whether the performance was comparable for number of object conditions prior to training. A significant effect for number of objects was found, $F(2,36) = 180.1623$, $p < .001$, indicating that there were significant differences in percent correct for 2 objects (M = 75.6%), 4 objects (M = 42.6%) and 8 objects (M = 16.4%). This indicates that performance across the number of objects were not at comparable levels prior to training.

Given that percent correct was not comparable prior to training, subsequent analyses were conducted separately by number of objects. Analyses on baseline percent correct was performed (pre-test only) and were separated by the number of objects. Assessment of baseline percent correct indicated no reliable differences between valid and neutral cue conditions for the 2 object [$F(1,18) = .6377$, $p = .4349$], 4 object [$F(1,18) = .5158$, $p = .4818$] and 8 object [$F(1,18) = .0103$, $p = .9202$], conditions, respectively.

Accuracy for test-day between attention cue conditions. Analyses were subsequently conducted for the attention cues (valid cue, neutral cue), number of objects (2,4 or 8) and test-day (pre-test, post-test). There was an effect of test-day found, $F(1,90) = 27.2126$, $p < .001$, with higher percent correct following training from pre-test (M = 44.9%) to post-test (M = 53.3%). There was an effect for number of objects found,

$F(2,90) = 420.3062$, $p < .001$, with higher percent correct observed with decreased number of objects in the scene (mean percent correct for 2, 4 and 8 objects were 77.8%, 48.7%, and 20.7%), respectively. This suggests that percent correct for older drivers was impacted by the number of objects in the scene with higher percent correct as a function of fewer number of objects in the scene.

Subsequent local analysis examined pre-test vs. post-test performance for the attention cue conditions and were separated by the number of objects. For the 2 object condition, there was no effect of attentional cues, $F(1,18) = 1.1534$, $p = .2970$, no test-day found, $F(1,18) = 3.8653$, $p = .0649$, and no attention cues x test-day interaction, $F(1,18) = .0392$, $p = .8453$. This suggests that there were no reliable changes in percent correct following training for 2 objects in the scene.

For the 4 object condition, there was an effect of test-day, $F(1,18) = 16.1819$, $p = .0007$, with higher percent correct following training from pre-test ($M = 42.6\%$) to post-test ($M = 54.7\%$). There was no effect of the attention cues, $F(1,18) = 1.4078$, $p = .2508$, and no attention cues x test-day interaction, $F(1,18) = .6300$, $p = .4376$.

For the 8 object condition, there was an effect of test-day, $F(1,18) = 13.0355$, $p = .0020$, with increased percent correct from pre-test ($M = 16.4\%$) to post-test ($M = 25.1\%$). However, no effect of attention cues was found, $F(1,18) = .1697$, $p = .6853$, and no attention cues x test-day interaction, $F(1,18) = 1.2240$, $p = .2831$. This indicates that PL training improved accuracy under conditions of greater attentional load such as in the 4 and 8 object condition but not the 2-object condition. Refer to figure 3.2 for percent correct for both older and younger adults as a function of test-day, attention cues and age group.

Correct RT

Correct RT was calculated as aggregate scores for correct responses expressed in seconds. These analyses were conducted to assess whether PL training could improve speed of correct responses enabling participants more time and thus less display time to make a correct decision. Attention cues (valid cues, neutral cues), number of objects 2,4, or 8), and test-day (pre-test, post-test) were conducted on correct RT.

Baseline correct RT between attention cue conditions. To assess whether differences in performance between valid and neutral cues for number of objects were due to differences in initial baseline, analyses correct RT at pre-test was assessed. There was a significant effect for number of objects, $F(2,36) = 10.9695$, $p = .0001$, indicating that there were significant differences in correct RT between the number of objects in the scene for 2 objects ($M = 6.07$s), 4 objects ($M = 6.56$s) and 8 objects ($M = 6.84$s).

Subsequent analyses were conducted separately by objects. Baseline performance between valid and neutral cues were separately assessed for each number of objects. Comparable performance differences between the valid and the neutral cue-condition, prior to training, for each number of objects was found for 2 objects [$F(1,18) = .005$, $p = .9444$] 4 objects [$F(1,18) = 2.0358$, $p = .1707$] and 8 objects [$F(1,18) = .0194$, $p = .8907$], respectively. Thus, no reliable differences in correct RT between older drivers trained in the valid or neutral cue conditions prior to training was found.

Correct RT for test-day between attention cue conditions. Subsequent analyses examined the effect of the attention cues (valid cue, neutral cue) at pre-test and post-test for number of objects (2,4 or 8) was conducted. An effect of test-day was found, $F(1,90) = 49.0016$, $p < .001$, with faster RT as a result of training from pre-test (M = 6.49s) to post-test (M = 5.76s). There was an effect for number of objects, $F(2,90) = 13.0902$, $p < .001$, for the 2 object (M = 5.76s), 4 object (M = 6.22s) and 8 object (M = 6.39s), conditions. Post-hoc (Tukey HSD) tests revealed that the effect for number of objects was attributed to significant differences between the 2 and 4 objects ($p = .0014$) as well as between the 2 and 8 object conditions ($p < .0001$). Thus, significant differences in correct RT were found in accordance with the number of objects in the scene.

Local analyses of correct RT were subsequently analyzed for valid and neutral training cue conditions and test-day separated by number of objects. There was an effect of test-day with faster correct RT following training for 2 objects [$F(1,18) = 14.7153$, $p = .0012$] from pre-test (M = 6.07s) to post-test (M = 5.45s), 4 objects [$F(1,18) = 19.3397$, $p = .0003$] from pre-test (M = 6.56s) to post-test (M = 5.88s), and 8 objects [$F(1,18) = 14.0271$, $p = .0014$] from pre-test (M = 6.84s) to post-test (M = 5.94s), respectively. Thus, correct RT was faster following training for all number of objects. For the 4 object condition, there was an attention cues x test-day interaction, $F(1,18) = 5.2992$, $p = .0334$. Specifically, decreases in correct RT changed at a slower rate for older drivers in the valid cue condition from pre-test (M = 6.29s) to post-test (M = 5.97s) than for those in the neutral cue condition from pre-test (M = 6.82s) to post-test (M = 5.79s) for the 4 object condition. This suggests changes in correct RT as a result of PL facilitated faster correct

RT in the neutral cue condition as compared to the valid cue condition. Figure 3.3 shows mean correct RT as a function of test-day and attention cue condition for older and younger drivers.

Speed-Accuracy Trade-Offs

Examination of accuracy and correct RT enabled assessment of whether there were any speed-accuracy trade-offs for older drivers. For 2 objects in the scene, there were no significant changes in accuracy but faster correct RT following training was observed from pre-test (M = 6.07s) to post-test (M = 5.45s). For both 4 and 8 objects in the scene, older drivers were both more accurate and faster in their correct responses following training. Specifically, there was increased percent correct from pre-test (M = 42.6%) to post-test (M =54.7%) accompanied with faster correct RT from pre-test (M = 6.56s) to post-test (M = 5.88s) with the presence of 4 objects. With the presence of 8 objects, there was increased percent correct from pre-test (M = 16.4%) to post-test (M = 25.1%) as well as faster correct RT from pre-test (M = 6.84s) to post-test (M = 5.94s). Overall, these results suggest that there were no speed-accuracy trade-offs.

Incorrect RT

Incorrect RT was assessed to examine whether changes in RT was observed when participants made errors in judgement. Because of an error in judgement, participants may have taken longer to respond. This possibility has important implications for driving performance as longer response times may provide drivers with insufficient time to respond to correct their judgement or drivers may fail to disengage an initiated incorrect action resulting in a collision with other objects in the driving scene. If improvements in the speed of incorrect responses are impacted by the type of attention cue and training, this may afford drivers with more time to allow for a corrected response. Thus, understanding the circumstances under which drivers make errors is important to driving safety.

Baseline incorrect RT between attention cue conditions. To investigate whether there were any differences in baseline performance, analyses of incorrect RT at pre-test was assessed for attention cues and number of objects. An effect for the number of objects was found, $F(2,36) = 3.8290$, $p = .0310$, indicating that there were significant differences in incorrect RT with number of objects in the scene for 2 objects ($M = 6.37$s), 4 objects ($M = 6.69$s) and 8 objects ($M = 6.80$s). Thus, RT for incorrect responses, prior to training, increased with an increase in the number of objects.

Subsequent analyses were then conducted for the attention cues and were separated by number of objects. Assessment of baseline performance (pre-test only) between valid and neutral cue conditions indicated comparable performance prior to training for 2 objects [$F(1,18) = .0401$, $p = .8434$], 4 objects [$F(1,18) = 1.5335$, $p = .2315$] and 8 objects [$F(1,18) = 0.00$, $p = .9974$], respectively. This finding indicated that performance was comparable between valid and neutral cues for all levels of the number of object condition.

Incorrect RT for test-day between attention cue conditions. Analyses of incorrect RT was then conducted for attention cues (valid cues, neutral cues), number of objects (2,4, or 8), and test-day (pre-test, post-test). An effect of test-day was also found, $F(1,90) = 34.3965$, $p < .001$, with faster incorrect RT following training (pre-test: $M =$

6.62s; post-test: *M* = 6.04s). There was an effect for number of objects, $F(2,90) = 6.2591$, $p < .0028$, with increased incorrect RT with increased number of objects in the scene for 2 (*M* = 6.11s), 4 (*M* = 6.36s) and 8 objects (*M* = 6.53s). Post-hoc (Tukey HSD) tests indicated that the effect for number of objects was due to significant differences in performance between the 2 object and 8 object conditions (p=.0020). These results indicated that older drivers' performance was affected by PL regardless of the attentional cue presented at training. Furthermore, the number of objects significantly increased the time it took for older participants to make an incorrect response.

An attention cues x test-day interaction was found, $F(1,90) = 4.1746$, $p = .0439$. According to this interaction, faster incorrect RT as a result of training occurred for older drivers but the performance change was greater in the neutral cue condition (pre-test: *M* = 6.71s; post-test: *M* = 5.93s) than for those in the valid cue condition (pre-test: *M* = 6.53s; post-test: *M* = 6.15s). Thus, older drivers trained with neutral cues exhibited greater decreases in incorrect RT than those trained with valid cues.

Next, analyses of incorrect RT were conducted for attention cues and test-day but were separated based on the number of objects. For the 2 object condition, an effect of test-day was found, $F(1,18) =10.7593$, $p =.0041$, with faster incorrect RT following training (pre-test: *M* = 6.37s; post-test: *M* = 5.84s). For the 4 object condition, an effect of test-day was found, $F(1,18) =16.9417$, $p =.0006$, with faster incorrect RT as a result of training from pre-test (*M* = 6.69s) to post-test (*M* = 6.03s). For the 8 object condition, there was an effect of test-day, $F(1,18) =5.9086$, $p =.0257$, with faster incorrect RT from pre-test (*M* = 6.80s) to post-test (*M* = 6.26s). Thus, older drivers were faster at incorrectly identifying the collision objects following training for all levels of the number of objects. Results for incorrect RT as a function of attention cues, test-day, and age group are presented in Figure 3.4.

RMSE

Steering error was examined to assess whether drivers' ability to steer was impacted by the presence of the cue. To assess the impact of the attentional cue on steering performance, the effect of RMSE (root mean square error in tracking performance) was conducted based on the tracking for 2 sec prior to onset of the objects (henceforth referred to as pre-onset) and the tracking for 2 sec after onset of the objects (henceforth referred to as the post-onset). Calculation of RMSE 2 seconds prior to and following appearance of the object allows for the examination of two issues. The first issue examines whether the collision detection task impacts the secondary steering control task. The second issue examines whether there is an attentional cue effect on steering performance. Given the time it takes to respond to differing number of objects, limiting analyses to 2 seconds, rather than the full duration, of the steering task rules out processing differences due to the differing number of objects. Steering control error was examined for the attentional cue conditions (valid cue, neutral cue), number of objects (2,4, or 8), object onset (pre-onset, post-onset) and test-day (pre-test, post-test). Steering error was calculated as the average deviation of the driver's response to the simulated wind gusts expressed in meters.

Baseline RMSE between attention cue conditions. RMSE was examined between attention cues for number of objects and object-onset prior to training (pre-test only). There was an effect of object-onset, $F(1,90) = 14.4918$, $p = .0002$, with significantly greater RMSE at post-onset ($M = 0.221$m) as compared to pre-onset ($M = 0.194$m). Additionally, an effect for number of objects at pre-test was found, $F(2,90) = 3.2010$, $p = .0454$, mean RMSE tracking for the 2, 4 and 8 object conditions were 0.196m, 0.208m, and 0.218m, respectively. This effect for the number of objects in the driving scene was due to significant differences in steering error between the 2 and 8-object condition, $p = .0351$. These results suggest that there was greater RMSE after the appearance of objects than prior to the appearance of the objects in the driving scene. Furthermore, steering error significantly increased when there were more objects in the scene from the 2-object condition to 8-object condition.

Because there were differences in steering error at pre-test, according to the number of objects, subsequent local analyses were conducted separately by number of objects. For 2 objects in the scene, there were no reliable differences in baseline steering performance which indicated comparable performance prior to training for the effect of attention cues, $F(1,36) = .3951$, $p = .5335$, object-onset, $F(1,36) = 2.8589$, $p = .0995$, or attention cue condition x object-onset interaction, $F(1,36) = .0330$, $p = .8569$. For the 4 object condition, there were no reliable differences in baseline steering control error for attention cues, $F(1,36) = 1.1565$, $p = .2893$, object-onset, $F(1,36) = .4755$, $p = .4949$, and attention cues x object-onset interaction, $F(1,36) = .5376$, $p = .4682$. For 8 object condition, there were no differences in baseline RMSE indicating comparable performance prior to training for attention cues, $F(1,36) = .0006$, $p = .9803$, and attention cues x object-onset interaction, $F(1,36) = .5133$, $p = .4784$. However, there was an effect for object-onset, $F(1,36) = 6.1800$, $p = .0177$, with greater steering error at post-onset ($M = 0.235$m) as compared to pre-onset ($M = 0.200$m) of the objects. Thus, no reliable effect for the attention cue was found for the 2 and 4 object conditions. However, greater steering error was found when 8 objects appeared in the scene (post-onset) as compared to prior to the appearance of the 8 objects (pre-onset). Furthermore, this effect was not reliably affected by the type of attention cue presented at training suggesting that an increase in visual clutter in the scene altered steering performance.

RMSE for test-day between attention cue condition. Next, analyses of RMSE included attention cues (valid cue, neutral cue), object-onset (pre-onset, post-onset), and test-day (pre-test, post-test) and were separated by number of objects (2,4, or 8) for older drivers. For the 2 object condition, there was no effect of object-onset [$F(1,54) = 3.1297$, $p = .0825$], no object-onset x test-day interaction [$F(1,54) = .0500$, $p = .8238$]and no attention cues x object-onset x test-day interaction [$F(1,54) = .0938$, $p = .7605$]. These results suggest that steering control was not affected by the onset of 2 objects in the scene. Furthermore, no reliable differences in steering error following training was observed.

For the 4 object condition, there was no effect of object-onset, [$F(1,54) = 1.1742$, $p = .2833$], no object-onset x test-day interaction, [$F(1,54) = .0017$, $p = .9676$], and no attention cues condition x object-onset x test-day interaction, [$F(1,54) = .1444$, $p = .7055$].

However, for the 8 object condition, there was an effect of object-onset, $F(1,54) = 10.8725$, $p = .0017$. Greater steering error at post-onset for the 8 objects ($M = 0.229$m) as compared to pre-onset ($M = 0.193$m) indicated that steering control was affected by the presence of 8 objects in scene. No object-onset x test-day interaction, $F(1,54) = .0001$, p $=.9917$, nor an attention cues x object-onset x test-day interaction, $F(1,54) = .0043$, p $=.9476$, was found. This indicated that greater steering error was attributed to the onset of 8 objects in the driving scene regardless of the type of attentional cue presented.

Figure 3.5 shows mean RMSE for older and younger drivers as a function of attention cues, test-day and object-onset. Overall, there does not appear to be reliable differences in object-onset between prior to the appearance of the objects (pre-onset) and after the appearance of the objects (post-onset) when few objects are in the scene (2 or 4 objects). However, post-onset of 8 objects appears to significantly increase steering error as compared to pre-onset. Furthermore, no effect of test-day and no interaction of object-onset x test-day was found, which suggests the PL did not impact steering error. These results suggest that PL training with attentional cues did not significantly impact steering performance. Any changes in steering error was due to the appearance of the large number of objects in the scene as observed in the 8-object condition.

UFOV

To assess whether attention changed as a result of training, participants were assessed using the UFOV test and performance was analyzed for processing speed, divided attention, and selective attention. Performance was calculated as the speed at which participants can accurately perform the task. The scores for attentional ability of the UFOV were expressed in ms at which the participant performed accurately on 75% of trials at different display durations. A two-step staircase method was used to estimate threshold with increased difficulty with lower display durations. Scores on each test can range from 16.67ms (fastest) to 500ms (slowest). Lower scores indicate better processing. Processing speed was calculated as the speed at which participants could accurately identify a centrally presented object. Divided attention was calculated as the speed at which participants could accurately identify a central and peripheral object presented simultaneously in the scene. Selective attention was calculated as the speed at which participants could accurately identify a central and peripheral object presented simultaneously in the scene in the presence of distracting objects. Attention cues (valid cue, neutral cue) by test-day (pre-test, post-test) analyses were conducted separately for each of the attentional abilities.

For processing speed, no test-day was found, $F(1,18) = .7178$, $p = .4080$, and no attention cues x test-day interaction was found, $F(1,18) = .8640$, $p = .3649$. This indicated that processing speed did not change with training. For divided attention, no test-day, $F(1,18) = 2.3003$, $p = .1467$, and no attention cues x test-day interaction was found, $F(1,18) = .0034$, $p = .9544$. This indicated that divided attention did not change with training. For selective attention, no test-day was found, $F(1,18) = 2.6200$, $p = .1229$, and no attention cues x test-day was found, $F(1,18) = 1.3340$, $p = .2632$. This indicated that selective attention did not change with training. Overall, changes in attentional abilities were not observed following training and performance did not differ by cue type.

Training Sessions for Older Drivers

Training sessions were evaluated to assess whether there were any differences in performance for the type of attentional cue used during training sessions. Different attention cue types were only presented at training (valid or neutral cue). In contrast, the neutral cue was only presented during test-days (pre-test, post-test). Given that test-days presented the neutral cue only, differences in performance may obscure any effects of training with attentional cues. Assessment of training sessions between the valid and neutral cue condition allow for a direct analysis for the effect of attention, if any, on performance. Training sessions were calculated as aggregate performance by training block. Accuracy, correct RT, and incorrect RT were aggregated across different display durations (7.2s, 4.8s, 3.6s) for a training block for that object.

Accuracy for training sessions. Analyses of accuracy expressed as percent correct were conducted for attention cues (valid cue, neutral cue), number of objects (2, 4, or 8 objects), and training sessions (blocks 1, 2, and 3) for older drivers. There was an effect of attention cues on percent correct, $F(1,18)= 21.6432$, $p = .0001$, with higher percent correct observed for older participants trained with the valid cues ($M = 79.4\%$) as compared to those trained with neutral cues ($M = 55.8\%$). These results show that older drivers significantly benefitted from training with valid cues than with neutral cues. There was also an effect for the number of objects for 2 ($M = 89.1\%$), 4 ($M = 68.2\%$), and 8 objects ($M = 45.5$), $F(2,144)= 812.3076$, $p < .001$. Post-hoc (Tukey HSD) analyses indicated that all pairwise comparisons between the number of objects were significant, $p < .0001$. This effect for number of objects indicated that percent correct during training was significantly higher with lower number of objects in the scene. There was a significant effect of training session, $F(2,144)= 8.4975$, $p = .0003$, for blocks 1($M = 67.6\%$), 2 ($M = 65.4\%$), and 3 ($M =69.8\%$). Pairwise comparisons indicated that blocks 2 and 3 were significantly different, $p = .0002$. This suggests that significant learning occurred during the last two blocks of training.

There was an attention cues x training session x number of objects interaction, $F(4,144) = 3.0080$, $p = .0202$. There was an attention cues x number of objects interaction, $F(4,144) = 16.0288$, $p < .001$. Specifically, there was greater percent correct for older drivers in the valid cue condition for 2 objects ($M = 99.1\%$), 4 objects ($M = 83.6\%$), and 8 objects ($M = 55.7\%$) as compared to the neutral cue condition for 2 objects ($M = 79.2\%$), 4 objects ($M = 52.9\%$), and 8 objects ($M = 35.3\%$). These results indicate that training with a valid cue, as compared to a neutral cue, resulted in increased percent correct with a lower number of objects in the scene. Post-hoc (Tukey HSD) tests indicated that the pairwise comparisons for valid and neutral cues and 2,4, and 8 object conditions were significant, $p < .0001$. There was an attention cues x training session interaction, $F(2,144) = 6.2171$, $p = .0025$. For the valid cue condition, percent correct reveal a U-shaped function pattern of results for block 1 ($M = 81.6\%$), block 2 ($M = 75.6\%$), and block 3 ($M = 81.2\%$). Post-hoc (Tukey HSD) tests indicated significant pairwise comparison between blocks 1 and 2 ($p = .0002$) as well as between blocks 2 and 3 ($p = .0005$). For the neutral cue condition, percent correct increased with training sessions for block 1 ($M = 53.7\%$), block 2 ($M = 55.2\%$), and block 3 ($M = 58.5\%$). Significant pairwise comparison between blocks 1 and 3 for those trained with neutral cues was found ($p = .0096$). The results for mean percent correct for training session as a function of age group and attention cues are shown in figure 3.6.

Correct RT for training sessions. Correct RT was analyzed by attention cues (valid cues, neutral cues), number of objects (2,4, or 8) and training session (blocks 1,2 or 3) for older drivers. There was an effect of attention cues on correct RT, $F(1,18)= 6.4169$, $p = .0208$, such that faster correct responses were observed for those trained with valid cues ($M = 5.28$s) as compared to participants trained with neutral cues ($M = 6.68$s). An effect for number of objects was also found, $F(2,144)= 66.2315$, $p < .001$, with increased correct RT with increasing number of objects in the scene for 2 ($M = 4.95$s), 4 ($M = 6.25$s), and 8 objects ($M = 6.75$s). Post-hoc (Tukey HSD) analyses indicated all pairwise comparisons were significant between the 2 and 4 object condition, $p <.0001$, the 2 and 8 object condition, $p < .0001$, and the 4 and 8 object condition, $p < .0059$, respectively. Mean correct RT for training session as a function of age group and attention cues are presented in Figure 3.7.

An attention cues x number of object interaction was found, $F(2,144)= 8.7188$, $p = .0002$. Specifically, older drivers were significant faster with lower number of objects in the scene and for participants trained with valid cues as compared to participants trained with neutral cues for 2 objects (valid: $M =3.92$s; neutral: $M = 5.97$s), 4 objects (valid: $M = 5.51$s; neutral: $M = 6.98$s), and 8 objects (valid: $M = 6.40$s; neutral: $M = 7.10$s). Pairwise comparisons indicated this interaction was due to differences between training with valid and neutral cues in the 2-object condition ($p = .0020$), and between valid and neutral cues in the 4-object condition ($p = .0202$).

Incorrect RT for training sessions. Incorrect RT was analyzed by attention cues (valid cues, neutral cues), number of objects (2,4, or 8) and training session (blocks 1,2,3) for older drivers. There was an effect of attention cues on incorrect RT, $F(1,18)= 21.7300$, $p = .0001$, such that faster incorrect RT was observed for those in the valid cue training condition ($M = 4.19$s) as compared to neutral cue training condition ($M = 6.09$s). An effect for number of objects was found, $F(2,144)= 69.0653$, $p < .001$, for 2 ($M = 3.55$s), 4 ($M = 5.91$s), and 8 objects ($M = 5.96$s). Post-hoc (Tukey HSD) analyses indicated 2 objects were significantly different from the 4 and 8 objects, $p < .0001$. The results for mean incorrect RT for each training sessions (block 1,2,3) as a function of age group and condition are shown in Figure 3.8. Lower scores indicate faster incorrect RT.

An attention cues x number of objects interaction was found, $F(2,144)= 47.3315$, $p < .001$. Specifically, faster RT was observed for valid cues than neutral cues and with decreasing number of objects in the scene, for 2 objects (valid: $M = 1.29$s; neutral: $M = 5.81$s), 4 objects (valid: $M = 5.45$s; neutral: $M = 6.36$s), and 8 objects (valid: $M = 5.82$s; neutral: $M = 6.11$s). Pairwise comparisons indicated this interaction was due to differences in incorrect RT between training with valid and neutral cues in the 2-object condition ($p < .0001$). The results indicate that older drivers trained with valid cues exhibited significantly greater change in faster incorrect RT as compared to those trained with neutral cues. Faster incorrect RT as a result of training in the 2-object condition was particularly pronounced for older drivers trained with valid cues as compared to the participants trained with neutral cues.

Younger Drivers

Accuracy

Baseline accuracy between attention cue conditions. Baseline accuracy was analyzed by calculating percent correct at pre-test to assess whether percent correct was comparable prior to training for attention cues (valid cue, neutral cue) and number of objects (2,4, or 8). There was no effect of attention cues, $F(1,22) = .0723$, $p = .7905$, and no attention cues x number of objects interaction, $F(2,44) = .0075$, $p = .9925$. However, an effect for number of objects was found, $F(2,44) = 182.8495$, $p < .001$, which indicated significant differences in percent correct, prior to training, for the 2 (M = 87.2%) 4 (M = 68.3%) and 8 object conditions (M = 40.6%).

Subsequent analyses on baseline percent correct were conducted and separated by number of objects. There were no differences in baseline percent correct which indicated comparable performance for the attention cues prior to training for 2 objects [$F(1,22) = .0747$, $p = .7872$], 4 objects [$F(1,22) = .0615$, $p = .8064$], and 8 objects [$F(1,22) = .0349$, $p = .8534$], respectively.

Accuracy for test-day between attention cue conditions. Analysis of percent correct as a function of attention cue (valid cues, neutral cues), number of objects (2,4,or 8) and test-day (pre-test, post-test) was conducted. There was an effect of test-day, $F(1,110) = 6.7611$, $p = .0106$, such that percent correct improved from pre-test (M= 65.4%) to post-test (M = 69.4%). There was an effect for number of objects, $F(2,110) = 283.0213$, $p < .001$, with higher percent correct with lower number of objects in the scene for 2 objects (M = 88.2%), 4 objects (M = 70.50%) and 8 objects M = 43.4%). Post-hoc

(Tukey HSD) tests on the effect for number of objects revealed all pairwise comparisons were significant suggesting that percent correct was significantly impacted by the number of objects in the scene, $p < .0001$. These results suggest that PL training significantly improved accuracy regardless of the type of attention cue presented. Furthermore, accuracy for older adults increased with lesser number of objects in the scene.

Subsequently, analyses were conducted for attention cues and test-day but analyses were separated by number of objects. For 2 objects, there was no effect of test-day, $F(1,22) = 1.4277$, $p =.2449$, and no attention cues x test-day interaction, $F(1,22) = .0099$, $p =.9216$. For 4 objects, there was no effect of test-day, $F(1,22) = 3.3684$, $p =.0800$, and no attention cues x test-day interaction, $F(1,22) = 1.2126$, $p =.2827$. For 8 objects in the scene, there was no effect of test-day, $F(1,22) = 3.6923$, $p =.0677$, and no attention cues x test-day interaction, $F(1,22) = .0428$, $p =.8379$. Separate analyses by objects suggest that there were no reliable changes in percent correct following training for 2,4, or 8 objects in the scene, respectively.

Correct RT

Correct RT were assessed by aggregating the speed of correct responses. Analysis of correct RT as a function of attention cues (valid cue, neutral cue), number of objects (2, 4, or 8) and test-day (pre-test, post-test) were conducted for younger drivers.

Baseline correct RT between attention cue conditions. First, analyses of baseline performance for correct RT, were conducted by examining pre-test performance between valid and neutral cues for number of objects. Indeed, an effect for number of objects was found, $F(2,44) =14.3200$, $p < .001$, which indicated significant differences in performance with number of objects in the scene for 2 objects (*M* = 5.61s), 4 objects (*M* = 6.08s), and 8 objects (*M* = 6.26s). Thus, younger drivers took longer to respond with increased number of objects in the scene prior to training.

Given initial differences in correct RT prior to training, analyses of baseline performance for 2,4, and 8 objects were conducted separately to ensure comparable performance between attention cues. Baseline performance for number of objects indicated no differences between attention cues prior to training for 2 objects [$F(1,22) = .0022$, $p = .9626$], 4 objects [$F(1,22) = .0291$, $p = .866$] and 8 objects [$F(1,22) = .0897$, $p = .7674$], respectively.

Correct RT for test-day between attention cue conditions. Analyses were then conducted as a function of attention cues, number of objects, and test-day. An effect of test-day was found, $F(1,110) = 35.7077$, $p < .001$, with faster RT from pre-test (*M* = 5.98s) to post-test (*M* = 5.06s). Furthermore, there was an effect for number of objects in the scene, $F(2,110) = 11.9535$, $p < .001$, for 2 objects (*M* = 5.00s), 4 objects (*M* = 5.69s), and 8 objects (*M* = 5.87s). This indicated that younger participants took longer to respond with an increased number of objects in the scene. This effect for number of objects was due to significant differences between the 2-object condition as compared to the 4 ($p = .0011$) and 8 object condition ($p < .0001$). There was an attention cues x test-day interaction, $F(1,110) = 6.1151$, $p = .0149$. Specifically, correct RT changed at a greater rate following training for those in the valid cue condition from pre-test (*M* = 5.97s) to post-test (*M* = 4.67s) as compared to those in the neutral cue condition from pre-test (*M* = 5.99s) to post-test (*M* = 5.45s). The results demonstrate that younger drivers trained in the valid cue condition significantly improved and were thus faster following training than those in the neutral cue condition.

Further local analyses were conducted for attention cues and test-day and were separated by number of objects. For the 2 object condition, there was an effect of test-day, $F(1,22) = 11.5899$, $p = .0025$, with faster correct RT following training from pre-test ($M = 5.61$s) to post-test ($M = 4.39$s). For the 4 object condition, there was an effect of test-day, $F(1,22) = 6.0116$, $p = .0226$, with faster correct RT following training from pre-test ($M = 6.08$s) to post-test ($M = 5.30$s). Finally, for the 8 object condition, there was an effect of test-day, $F(1,22) = 7.4427$, $p = .0122$, with faster correct RT following training from pre-test ($M = 6.26$s) to post-test ($M = 5.49$s). In summary, the results indicate that PL improves the speed of correct responses regardless of the type of attentional cue presented. Although an interaction of attention cues x test-day was found when analyses included number of objects as a factor, this interaction was not robust when local analyses were then separated by number of objects.

Speed-Accuracy Trade-Offs

Speed-accuracy trade-off were assessed for younger drivers. For 2 objects in the scene, there were no significant changes in percent correct but faster correct RT following training (pre-test: M = 5.61s; post-test: M = 4.39s). For both 4 objects in the scene, there were faster correct RT (pre-test: M = 6.08s; post-test: M = 5.30s) and no reliable changes in percent correct. For 8 objects in the scene, there was faster RT (pre-test: M = 6.26s; post-test: M = 5.49s) and no reliable changes in percent correct. Overall, these results suggest that there were no speed-accuracy trade-offs.

Incorrect RT

Baseline Incorrect RT between attention cue conditions. Baseline performance was assessed to observe whether incorrect RT was comparable prior to training for attention cues (valid cue, neutral cue) and number of objects (2, 4, or 8). There was no effect of attention cues [$F(1,22) = .5013$, $p = .4864$], no effect for number of objects [$F(1,44) = .6523$, $p = .5258$], and no attention cues x number of objects interaction [$F(2,44) = .6449$, $p = .5296$]. These results suggest that baseline incorrect RT for younger drivers trained with valid or neutral cues were at comparable levels of performance prior to training.

Incorrect RT for test-day between attention cue conditions. Analyses of incorrect RT was assessed for the attention cues (valid cues, neutral cues), number of objects (2,4, or 8), and test-day (pre-test, post-test). There was an effect of test-day, $F(1,110) = 28.4409$, $p < .001$, with faster incorrect RT from pre-test ($M = 6.55$s) to post-test ($M = 5.36$s). There was an attention cues x test-day interaction found, $F(1,110) = 7.4575$, $p = .0073$. With regard to the interaction, there was greater change in incorrect RT for younger participants in the valid cue condition from pre-test ($M = 6.72$s) to post-test ($M = 4.92$s) as compared to those in neutral cue condition from pre-test ($M = 6.39$s) to post-test ($M = 5.81$s). This result indicates that performance for younger drivers decreased at a greater rate and were thus faster as a result of training with valid cues as compared to those trained with neutral cues.

Next, analyses were conducted for attention cues and test-day and were separated by number of objects. For the 2 object condition, there was an effect of test-day, $F(1,22)$

= 10.9694, *p* =.0031, from pre-test (*M* = 6.60s) to post-test (*M* = 4.77s). For the 4 object condition, there was an effect of test-day, $F(1,22) = 7.9806$, $p = .0098$, from pre-test (*M* = 6.42s) to post-test (*M* = 5.50s). For the 8 object condition, there was an effect of test-day, $F(1,22) = 7.4034$, $p = .0124$, from pre-test (*M* = 6.64s) to post-test (*M* = 5.82s). These results suggest that the RT for incorrect responses was faster following training across all number of object conditions. With regard to the interaction, incorrect responses of younger drivers were faster following training with greater rate of decrease for those trained with valid cues than those trained with neutral cues across all number of object conditions. However, the attention cues x test-day interaction was not reliable upon local analyses when separated by number of objects.

RMSE

RMSE was assessed for attention cues (valid cue, neutral cue), number of objects (2,4, or 8), object onset (pre-onset, post-onset) and test-day (pre-test, post-test) in younger drivers. There was no effect of object-onset [$F(1,242) = .0037$, $p = .9516$], no object-onset x test-day interaction [$F(1,242) = .1574$, $p = .6919$] and no attention cues x object onset x test-day interaction was found [$F(1,242) = .1440$, $p = .7046$]. Regardless of being trained with valid or neutral cues, steering control of younger adults was not impacted. Furthermore, the onset of the objects (pre-onset versus post-onset) in the scene did not affect steering control.

UFOV

The purpose of this analyses was to examine whether changes in performance in the driving simulator would transfer to performance on the UFOV task. Three different attentional abilities were examined; processing speed, divided attention, and selective attention. For processing speed, there was no effect of test-day, $F(1,22) = 1$, $p = .3282$, and no attention cues x test-day interaction, $F(1,22) = 1$, $p = .3282$. These results indicated that processing speed did not change with training and did not differ by attention cue type. For divided attention, there was no effect of test-day, $F(1,22) = 1.7282$, $p = .2022$, and no attention cues x test-day interaction, $F(1,22) = 2.9207$, $p = .1015$. These findings indicated that divided attention did not significantly change with the type of attentional training cue presented. For selective attention, there was no effect of test-day, $F(1,22) = .8312$, $p = .3718$, and no attention cues x test-day interaction, $F(1,22) = 2.2406$, $p = .1486$. These results indicated that selective attention did not change following training with attentional cues. Overall, no significant changes in attentional abilities were observed following training and regardless of the type of attention cue presented at training.

Training sessions for Younger Drivers

Accuracy for training sessions. Analyses on accuracy (percent correct) was conducted by attention cues (valid cues, neutral cues), number of objects (2,4 or 8) and training session (blocks 1, 2, 3) for younger drivers. There was an effect of attention cues on percent correct, $F(1,22) = 7.8199$, $p = .0105$, with higher percent correct observed for younger drivers in the valid training cue condition ($M = 81.8\%$) as compared to those in the neutral training cue condition ($M = 69.8\%$). There was also an effect for number of objects, $F(2,176) = 394.0738$, $p < .001$, with increased percent correct with lower number of objects in the scene, for 2 ($M = 94.1\%$), 4 ($M = 76.3\%$), and 8 objects ($M = 57.1\%$).

Post-hoc (Tukey HSD) tests indicated that all pairwise comparisons between number of objects were significant, $p < .0001$. This suggests that percent correct during training, was significantly higher with lower number of objects in the scene. However, no significant effect of training session [$F(2,176)=.8360$, $p = .4351$] and no attention cues x number of objects x training sessions interaction [$F(4,176)=.1178$, $p = .9760$] were found. This indicated that changes in percent correct were not observed with training sessions suggesting that percent correct was stable within a training session.

Correct RT for training sessions. Correct RT was analyzed by attention cues (valid cue, neutral cue), number of objects (2,4 or 8), and training sessions (blocks 1,2,3) for younger drivers. There was an effect of attention cues on correct RT, $F(1,22)=7.2623$, $p = .0132$, with faster correct RT observed for younger drivers in the valid training cue condition ($M = 4.19$s) as compared to those in the neutral training cue condition ($M = 5.60$s). An effect for number of objects was found, $F(2,176)=136.1345$, $p < .001$, with faster correct RT with less number of objects in the scene for 2 ($M = 3.64$s), 4 ($M = 5.08$s), and 8 objects ($M = 5.97$s). Post-hoc (Tukey HSD) tests indicated all pairwise comparisons between number of objects were significant, $p <.0001$.

An attention cues x number of objects interaction was found, $F(2,176)=4.5661$, $p = .0116$. Specifically, younger drivers were faster when training with valid cues as compared to neutral cues and with less number of objects in the driving scene, for 2 objects (valid: $M = 2.81$s; neutral: $M = 4.48$s), 4 objects (valid: $M = 4.62$s; neutral: $M = 5.53$s), and 8 objects (valid: $M = 5.14$s; neutral: $M = 6.80$s). Pairwise comparisons indicated this interaction was due to differences between training with valid and neutral cues in the 2-object condition (p = .0054), and between valid and neutral cue in the 8-object condition (p = .0055).

Incorrect RT for training sessions. Incorrect RT was analyzed by attention cues (valid cue, neutral cue), number of objects (2,4 or 8) and training sessions (blocks 1,2,3) for younger drivers. There was an effect of attention cues on incorrect RT, $F(1,22)=4.7483$, p = .0403, such that faster incorrect RT was observed for those in the valid training cue condition (M = 4.03s) as compared to those in neutral training cue condition (M = 5.33s). An effect of object was found, $F(2,176)=16.3318$, p < .001, with faster incorrect RT with less number of objects in the scene for 2 (M = 3.20s), 4 (M = 5.27s), and 8 objects (M = 5.57s). Post-hoc (Tukey HSD) analyses indicated 2 objects were significantly different from the 4 and 8 object conditions, p <.0001, respectively.

There was an attention cues x object interaction was found, $F(2,176)=7.4178$, p = .0008. Specifically, faster incorrect RT for younger drivers trained with valid cues for 2 objects (valid: M = 1.61s), 4 objects (valid: M = 5.41s) and 8 object (valid: M = 5.05) conditions as compared to those trained with neutral cues for the 2 object (neutral: M = 4.79s), 4 object (neutral: M = 5.14s), and 8 object (neutral: M = 6.08s) conditions. Pairwise comparisons indicated this interaction was due to incorrect RT differences between valid and neutral cues in the 2-object condition (p = .0002).

Magnitude of Learning (Older & Younger Drivers)

Magnitude of learning was calculated to the test the hypothesis that magnitude of learning increases with age. To investigate the prediction that older drivers exhibit greater learning than younger drivers, magnitude of learning was assessed. Magnitude of learning is defined as the amount of improvement in performance between initial baseline performance from pre-test to post-test. Magnitude of learning was computed using the following formula:

$$\text{Magnitude of learning} = \frac{\text{PostTest} - \text{PreTest}}{\text{PreTest}}$$

Using this formula accounts for initial performance level by evaluating any changes in performance are with respect to each participant's initial performance level. This enabled comparison between age groups in order to assess whether differences were observed in the following dependent measures for magnitude of learning on percent correct, correct RT, and incorrect RT. Greater magnitude of learning in percent correct was calculated as higher positive values. For correct and incorrect RT, greater magnitude of learning was calculated as greater negative values. Magnitude of learning was calculated for each of the dependent measures as a function of age-group (older drivers, younger drivers) and attention cues (valid cue, neutral cue).

For percent correct, there was an effect of age group, $F(1,128)=3.8624$, $p = .0001$, such that there was greater improvement in percent correct for older drivers (M = .4210%) as compared to younger drivers (M = .0765%). For correct RT, greater negative values indicate faster correct RT. For correct RT, there was an age-group x attention cues interaction, $F(1,128)=10.8466$, $p = .0012$. Specifically, greater magnitude of learning for younger drivers trained with valid cues (younger adults: M = -.2182s) than those trained with neutral cues (younger adults: M = -.0700s). In contrast, greater magnitude of learning for older drivers was observed for older drivers trained with neutral cues (older adults: M = -.1332s) than those trained with valid cues (older adults: M = -.0766s). Pairwise comparisons indicated a significant difference for valid cues between older and younger drivers (p = .0012), but not neutral cues (p = .1641). These results demonstrate opposite patterns of results between older and younger drivers. Greater improvement of correct RT was observed for younger drivers trained with valid cues than with neutral cues. In contrast, greater improvement of correct RT was observed for older drivers trained with neutral cues as compared to valid cues.

Discussion

The incidence of motor vehicle crashes is particularly high for younger adults under the age of 25 and for older adults over the age of 65 (Evans, 2004; Williams & Carsten, 1989; Son & Suh, 2011). Important driving abilities include the ability to successfully detect and avoid collisions and to successfully steer. An important issue in driving safety is to identify and mitigate the factors that lead to increased crash risk. For older drivers, the increased crash risk may be attributed to age-related declines in visual perception and attention that may impair the ability to detect and avoid collisions. In contrast, for younger drivers, the increased crash risk may be attributed to driving inexperience.

PL is one method by which training can reduce crash risk for both older and younger drivers. Previous research has demonstrated that training can improve the ability to detect impending collisions (Lemon, Deloss & Andersen, 2017; Deloss, Bian, Watanabe & Andersen, 2015). PL can be enhanced by directing attention to relevant information for learning. In the context of driving, attention is important to driving ability. The failure to attend to and respond to impending collisions can have serious consequences for the driver as well as other individuals in or near the roadway. An important question is whether training with attentional cues improves collision detection and steering control in an applied driving context?

The present study examined age-related differences in training on a collision detection and steering control task when provided with attentional cues. Drivers were to identify the collision object when multiple moving objects were present and while steering to maintain the traffic lane in the center. The simulated vehicle translated down a straight roadway at a constant speed. Objects were presented in the driving scene and approached the driver at a constant speed and on a linear trajectory. Drivers were to identify which object was the collision object among other distracting non-collision objects in the scene.

Four hypotheses were examined. The first hypothesis was that magnitude of learning increases with age. With regard to the first hypothesis, it was predicted that older drivers, as compared to younger drivers, would improve at a greater magnitude as a result of PL training. Consistent with this first hypothesis, greater magnitude of learning, as assessed via accuracy, was observed for older drivers as compared to younger drivers. However, a greater rate of learning was not observed for correct RT. This suggests that the magnitude of learning observed in this study was primarily attributed to changes in accuracy and not to speed of responses.

It could be that overall accuracy of older drivers was lower as compared to younger drivers and thus older drivers had a greater range for improvement. This can be assessed by looking at percent correct performance of older and younger drivers. As depicted in Figure 3.2, older drivers had comparatively lower percent correct from pre-test to post-test across each number of objects as compared to younger drivers. This greater learning, as measured via percent correct, is consistent with previous studies that observed initial baseline performance was predictive of magnitude of learning. Specifically, participants with the lowest initial performance, as compared to those with higher initial performance level, have the greatest potential to improve (Yehezkel et al., 2016). In contrast, individuals with the best initial performance may already be at near optimal performance on a task and thus no range for improvement. However, it is unclear whether the improvements were due to task performance or due to changes in the fundamental aspects of visual processing.

An important question, then, is what might be the reason for age-related differences in learning? The source of improvements between older and younger drivers may differ. Specifically, older drivers have high expertise but may have compromised perceptual processing whereas younger drivers have low expertise but optimal perceptual processing. Improvements observed in younger drivers may be due to the development of driving expertise whereas improvements in older drivers may be changes in perceptual processing. Older drivers had, on average, 56 years of driving experience which is much greater than the average 3 years of driving experience for younger drivers. Previous studies have reported that the driver fatality rate is particularly high among younger and older drivers (Son & Suh, 2011). The incidence of high crash risk among younger drivers may be due to a lack of driving experience given that general perceptual performance may be optimal at a young age.

Given that collision detection may be primarily dependent on perceptual performance, younger drivers may be at or near optimal performance which may attenuate any training-related improvements. Evidence for optimal performance in younger drivers is the lack of reliable results for training-induced changes in percent correct despite high performance. Percent correct, across all number of objects, were higher in younger drivers as compared to older drivers. High percent correct observed in younger drivers indicated that the younger drivers were better able to discriminate, relative to older drivers, the collision object among non-collision objects. Higher performance for younger adults relative to older adults is further supported by previous studies (Bower, Watanabe & Andersen, 2013; Andersen, Ni, Bower & Watanabe, 2010). Thus, perceptual discrimination of younger drivers may already be near ceiling prior to training and thus training-induced changes, as measure via percent correct, may not be possible. Thus, the finding of training-related improvements in younger drivers suggest training may be beneficial for younger drivers to the development of driving skills.

On the other hand, the finding of training-related improvements in older drivers may be due to changes in perceptual processing given age-related declines in visual processing. An alternative explanation may be that greater experience at a specific task may lead to rapid learning to related tasks. A previous study examined the effect of experience on training-related improvements on video game play, a high-level complex perceptual task (Green & Bavelier, 2003). Video game players (VGP) exhibit enhanced abilities in many aspects of attention and often outperform non-video game players (NVGP) in many attentional tasks. In the context of PL, it was observed that VGP improved at a much more rapid rate as compared to NVGP on many different training tasks (Green & Bavelier, 2003). This advantage of video game experience known as learning to learn is an enhanced learning capacity as a result of experience (Green & Bavelier, 2012). This viewpoint predicts that performance between groups with reasonably equivalent levels in performance on a novel video game should show a learning advantage during training for the group with video game experience. Extending these findings to the current study, older drivers, as compared to younger drivers, have greater years of driving experience and thus may be better situated to exhibit enhanced learning effects. The present study does not distinguish between these two possible explanations.

One way to address this issue for future research is to assess whether performance improvements are due to task practice. If improvements are as a result of expertise, improvements should be observed as a result of task learning. Previous studies investigated this issue to rule out improvements due to task practice (Andersen, Ni, Bower & Watanabe, 2010; Deloss, Bian, Watanabe & Andersen, 2015). Future research should delineate the source of improvements for older and younger drivers. Understanding this issue is informative for developing specialized training interventions targeted towards specialized populations.

The second hypothesis was that processing efficiency of endogenous attention declines with age. Specifically, differences in PL with valid and neutral cues would be observed in younger adults but not older adults. Evidence for this hypothesis was inconclusive. A review of this hypothesis will be discussed separately for each age group. First, the results for younger drivers suggest support for this hypothesis. The training sessions for younger drivers indicated that participants trained with valid cues consistently performance higher than those trained with neutral cues. Furthermore, a review of RT for test-days (pre-test vs. post-test) indicated that participants trained with valid cues improved at a greater rate, and thus were faster in their responses, than those trained with neutral cues. However, this finding was not statistically robust when analyses were then separated by number of objects. If more training sessions were given, it is possible that this attentional benefit may have been robust. Notably, the attentional benefit in younger drivers persisted even when the attentional cues changed from valid cues during training to neutral cues at post-test. This suggests that training with valid cues may be beneficial to perceptual driving performance.

Specifically, responses to correctly identified collision objects afforded younger drivers with nearly 780ms of additional reaction time as a result of training with valid cues over the neutral cues. This translates to providing younger drivers additional time to recognize and react to an impending collision. Even under conditions in which younger drivers made an error in judgment by incorrectly identifying the collision object, those trained with valid cues were provided with additional reaction time to respond. Higher performance with the use of valid cues than neutral cues is consistent with previous work in PL training (Mukai et al. 2011; Ito, Wesheimer & Gilbert, 1998) and perceptual performance (Posner, Nissen & Ogden,1978; Posner, 1980). Although there was no impact of attentional cue on the percent correct measure in younger drivers, this is not inconsistent with this hypothesis. Percent correct performance for younger drivers were near ceiling across the number of objects and so engaging attention may not have been necessary because of high performance level. The current findings for younger drivers are consistent with previous findings that there is a benefit to perceptual performance with valid cues as compared to neutral cues.

In contrast, a review of the results for older drivers indicate a different pattern of results that make it difficult to make a definitive conclusion. A review of the training sessions for older drivers suggest conflicting patterns of results between the test days and training days for older drivers. For the test days, the results for older drivers suggest that training with neutral cues, as compared to valid cues, improved speed of responses. In contrast, training sessions indicated that older drivers training with valid cues consistently performed with higher accuracy and faster correct RT than those in the neutral cue condition. Thus, the opposing pattern of results for the older drivers between test days and training sessions indicate conflicting results.

In general, neutral cues presumably distribute attentional resources across the driving display and consequently should produce costs in perceptual processing that lead to relatively lower training-related improvements. In contrast, valid cues may more effectively allocate attentional resources in order to produce relatively higher training-related improvements. This idea is consistent with previous studies that observed a benefit of valid cues over neutral cues (Posner, Nissen & Ogden, 1978; Posner, 1980; Mukai et al. 2011; Ito, Wesheimer & Gilbert, 1998). If there were age-related declines in the efficiency of endogenous attention, then it would be expected that performance of older drivers trained with valid cues would not significantly differ from those trained with neutral cues. Instead, a surprising finding is a benefit of neutral cues over valid cues for older drivers.

Why was greater improvement for older drivers found with neutral cues, in which attention was likely distributed across the scene, as compared to performance for valid cues, in which attention was directed? Older drivers may have been negatively affected by the switch from valid cues in the training sessions to neutral cues at post-test. Notably, the switch from valid cues during training to neutral cues at post-test is unique to participants in the valid cue condition. Previous research has shown evidence of a cost in task-switching abilities in older adults (Wasylyshyn, Verhaeghen & Sliwinski, 2011). Thus, it is possible this switch may have interfered with learning. A switch from informative valid cues to uninformative neutral cues may have introduced a reconfiguration in the task set (see Monsell, 2003) and may have disrupted improvements on the task. And so, performance for the older drivers may have been negatively affected by the presence of the neutral cues at post-test after being trained with valid cues. This may account for the finding of consistently higher performance in older adults for the valid cue condition as compared to the neutral cue condition during training sessions but opposite results at post-test.

This idea of an age-related cost of task-switching is further supported by the evidence for younger drivers. Younger drivers exhibited an attentional benefit during the training sessions. At post-test, this attentional benefit was maintained in younger drivers even when there was a switch from valid to neutral cues. It is likely that if the older drivers were provided consistent attentional cues at training and post-test, then performance may have been similar or greater than the performance for older drivers trained with neutral cues. As a result, age-related changes in the efficiency with which endogenous cues are engaged could not be observed. Given performance was affected by the switch from valid to neutral cues for older adults in the valid cue condition, this prevented any assessment of processing efficiency of endogenous attention. In conclusion, the hypothesis that processing efficiency of endogenous attention declines with age could not be evaluated and is therefore inconclusive.

The third hypothesis was that decrements in performance occur with increased number of objects. Given that PL should improve task performance, both younger and older drivers should improve in collision detection, but performance should be affected by the number of objects in the scene. Decrements in collision judgements have been observed with increased number of objects in a driving scene (Andersen & Kim, 2001). In the current study, both accuracy and correct RT decreased with increased number of objects in the scene. Consistent with this hypothesis, the number of objects in the driving scene impacted both older and younger drivers' ability to detect impending collisions. Increased number of objects in the scene led to reduced accuracy and longer RT in detecting collisions. These performance declines, as a function of the number of objects in the scene, were present at both pre-test and post-test.

The finding of improvements in collision detection suggest an effect of training. However, PL improvements appear to be limited by the number of objects in the scene. For instance, training-related improvements in accuracy for older drivers were observed for 4 and 8 objects in the scene but not for 2 objects. However, accuracy was high with 2 objects in the scene which may account for why no improvements in accuracy was observed. Thus, not much range for improvement would be expected for 2 objects. In summary, as the number of objects increase in the scene, the ability to perform collision detection degrades. This means that performance degrades with increased visual clutter in the driving scene, which is consistent with the third hypothesis. Therefore, development of a training protocol should include training with at least 4 objects in the scene. Previous studies involved training collision detection with only a single object (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss & Andersen, 2017). Training with multiple objects is akin to a real-world driving scene and thus any improvements may translate to real-world benefits in driving skill. An important goal for driving safety is to employ this type of training as a methodology for driver retraining in older adults or for graduated licensing in younger adults.

Additionally, steering performance appears to be affected by number of objects in the scene for older drivers. Analyses of RMSE indicate different patterns of results between older and younger drivers. In younger drivers, there did not appear to be any significant changes in RMSE following training as a function of the number of objects in the scene. It is possible the steering task was not sufficiently difficult for younger drivers to experience decrements in steering control. However, in older drivers, steering control was affected with 8 objects in the scene but not 2 or 4 objects. Greater steering error was observed with 8 objects prior to training and this increased steering error was still pronounced following training. This suggests that with increased visual clutter in the scene, older drivers may have experienced increased attentional load with 8 objects which may have affected their ability to effectively steer. Furthermore, this increased error after training with 8 objects suggests that PL does not appear to mitigate steering error for a large number of objects, akin to high visual clutter in a driving scene. Older drivers may be overwhelmed by the increased visual distractors in the driving scene that does not allow for them to effectively filter irrelevant objects in the scene even with the presence of attentional cues intended to aid driving performance. This has important implications for the design of driving displays. Understanding how older drivers may be affected by increased visual clutter in the driving scene is informative for how displays should be designed to aid older drivers.

The fourth hypothesis was that PL training with attention cues will broadly generalize to visual attention. Generalized learning is often observed with training in complex tasks. For instance, action video game play, a complex perceptual task, translated to improvements in UFOV (Green & Bavelier, 2003; 2006; Achtman, Green, & Bavelier, 2008; Belchior et al., 2014). Although training-related improvements in driving performance was observed in the current study, these improvements did not transfer to indices of attentional measures in the UFOV task. Given evidence in the literature that the UFOV task is predictive of driving performance (Roenker, Cissell, Ball, Wadley & Edwards, 2003; Goode, Ball, Sloane, Roenker, Roth, Myers, & Owsley, 1998; Myers, Ball, Kalina, Roth, & Goode, 2000), changes in attentional abilities as measured by the UFOV should be sensitive to any changes in driving performance. However, the findings in the present study do not support this hypothesis.

Several explanations are put forth to explain the failure to observe transfer to the UFOV task. One explanation for the failure to transfer training-related improvements in driving performance to UFOV may be that the improvements observed may be specific to improvement in task performance that may not necessarily include changes in attentional processing. Although attention may be primarily involved in facilitating learning, attention itself may not necessarily be modified with learning (see Watanabe & Sasaki, 2015).

The UFOV task measures the efficiency with which an individual can reliably extract visual information from a cluttered static 2D scene. In contrast, the current study examines the ability for individuals to extract visual information from a cluttered dynamic 3D scene.

Multiple explanations from the differences between these two tasks can be drawn. First, the UFOV task may be insensitive to the range of timescale that was measured in the driving task. First, the longer presentation times, on the order of seconds, was examined in the current study relative to the UFOV task which examined performance on the order of milliseconds. The driving task may not have been sensitive enough to tap into the same set of processes in that time course. For instance, the accumulation of information is different for the UFOV task relative to the driving task. The speed at which a participant accurately responds to the UFOV task is on a much shorter timescale than the driving task, which requires a longer time scale. This is likely due to UFOV assessing performance at an earlier stage of processing, likely sensory, whereas the driving task may assess information at a later stage of processing, likely cognitive. It is possible that the UFOV task may index earlier stages of information processing whereas the driving task taps into later stages of information processing. This suggests that any improvements observed in the driving task may due to changes at later stages of information processing.

Second, the UFOV measures 2D visual-spatial attention. The current task involves multiple objects moving in depth. Drivers may have allocated their attention in depth to the multiple forward-translating objects in the scene. In a previous driving study, it was observed that driving performance for both older and younger drivers were affected by both depth and horizontal position (Pierce & Andersen, 2014). For younger drivers, performance varied as a function of both depth and horizonal position whereas for older drivers' performance varied as a function of depth. Thus, it is possible that any improvements in the driving task may have been with respect to improvements in 3D spatial attention. As a result, 2D measures of attention may not predict the spatial extent of attention in depth (Pierce & Andersen, 2014). The UFOV, which measures 2D attention, may be insensitive to any changes in 3D attention. Extending these findings to the current study, the UFOV task, which measures 2D spatial attention, may have been insufficient to capture trained-induced changes in performance on the 3D driving task. Moreover, driving is a complex varied task that relies on a number of perceptual and cognitive skills. It could be that the UFOV task only indexes a small component of those skills. Thus, these two tasks may not rely, to the same degree, on the same component processes.

The present study examined PL with attentional cues on the ability to detect impending collisions in both older and younger drivers. The findings here suggest that both older and younger drivers benefit from PL training with attentional cues in the detection of collision objects. In addition, training on a collision detection task resulted in more time to respond to a collision event for older and younger drivers. Notably, these improvements were observed in as few as three days of training. This suggests that increasing the number of training sessions could result in greater training-related benefits.

Generalization of this work to real-world driving conditions should be considered with some caution. In most real-world driving conditions, collisions events are rare. The present study was designed with recurring collision objects aimed at examining whether training could improve collision detection and steering performance. Future research should examine the impact of PL under rare collision events. Major contributing factors to the increased risk of vehicle motor accidents are the lack of driving experience as well as normal perceptual and cognitive declines associated with aging. These factors have been associated with increased risk of crashes for both age groups. Furthermore, this suggests that older and younger drivers may not be affected in the same way. Human factors implications of this work suggest PL as a useful countermeasure to reduce the likelihood of a crash. Understanding the type of driver and the errors they make is useful for developing a broad effective training method designed to mitigate these specific types of decrements in driving performance. The findings presented here suggest the benefit of PL training with attentional cues that lead to similar improvements in different groups of drivers. An important issue for future research will be to design training interventions to compensate for decreased driving performance.

Figures & Tables

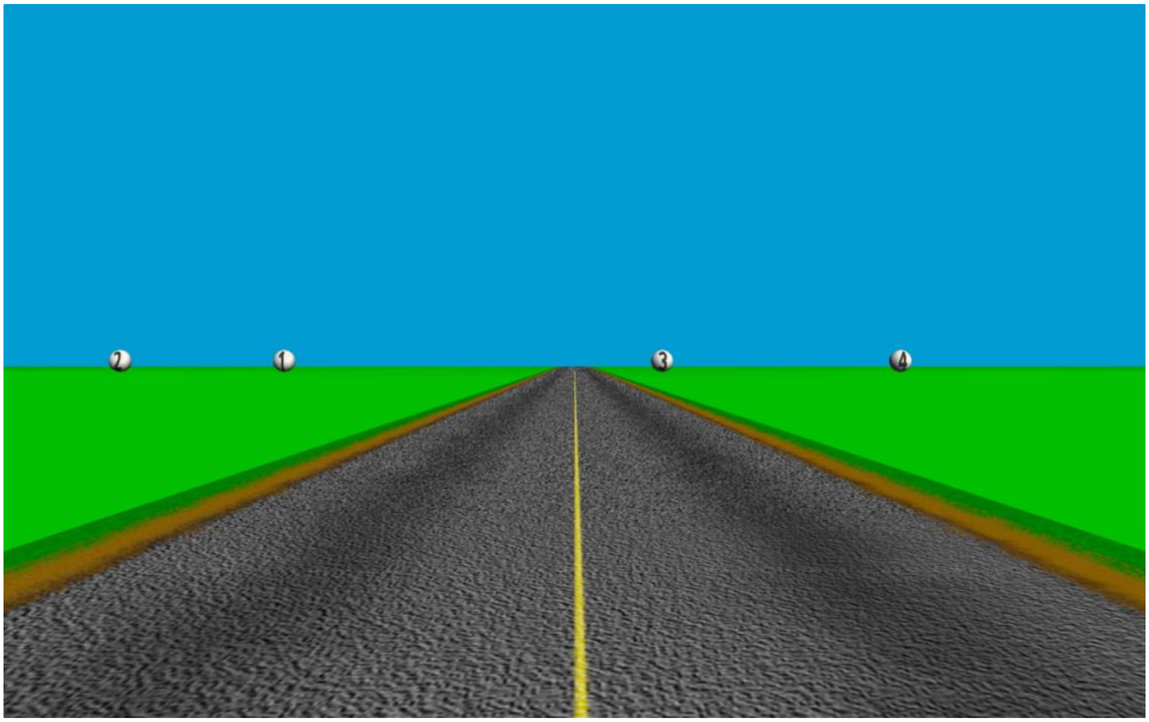

Figure 3.1. Sample stimulus display trial for 4 objects. 2, 4 or 8 objects traveled in the opposite direction to the driver. Drivers had to steer to stay in the center lane and had to verbally identify which object among a number of objects was the collision object.

Table 3.1. Demographic information and results from Weschler Adult Intelligence Scale (WAIS) and Mini-Mental State Examination (MMSE)

Older Adults	Mean	SD
Age (years)	73.7500	4.6552
Education (years)	15.45	4.0324
Driving Experience (years)	56.65	5.7241
Driving Frequency (days per week)	5.775	1.2510
Average freeway speed (mph)	67.65	5.1224
Far Acuity: Both Eyes (LogMAR)	0.1960	0.1360
Near Acuity: Both Eyes (LogMAR)	0.2260	0.1722
Contrast Sensitivity: Both Eyes	1.12	0.5093
WAIS: Digit Symbol - Coding - [out of 133]	58.2105	12.7435
WAIS: Digit Symbol - Copy - [out of 133]	92.7895	18.2744
WAIS: Digit Span Forward - [out of 16]	9.9474	1.9285
WAIS: Digit Span Backward - [out of 14]	6.4211	1.8048
WAIS: Matrix Reasoning - [out of 26]	15.0526	5.2649
WAIS: Total Digit Span - [out of 30]	16.3684	3.0223
Mini-Mental State Examination - [out of 30]	28.4211	1.7738

Younger Adults	Mean	SD
Age (years)	20.7917	2.7502
Education (years)	14.8333	2.4257
Driving Experience (years)	3.5833	3.1021
Driving frequency (days per week)	4.1875	2.2302
Average freeway speed (mph)	70.1666	5.5455
Far Acuity: Both Eyes (LogMAR)	-0.0150	0.0721
Near Acuity: Both Eyes (LogMAR)	-0.0958	0.0806
Contrast Sensitivity: Both Eyes	1.44	0.1155
WAIS: Digit Symbol - Coding - [out of 133]	91.0833	13.0148
WAIS: Digit Symbol - Copy - [out of 133]	128.2500	9.6875
WAIS: Digit Span Forward - [out of 16]	10.1250	2.0283
WAIS: Digit Span Backward - [out of 14]	7.7500	1.8238
WAIS: Matrix Reasoning - [out of 26]	18.6667	4.1980
WAIS: Total Digit Span - [out of 30]	17.8750	3.3791
Mini-Mental State Examination - [out of 30]	29.0417	0.9079

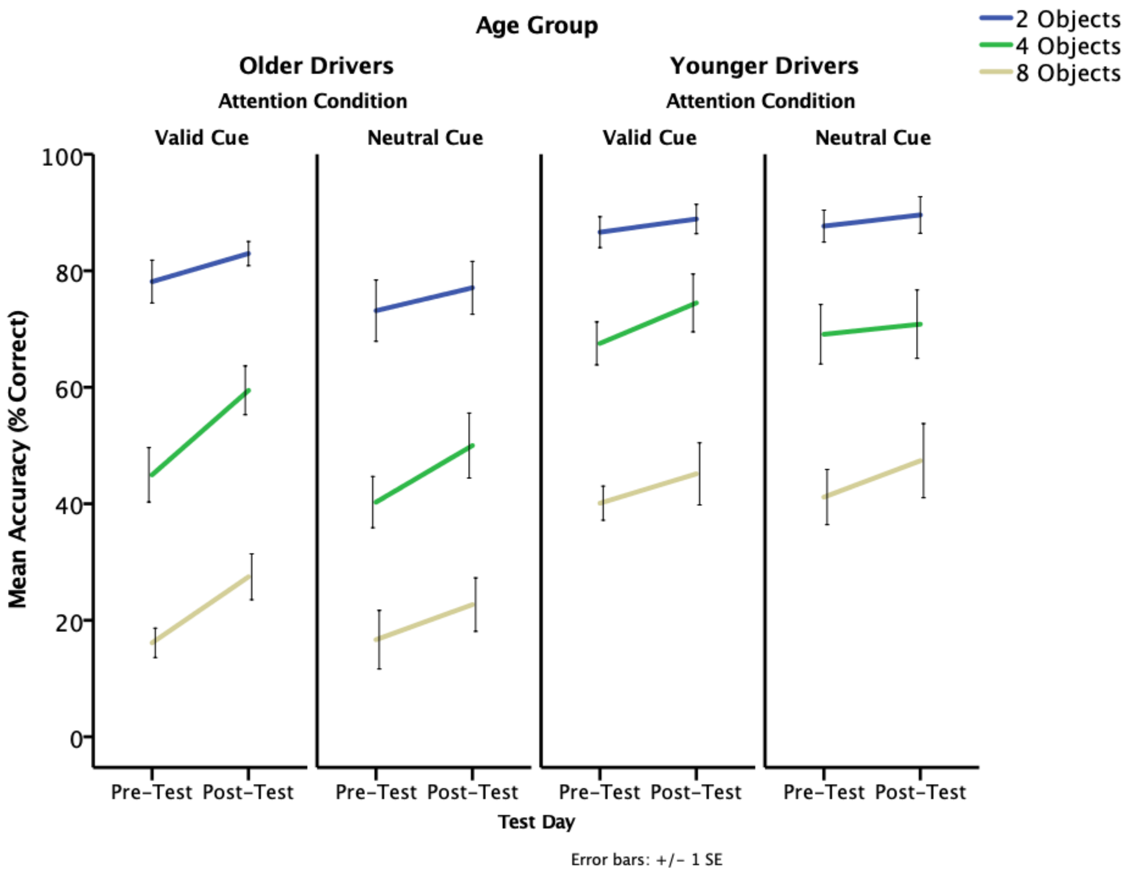

Figure 3.2. Mean accuracy (percent correct) as a function of test-day and attention cues condition for older drivers (left graph) and younger drivers (right graph).

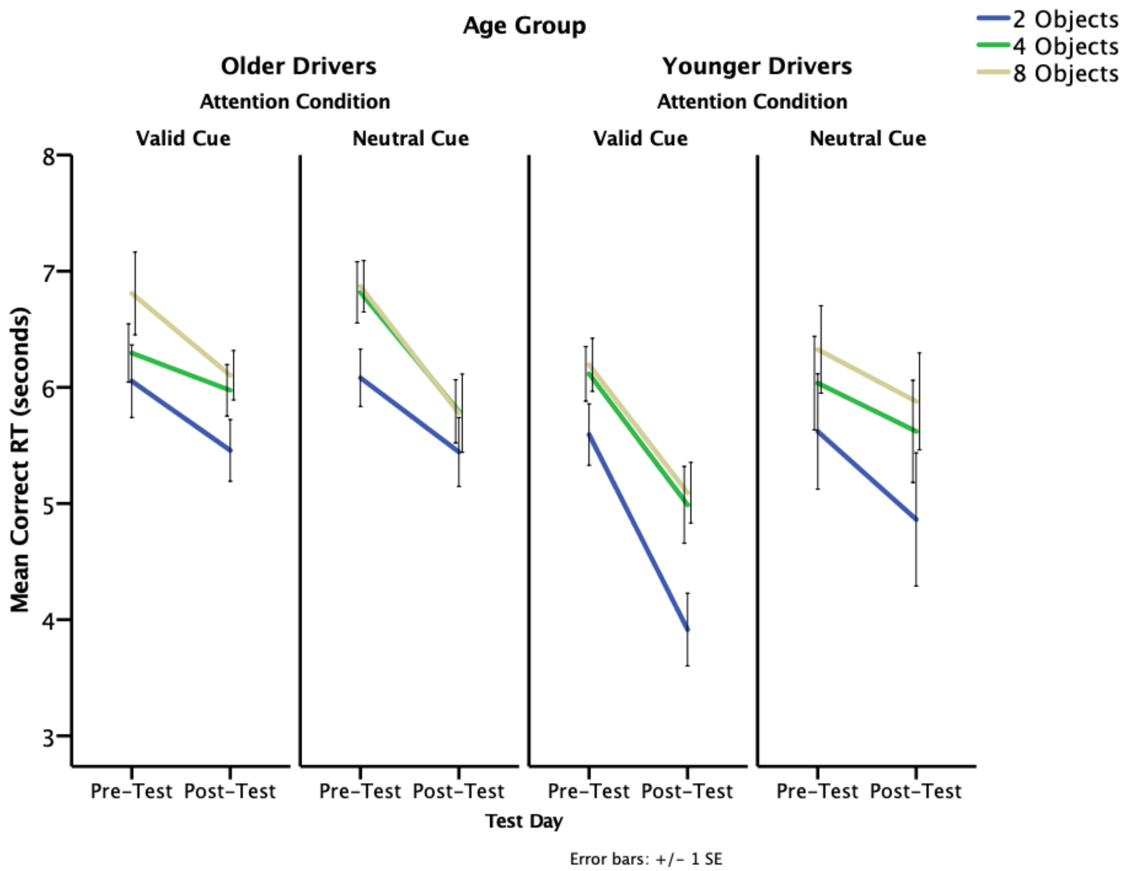

Figure 3.3. Mean correct response time (RT) as a function of test-day and attention cues condition for older drivers (left graph) and younger drivers (right graph).

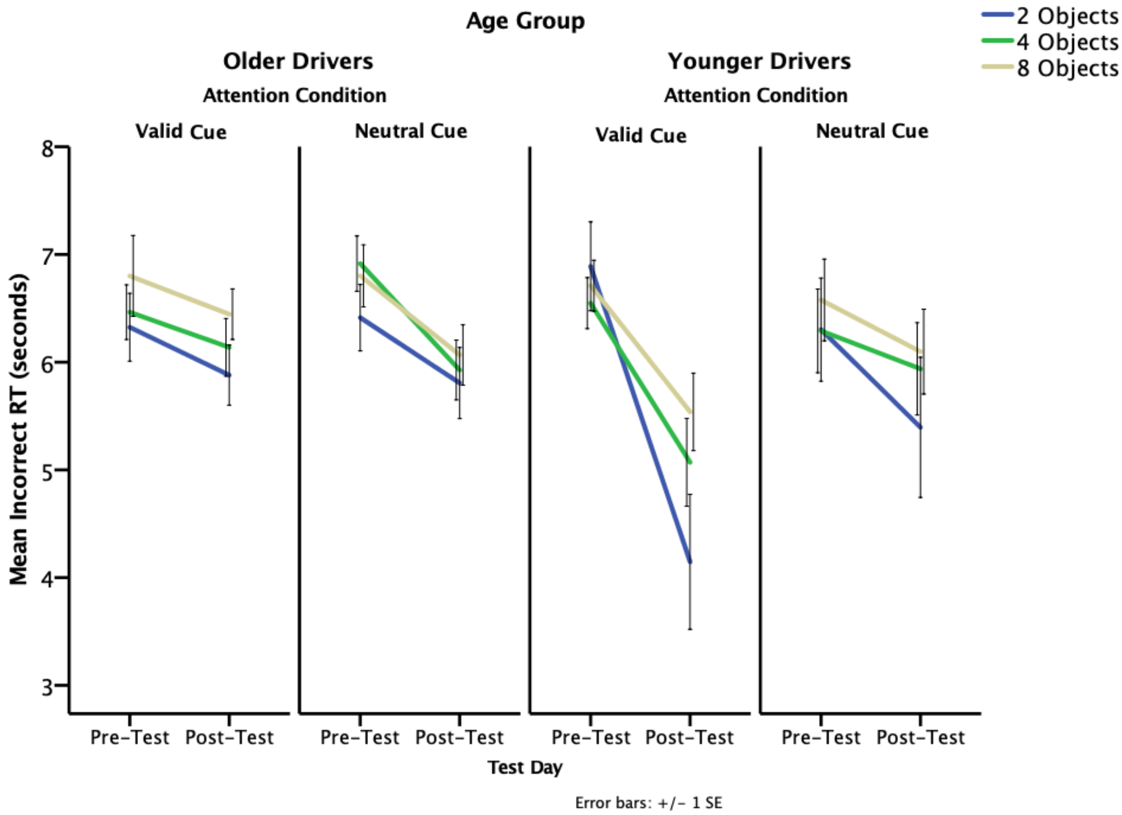

Figure 3.4. Mean incorrect response time (RT) as a function of test day and attention cues condition for older drivers (left graph) and younger drivers (right graph).

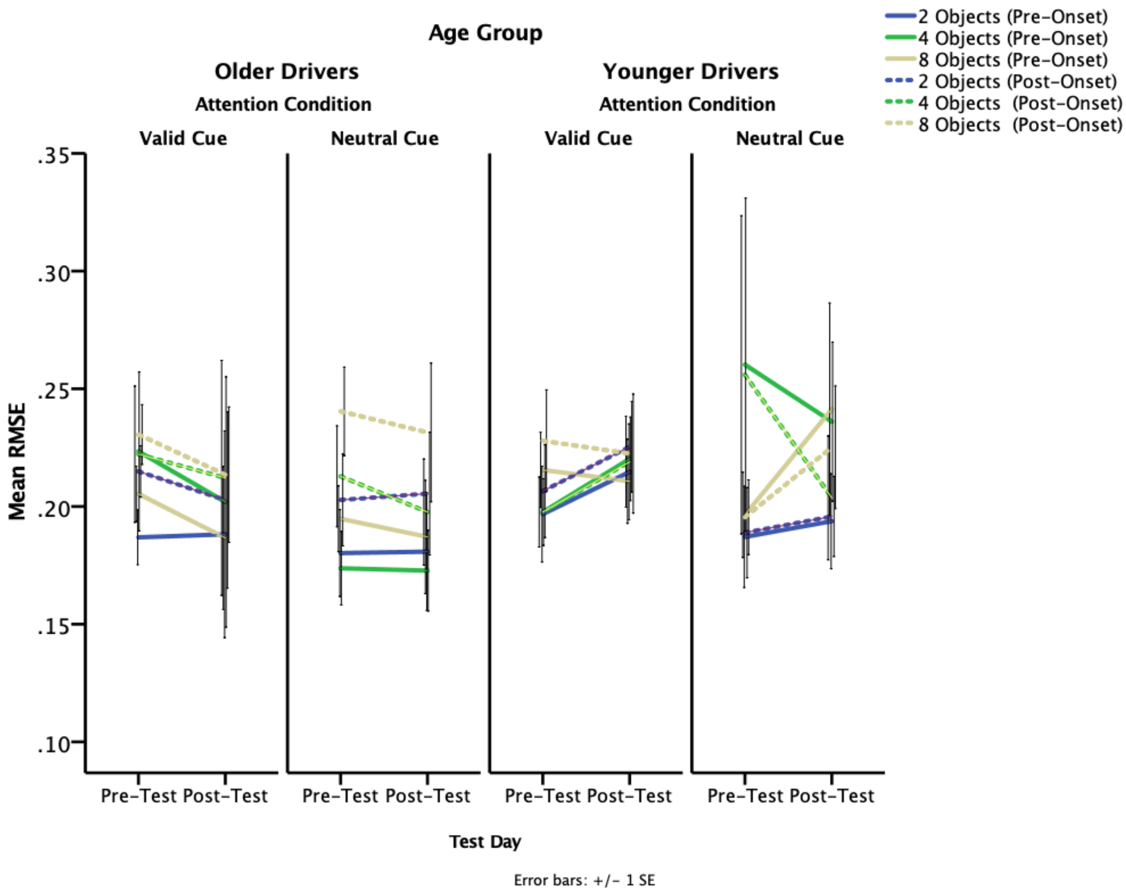

Figure 3.5. Mean root-mean-square error (RMSE) for steering control 2 seconds before objects appeared (labeled: pre-onset) and after objects appeared (labeled: post-onset) as a function of test day and attention cues condition for older drivers (left graph) and younger drivers (right graph).

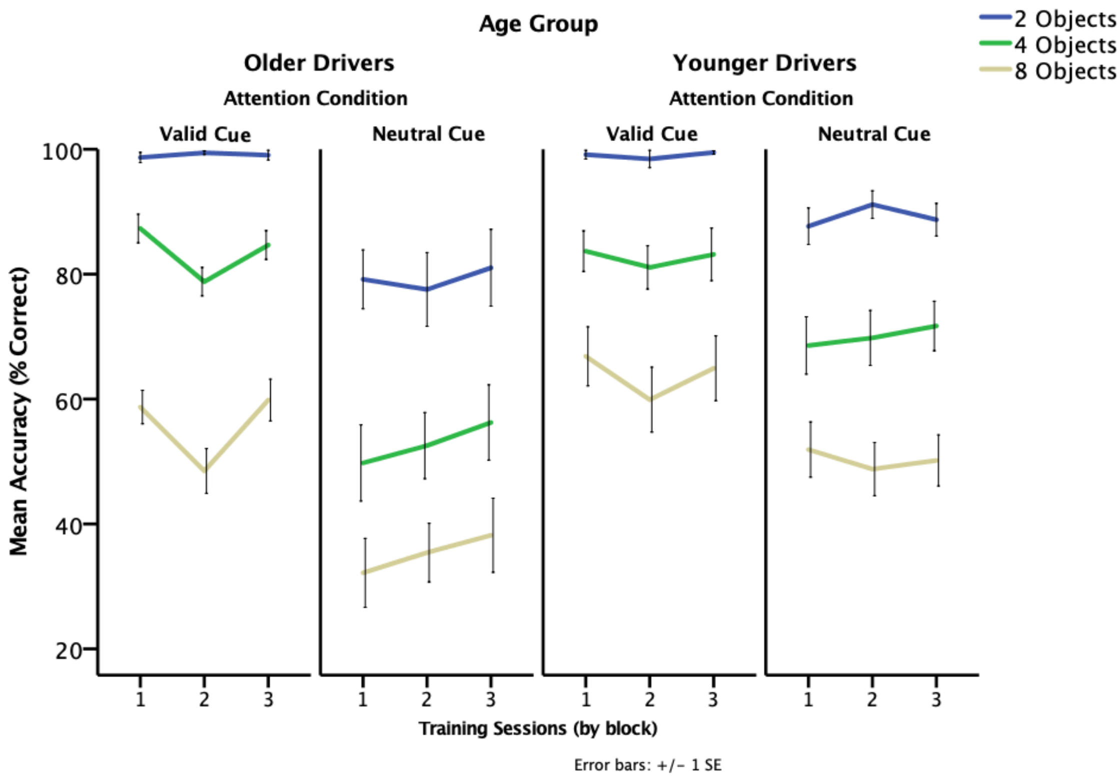

Figure 3.6. Mean accuracy (percent correct) for each training block as a function of age group and attention cues condition. Higher scores indicate higher accuracy (percent correct).

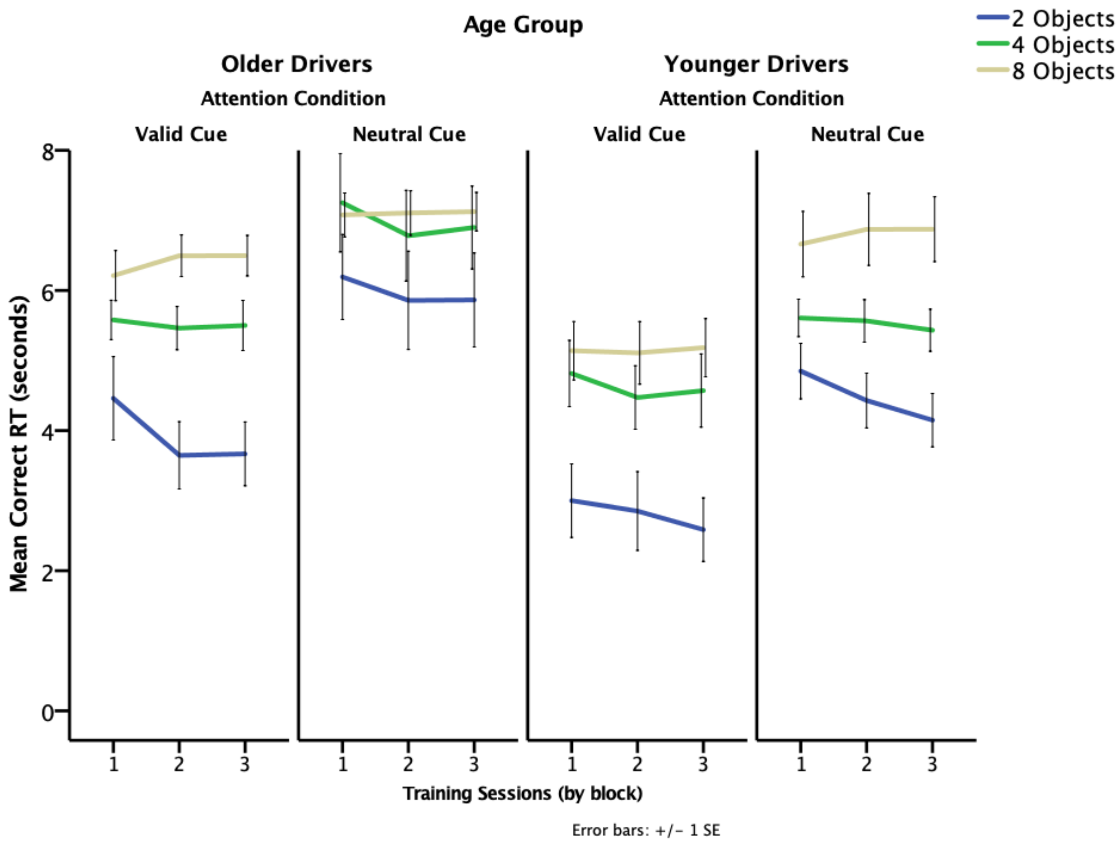

Figure 3.7. Mean Correct RT for each training sessions (block 1,2,3) as a function of age group and attention cues. Lower scores indicate faster correct RT.

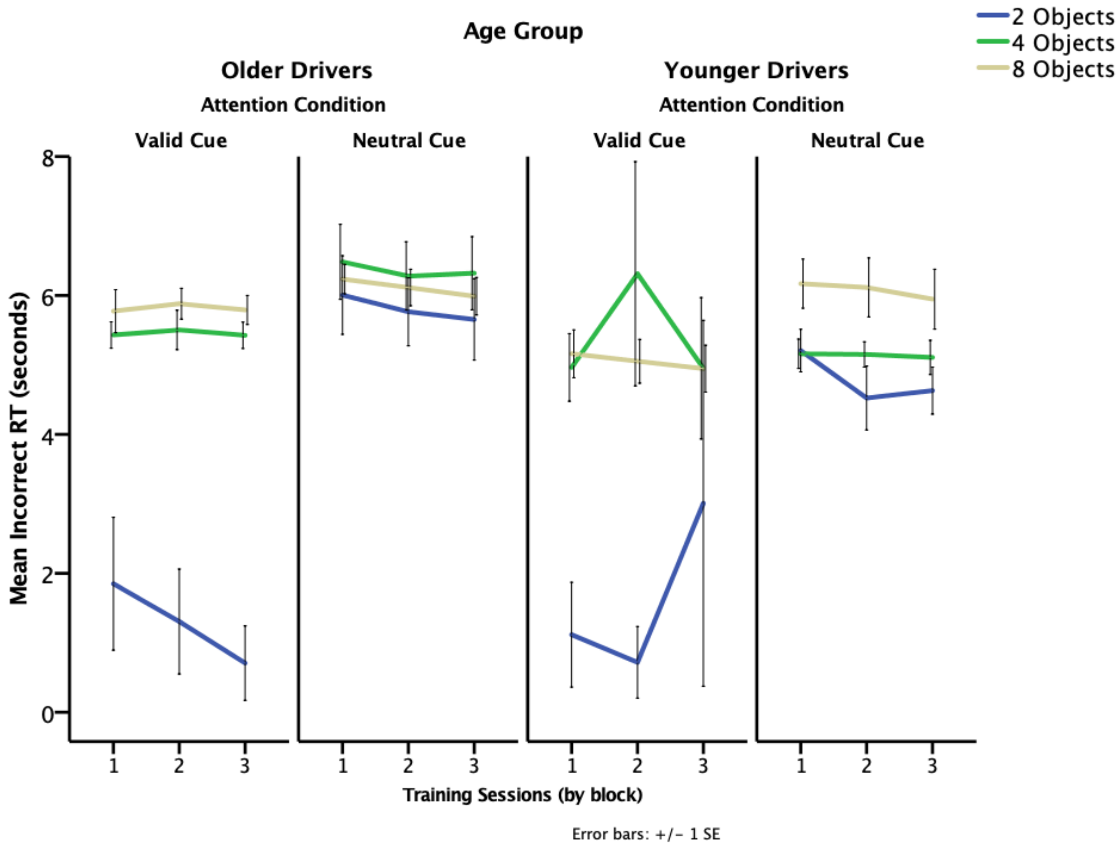

Figure 3.8. Mean Incorrect RT for each training sessions (block 1,2,3) as a function of age group and attention cues. Lower scores indicate faster incorrect RT.

References

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative neurology and neuroscience*, *26*(4-5), 435–446.

Adini, Y., Sagi, D., & Tsodyks, M. (2002). Context-enabled learning in the human visual system. *Nature*, 415,790–93.

Andersen, G. J. (2012). Aging and vision: Changes in function and performance from optics to perception. *Wiley Interdisciplinary Reviews. Cognitive Science*, *3*(3), 403–410. https://doi.org/10.1002/wcs.1167.

Andersen, G. J., & Atchley, P. (1995). Age-related differences in the detection of three-dimensional surfaces from optic flow. *Psychology and Aging, 10(4),* 650-658.

Andersen, G. J., Cisneros, J., Atchley, P., & Saidpour, A. (1999). Speed, size, and edge-rate information for the detection of collision events. Journal of Experimental Psychology. Human Perception and Performance, 25(1), 256–269.

Andersen, G. J., & Enriquez, A. (2006). Aging and the detection of observer and moving object collisions. *Psychology and Aging, 21*(1), 74-85.

Andersen, G. J., & Kim, R. D. (2001). Perceptual information and attentional constraints in visual search of collision events. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(5), 1039.

Andersen, G. J., Ni, R., Bower, J. D., & Watanabe, T. (2010). Perceptual learning, aging, and improved visual performance in early stages of visual processing. *Journal of Vision, 10*(13):4, 1–13.

Andersen G.J. & Sauer C.W. (2004) Optical information for collision detection during deceleration. In: Hecht H, Savelsbergh G, editors. Advances in Psychology Volume 135: Time to Contact. Elsevier; Amsterdam, Netherlands, 93–108.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. K. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America A, 5(*12), 2210–2219.

Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*, *33*(5), 583–595. https://doi.org/10.1177/001872089103300509.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology & Visual Science*, *34*(11), 3110–3123.

Ball, K., & Sekuler, R. (1987). Direction-specific improvement in motion discrimination. *Vision Research, 27*, 953–65.

Ball, K., & Sekuler, R. (1986). Improving visual perception in older observers. Journal of Gerontology, 41(2), 176–182. http://dx.doi.org/10.1093/geronj/41.2.176.

Ball, K., & Sekuler, R. (1982) A specific and enduring improvement in motion discrimination. *Science, 218,* 697-698.

Bates D, Mächler M, Bolker B, Walker S (2015). "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software*, *67*(1), 1–48. doi: 10.18637/jss.v067.i01.

Bays, B. C., Visscher, K. M., Le Dantec, C. C., & Seitz, A. R. (2015). Alpha-band EEG activity in perceptual learning. *Journal of Vision*, *15*(10), 7–7. PubMed. https://doi.org/10.1167/15.10.7.

Belchior, P., Marsiske, M., Sisco, S. M., Yam, A., Bavelier, D., Ball, K., & Mann, W. C. (2013). Video game training to improve selective visual attention in older adults. *Computers in Human Behavior*, *29*(4), 1318–1324. PubMed. https://doi.org/10.1016/j.chb.2013.01.034.

Betts, L. R., Sekuler, A. B., & Bennett, P. J. (2007). The effects of aging on orientation discrimination. Vision Research, 47(13), 1769–1780. http://dx.doi.org/10.1016/j.visres.2007.02.016.

Betts, L. R., Taylor, C. P., Sekuler, A. B., & Bennett, P. J. (2005). Aging reduces Center-surround antagonism in visual motion processing. *Neuron, 45,* 361-366.

Bower, J. D., Watanabe, T., & Andersen, G. J. (2013). Perceptual learning and aging: Improved performance for low-contrast motion discrimination. *Frontiers in Psychology, 4*, 1–7.

Bower, J. D., & Andersen, G. J. (2012). Aging, perceptual learning, and changes in efficiency of motion processing. *Vision Research, 61*, 144–156.

Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012.

Cassavaugh, N. D., Kramer, A. F., & Irwin, D. E. (2003) Influence of task- irrelevant onset distractors on the visual search performance of young and old adults, *Aging, Neuropsychology* & *Cognition,* 10, 44-60.

Chang, L.-H., Shibata, K., Andersen, G. J., Sasaki, Y., & Watanabe, T. (2014). Age-related declines of stability in visual perceptual learning. *Current Biology : CB*, *24*(24), 2926–2929. https://doi.org/10.1016/j.cub.2014.10.041.

Deloss, D. J., Bian, Z., Watanabe, T., & Andersen, G. J. (2015). Behavioral training to improve collision detection. *Journal of Vision, 15*(10), 2-2.

Deloss, D.J., Watanabe, T., & Andersen, G.J. (2014). Optimization of perceptual learning: effects of task difficulty and external noise in older adults. *Vision Research, 99*, 37–45.

Donovan, I. & Carrasco, M. (2018). Endogenous attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7, 1-16.

Evans, L. (2004). Overview of traffic fatalities. In Traffic safety (pp. 36–62). Bloomfield Hills, MI: Science Serving Society.

Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S. & Owsley, C. (1998). Useful field of view and other neurocognitive indicators of crash risk in older adults. Journal of Clinical Psychology in Medical Settings, 5(4), 425-440.

Fahle, M. (2005). Perceptual learning: Specificity versus generalization. *Current Opinion in Neurobiology*, *15*(2), 154–160. https://doi.org/10.1016/j.conb.2005.03.010.

Fine, I., & Jacobs, R. A. (2002). Comparing perceptual learning tasks: A review. *Journal of Vision*, *2*(2), 190–203. https://doi.org/10.1167/2.2.5.

Fiorentini, A., & Berardi, N. (1981) Learning in grating wave form discrimination: specificity for orientation and spatial frequency. *Vision Research*, *21*, 1149–1158.

Fiorentini A, Berardi N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature, 287*, 43–44.

Folk, C. L., & Hoyer, W. J. (1992). Aging and shifts of visual spatial attention. *Psychology and aging*, *7*(3), 453–465. https://doi.org/10.1037//0882-7974.7.3.453.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189–198. https://doi.org/10.1016/0022-3956(75)90026-6.

Gibson, J.J (1947). Motion picture testing and research. AAF Aviation Psychology program report 7; U.S. Government Printing Office.

Green, C.S., & Bavelier, D. (2012). Learning, attentional control and action video games. *Current Biology, 22*(6), R197–R206.

Green, C.S., & Bavelier, D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(6), 1465–1478. PubMed. https://doi.org/10.1037/0096-1523.32.6.1465.

Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–537. https://doi.org/10.1038/nature01647.

Hartley A.A. & Little D.M. (1999) Age-related differences and similarities in dual-task interference. Journal of Experimental Psychology. 128, 416–449.

Hua, T., Kao, C., Sun, Q., Li, X., & Zhou, Y. (2008). Decreased proportion of GABA neurons accompanies age-related degradation of neuronal function in cat striate cortex. *Brain research bulletin*, *75*(1), 119–125. https://doi.org/10.1016/j.brainresbull.2007.08.001.

Ito, M., Westheimer, G. & Gilbert, C. D. (1998). Attention and perceptual learning modulate con- textual influences on visual perception. *Neuron, 20*(6), 1191–1197, https://doi.org/S0896- 6273(00)80499-7.

Kaiser, M. K., & Mowafy, L. (1993). Optical specification of time-to- passage: Observers' sensitivity to global tau. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1028-1040.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: evidence for primary visual cortex plasticity. *Proc. Natl. Acad. Sci.* USA, *88*, 4966–70.

Koenderink, J. J. (1986). Optic flow. *Vision Research, 26*(1), 161–179.

Kramer A.F., Hahn S., Irwin D.E. & Theeuwes J. (1999). Attentional capture and aging: Implications for visual search performance and oculomotor control. Psychology and aging. 14, 135–154.

Lam, L. T. (2002). Distractions and the risk of car crash injury: The effect of drivers' age. *Journal of Safety Research, 33*(3), 411–419. https://doi.org/10.1016/S0022-4375(02) 00034-8.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2017). Training to improve collision detection in older adults. *Driving Assessment Conference.* DOI: 10.17077/drivingassessment.1651.

Leventhal, A. G., Wang, Y., Pu, M., Zhou, Y., & Ma, M. (2003). GABA and its agonists improved visual cortical function in senescent monkeys. *Science, 300*, 812-815.

Lord, S. & Dayhew, J. (2001). Visual Risk Factors for Falls in Older People. Journal of the American Geriatrics Society. 49. 508-15. 10.1093/ageing/afl085.

Ma, L., & Yan, X. (2014). Examining the nonparametric effect of drivers' age in rear-end accidents through an additive logistic regression model. A*ccident Analysis and Prevention, 67*, 129–136. https://doi.org/10.1016/j.aap.2014.02.021.

Madden, D. J. (2007). Aging and Visual Attention. *Current Directions in Psychological Science*, *16*(2), 70–74. https://doi.org/10.1111/j.1467-8721.2007.00478.x

McAndrews, C., Beyer, K., Guse, C. E., & Layde, P. (2013). Revisiting exposure: Fatal and non-fatal traffic injury risk across different populations of travelers in Wisconsin, 2001–2009. *Accident Analysis and Prevention, 60*, 103–112. https://doi.org/10.1016/j.aap.2013.08.005.

Monsell S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134–140. https://doi.org/10.1016/s1364-6613(03)00028-7

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision, 11*(1), Article 25. doi:10.1167/11.1.125.

Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience*, 27, 11401–11411.

Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., & Goode, K. T. (2000). Relation of useful field of view and other screening tests to on-road driving performance. Perceptual and Motor Skills, 91, 279-290.

Ni, R. & Andersen, G.J (2006). Age Related Performance in Driving: Steering and Collision Detection. *Vision in Vehicles 11*, Dublin, Ireland.

Ni, R., Bian, Z. & Andersen, G.J. (2009) Age-related differences in using optical flow and landmark information for steering control, *2009 IEEE Intelligent Vehicles Symposium*, Xi'an, 691-694, doi: 10.1109/IVS.2009.5164360.

Owsley, C. (2013). Visual processing speed. *Vision Research*, *90*, 52–56. https://doi.org/10.1016/j.visres.2012.11.014.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, *6*(3), 403–415. https://doi.org/10.1037//0882-7974.6.3.403.

Owsley, C. & Mcgwin, G. (2004). Association Between Visual Attention and Mobility in Older Adults. Journal of the American Geriatrics Society. 52. 1901-6. 10.1111/j.1532-5415.2004.52516.x.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision research*, *23*(7), 689–699. https://doi.org/10.1016/0042-6989(83)90210-9.

Pierce, R.S. & Andersen, G.J. (2014) The effects of age and workload on 3D spatial attention in dual-task driving, *Accident Analysis and Prevention, 67*, 96–104.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

R Foundation for Statistical Computing (2020). R: A language and environment for statistical computing. Vienna, Austria.

Richards, O, W. (1977). Effects of luminance and contrast on visual acuity, ages 16 to 90 years. *American Journal of Optometry and Physiological Optics, 54,* 178-184.

Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V.G., & Edwards, J, D. (2003). Speed-of- processing and driving simulator training result in improved driving performance. Human factors, 45(2), 218-233.

Roudaia, E., Bennett, P. J., & Sekuler, A. B. (2008). The effect of aging on contour integration. *Vision research*, *48*(28), 2767–2774. https://doi.org/10.1016/j.visres.2008.07.026.

Salthouse, T. A. (1991). *Theoretical perspectives on cognitive aging.* Lawrence Erlbaum Associates, Inc.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*(3), 403–428. https://doi.org/10.1037/0033-295X.103.3.403

Sanders, M. S., & McCormick, E. J. (1993). *Human factors in engineering and design* (7th ed.). Mcgraw-Hill Book Company.

Schiff, W., Oldak, R., & Shah, V. (1992). Aging persons' estimates of vehicular motion. *Psychology and Aging, 7*(4), 518–525. https://doi.org/10.1037/0882 7974.7.4.518.

Schmolesky, M.T., Wang, Y., Pu, M., & Leventhal, A.G. (2000) Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, 3(4), 384-390.

Scialfa, C. T., Kline, D. W., & Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging, 2*(1), 14–19. https://doi.org/10.1037/0882-7974.2.1.14.

Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America A, 3*, 863–867.

Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research*, *26*(2), 103–120. https://doi.org/10.1080/036107300243588.

Sekuler, R., Owsley, C., & Hutman, L. (1982). Assessing spatial vision of older people. *American Journal of Optometry and Physiological Optics*, *59*(12), 961–968. https://doi.org/10.1097/00006324-198212000-00005.

Sigman, M., Pan, H., Yang, Y., Stern, E., Silbersweig, D., & Gilbert, C. D. (2005). Top-down reorganization of activity in the visual pathway after learning a shape identification task. *Neuron*, *46*(5), 823–835. https://doi.org/10.1016/j.neuron.2005.05.014.

Sims R.V., Owsley C., Allman R.M., Ball K. & Smoot T.M. (1998) A preliminary assessment of the medical and functional factors associated with vehicle crashes in older adults. *Journal of the American Geriatrics Society, 46*, 556–561. [PubMed: 9588367].

Son, J. & Suh, J. (2011) Design considerations for the older population: A human-vehicle interface perspective. SHUSER 2011 - 2011 International Symposium on Humanities, Science and Engineering Research. 10.1109/SHUSER.2011.6008506.

Stalvey, B.T., Owsley, C., Sloane, M.E., & Ball, K. (1999). The life space questionnaire: A measure of the extent of mobility of older adults. *Journal of Applied Gerontology*, *18(4)*, 460-478.

Tefft, B. C. (2008). Risks older drivers pose to themselves and to other road users. *Journal of Safety Research, 39*(6), 577–82. doi:10.1016/j.jsr.2008.10.002.

US Census (2014), https://www.census.gov/newsroom/press-releases/2014/cb14-84.html.

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching: a meta-analysis. *Psychology and aging*, *26*(1), 15–20. https://doi.org/10.1037/a0020912

Watanabe, T., Nanez, J.E., & Sasaki, Y. (2001). Perceptual learning without perception. *Nature, 413*, 844–48.

Watanabe, T., & Sasaki, Y. (2015). Perceptual learning: toward a comprehensive theory. *Annual review of psychology*, *66*, 197–221. https://doi.org/10.1146/annurev-psych-010814-015214

Wechsler, D. (1997). *WAIS-III Administration and scoring manual*. San Antonio, TX: The Psychological Association.

Williams, A., & Carsten, O. (1989). Driver age and crash involvement. *American Journal of Public Health, 79*(3), 326–327.

Williams, A. F., & Shabanova, V. I. (2003). Responsibility of drivers, by age and gender, for motor-vehicle crash deaths. *Journal of Safety Research, 34*(5), 527–531. https://doi.org/10.1016/j.jsr.2003.03.001.

World Health Organization (2015). Global status report on road safety 2015. https://www.who.int/violence_injury_prevention/road_safety_status/2015/en/

Yehezkel O., Sterkin A., Lev, M. & Polat U. (2015) Training on spatiotemporal masking improves crowded and uncrowded visual acuity *Journal of Vision, 15*:12.

Yotsumoto Y., Chang L., Ni R., Pierce R., Andersen G.J., Watanabe T., Sasaki Y. (2014) White matter in the older brain is more plastic than in the younger brain. *Nature Comm.*

General Discussion

The primary goal of this dissertation was to examine the effect of spatial attention on visual perceptual learning (PL). The studies in this dissertation were designed to increase our understanding of the role of attention in the acquisition and modulation of PL and how this role is impacted by age. Specifically, this dissertation addresses PL in the context of the type of attention important to PL, how PL is moderated by aging, and how PL may differ along different levels of visual processing in accordance with whether the task is an early level (sensory) or higher level (complex) task.

There are several reasons for the importance of these studies to expanding our understanding of the relationship between attention and PL. First, PL is an inherent property of our perceptual system. PL extends beyond early development and continues to be capable of change throughout life. The ability to understand our visual world is dependent on the development of our perceptual systems. This development, which occurs during the early years of life, is dependent on visual experience. PL can occur through our experience with the world and enables us to better perceive visual information. This allows us to more efficiently respond and adapt to our environment. For instance, driving is skill highly dependent on visual perception. As experience is gained through driving, the driver becomes more adept at extracting the relevant visual information critical to performing certain driving tasks. In the case of perceptual expertise, extensive practice on a perceptual skill enhances sensitivity to the critical visual information required to perform that skill. For example, experienced radiologists have greater sensitivity, as compared to novices, for detecting abnormalities in x-ray images as a result of practice (Sowden, 2000).

However, the visual system can easily become overwhelmed with the extensive visual information from our environment. The ability to extract relevant information can be aided by the use of attention. Attention can be restricted to processing important signals while ignoring irrelevant information. It is well-documented in the literature that attention can enhance perception (see Carrasco, 2011, for a detailed review). Furthermore, directing attention to allow for repeated exposure to relevant signals improves perceptual discrimination and detection of that signal. Therefore, a greater understanding of the relationship between these two processes is fundamental to understanding perception.

Beyond the role of PL in improving performance, PL can modify the perceptual system. A remarkable outcome of PL is the associated modifications in brain processing (Yotsumoto, Watanabe, & Sasaki, 2008; Mukai, Kim, Fukunaga, Japee, Marrett & Ungerleider, 2007). PL improvements can be relatively long-lasting (Crist, Li, & Gilbert, 2001; Sagi & Tanne, 1994; Ball & Sekuler, 1981) and can manifest as modifications in early level visual processing (Yotsumoto, Chang, Ni, Pierce, Andersen, Watanabe & Sasaki, 2014). Enhanced functional activation (Mukai et al., 2007) and structural connections (Yotsumoto, et al., 2014) can underlie improvements in PL and imply a high degree of brain plasticity.

The possibility for training-induced visual cortical plasticity is important for individuals that experience deficits in visual processing. Research has found that PL can be used to ameliorate decrements in visual function (Levi & Li, 2009; Levi, 2005; Polat, Ma-Naim, Belkin, & Sagi 2004; Levi & Polat, 1996) and counteract declines in visual performance (Andersen et al. 2010, Bower et al., 2013; Deloss et al. 2014). These types of declines and improvements resulting from PL can be useful for the design of training protocols. For instance, there is well-documented evidence that attention (see Madden, 2007) and visual function (see Andersen, 2012) decline with age. PL training studies with older adults have shown promising results in improving aspects of visual function (e.g., Andersen, Ni, Bower & Watanabe, 2010).

Although improvements via PL have been observed for older adults, research suggests that improvements in older adults may differ from younger adults (Chang et al., 2014). It is worth noting that older adults have shown decreased performance in attention tasks, suggesting a decline in attention (see Kramer & Madden, 2008, for a detailed review of this literature). Given the role of attention in learning, it is important to understand how individuals with decrements in visual attention may modulate learning. Understanding how older individuals with visual declines can benefit from PL and how improvements from training may differ based on age is important for the design of specialized targeted training protocols. Therefore, PL is important for the development of perceptual expertise as well as for addressing perceptual deficits and declines.

The goal of this general discussion was to review and interpret the major findings of the dissertation. First, a general overview of each chapter and the general findings will be reviewed. Following this presentation, the findings will be organized into a review of the major themes in this dissertation and interpretation of the findings, limitations and future directions are discussed.

General Findings

Study 1 (Chapter 1) Aim: Role of endogenous and exogenous attention in task-relevant visual perceptual learning

The aim of Study 1 was to examine the effect of exogenous and endogenous attention in PL and feature specificity. This study was conducted to assess whether there were differential effects of the type of attention in PL and transfer of learning. This study was motivated by previous studies that have reported variability in PL and variability in the transfer of PL to feature, location, or task. Attention has been postulated as important to PL and to the generalization of PL. Research has reported differences in learning based on the type of attention (Mukai, 2011). In terms of transfer, exogenous and endogenous attention were found to both facilitate learning and location-transfer (Donovan & Carrasco, 2018; Donovan, Szpiro & Carrasco, 2015). However, PL with exogenous attention was not found to transfer to untrained features (Szpiro & Carrasco, 2015). This suggests that the type of attention may differentially affect the type of PL transfer.

College-aged adults were trained with either exogenous or endogenous attention cues in one of three cue-validity conditions. A novel paradigm was employed in which participants had to detect the presence of a complex Gabor patch embedded in fixed Gaussian contrast noise while contrast thresholds were varied. Exogenous and endogenous attention were both found to facilitate learning and feature transfer when investigating pre-test and post-test thresholds. Furthermore, rapid improvements in behavioral performance was observed in as few as two days of training. Examination of the training sessions indicate attentional differences; with endogenous attention showing a greater effect on performance than exogenous attention.

Study 2 (Chapter 2) Aim: Aging, endogenous attention, and perceptual learning

The aim of Study 2 was to examine whether there were age-related differences in learning and location-transfer and the possible underlying processes when older adults are trained with endogenous attention. For college-aged adults, it was found that endogenous attention facilitated performance at both trained and untrained locations in PL (Donovan & Carrasco, 2018). Furthermore, learning and location transfer occurred through changes in contrast sensitivity which suggests a contrast gain mechanism. Several studies have examined aging and PL in texture discrimination (Andersen et al. 2010), motion discrimination (Ball & Sekuler, 1986), orientation discrimination (Deloss, Watananbe, & Andersen, 2014), divided attention (Richards, Bennett, & Sekuler, 2006), collision detection (Lemon, Deloss & Andersen, 2017; Deloss, Bian, Watanabe & Andersen, 2015), and action video game play (Belchior et al., 2014). However, few studies have examined how both attention and learning may differ in older and younger adults.

Given the reported age-related declines in visual function and attention, an important question is whether older adults benefit from PL with attention and whether PL training with attention cues improves attentional processing. Both older and younger adults were assigned to be trained in one of two endogenous cues; a valid cue or a neutral cue. Participants came into the lab for 6 days and were administered practice sessions, pre-test and post-test with intervening training sessions. To assess changes in learning and location transfer, performance was measured at pre-test and post-test. To assess changes in attention processing, UFOV was measured at pre-test and post-test.

The findings of this study show different patterns of performance between age groups. For both age groups, endogenous attention facilitated learning and these performance improvements transferred to untrained locations but were potentially achieved via different processes. Transfer was achieved through improved contrast thresholds for younger adults when trained with valid cues. For older adults, transfer was achieved through improved asymptotic performance irrespective of the type of attention cue presented. These findings indicate that older adults benefit from attention-induced PL but the optimal type of training protocol may differ between older and younger adults.

Study 3 (Chapter 3) Aim: Aging, perceptual learning and attention on driving performance

The aim of Study 3 was to investigate age-related differences in attention and PL in the context of a high-level dual-task driving paradigm. The importance of this study is two-fold; (1) to assess whether performance changes in a high-level perceptual task are similar to patterns of performance reported for low-level perceptual tasks and (2) to assess attention-induced training-related improvements in driving performance and its implications for driving safety.

This study was motivated by previous findings that found both younger and older adults benefit from PL in a collision detection task (Deloss, Bian, Watanabe & Andersen, 2015; Lemon, Deloss & Andersen, 2017) and from PL with UFOV (Richards, Bennett &

Sekuler, 2006). UFOV measures have been shown to be predictive of crash risk among older adults (Sims et al. 2000). Of particular relevance is the finding that automotive crashes are known to be particularly high among drivers under the age of 25 (Evans, 2004; Williams & Carsten, 1989) and over the age of 65 (Tefft, 2008; Evans, 2004). Given age-related differences in attention and visual function, improvements related to PL with attention may differ between older and younger adults and that driving-related improvements as a result of PL may translate to better UFOV scores.

Older and younger drivers were presented with a computer-simulated roadway scene and maintained within-lane vehicle steering while also identifying which object among a number of objects (2,4,8) will collide with the driver. Drivers were trained over several days in which the number of objects were varied. Drivers were either presented with an endogenous valid cue (identifying the visual field location of the collision object) or an endogenous neutral cue. The general findings indicated that PL resulted in improved collision detection performance for both older and younger drivers. There were performance decrements with an increase in the number of objects in the driving scene. Lastly, performance during training sessions indicated that both older and younger drivers, when presented with a valid cue, performed consistently higher than those trained with a neutral cue.

Across these three studies 9 hypotheses were tested. These hypotheses will be discussed in further detail within the major themes of this dissertation.

The Role of Attention in PL

Attention appears to play a critical role in the acquisition of learning. Across the studies conducted in this dissertation, there was a consistent finding of learning enabled by attention. In Study 1, younger adults trained with endogenous or exogenous cues both exhibited learning. In Studies 2 and 3, there was significant learning in both older and younger adults as a result of training with endogenous attention. A common finding in PL is considerable intra- and inter- observer variability in the reliability of producing PL (Hung & Seitz, 2014; Jeter, Dosher, Petrov, & Lu, 2009; Fahle, Edelman, Poggio, 1995; Fahle, M., & Henke-Fahle, 1996; Fine & Jacobs, 2002; Kumar & Glaser, 1993; Fahle & Edelman, 1993). Previous research suggests that attention may indeed reduce any individual differences in learning (Donovan, Szpiro & Carrasco, 2015). Thus, attention is likely to be an important factor in increasing the magnitude of learning in PL studies.

The present dissertation studies add to the literature that attention can improve learning. Hypotheses 1- 4 were evaluated in Study 1 (Chapter 1) with respect to the Dual-Plasticity model (Watanabe, & Sasaki, 2015; Shibata, Sagi, & Watanabe, 2014). First, Hypotheses 1-2 tested the type of attention on learning in the Dual-Plasticity model (Watanabe, & Sasaki, 2015; Shibata, Sagi, & Watanabe, 2014). As mentioned in Study 1, this model proposes two types of plasticity; task-based plasticity and feature-based plasticity. It is likely that task-based plasticity involves endogenous attention and likely has relevance to task-relevant learning. In contrast, feature-based plasticity involves exogenous attention and likely has relevance to both task-relevant and task-irrelevant learning.

The first hypothesis was concerned with the role of endogenous attention in task-relevant PL (TR-PL). According to Hypothesis 1, endogenous attention is important for TR-PL**.** Based on this hypothesis, it was predicted that learning will be enhanced when participants are trained with endogenous attention, with greater learning for higher cue-validity conditions as opposed to lower cue-validity conditions. This hypothesis was assessed by comparing pre-test and post-test thresholds values of participants trained with endogenous attention in one of three cue-validity conditions (100% cue validity, 80% cue-validity, neutral). Learning was facilitated by training regardless of the type of endogenous cue presented. However, local examination of the data separated by the cue-validity condition for the endogenous attention indicated an effect of the endogenous attention cue. Learning was observed for participants trained with the 100% and neutral cue-validity conditions but no learning was observed for those trained with the 80% cue-validity condition.

Although comparable learning was observed between 100% valid and neural cue-validity conditions, the results may support Hypothesis 1. Recall that the 100% cue-validity condition utilizes valid informative cues. In contrast, the neutral cue-validity condition utilizes uninformative cues. The 80% cue-validity condition utilizes a combination of both informative and uninformative cues. Endogenous attention appears to be important to task-relevant learning regardless of whether attention is directed, as indexed by the 100% valid cue condition, or distributed, as indexed by the neutral cue condition. However, when learning is misdirected, as indexed by the 80% valid cue-validity condition, endogenous attention can disrupt learning. Specifically, the use of an invalid endogenous cue interfered with learning. These results suggest the selective allocation of attention can modulate learning. This suggests that endogenous attention is important to task-relevant learning.

Hypothesis 1 is also relevant to the results reported in Study 2 (Chapters 2) and Study 3 (Chapter 3). In Study 2, younger adults were trained with either valid or neutral endogenous cues in a low-level perceptual orientation discrimination task. In Study 3, younger adults were trained with either valid or neutral endogenous cues in a high-level perceptual driving task. Notably, analysis of pre-test and post-test performance for younger participants trained with valid cues, as compared to those trained with neutral cues, indicated that there was no attentional benefit to learning. Specifically, the results reported in Studies 1, 2, and 3 (Chapters 1, 2, and 3, respectively) suggest no effect of attention when performance was assessed with pre-test and post-test in which no cues (Study 1) or neutral cues (Study 2 & 3) were presented. Although improvements were observed---which suggests improvements were training-related---there does not seem to be compelling evidence of an attentional benefit.

However, when performance was assessed via training sessions, an effect of endogenous attention was observed with higher performance for participants trained in the endogenous attention cue conditions as compared to the exogenous attention cue conditions (Study 1) or trained with valid endogenous cues as compared to trained with neutral endogenous cues (Studies 2 & 3). Thus, this attentional benefit is observed only when participants were actively engaged with the attentional cues during the training sessions. Therefore, an important question is why was there no attention-related benefit observed following training? One explanation is that improvements may just be due to task practice.

Improvements in task practice may account for the lack of a finding for an attentional effect despite observing training-related improvements. However, this explanation is not likely given the unique condition for those trained with valid cues. Participants trained with valid cues during training were presented with neutral cues at post-test. If improvements were related to task practice, then performance improvements should not have been observed for participants trained with valid cues as the task has changed when a neutral cue is presented. Future research should address whether improvements were related to task practice. For example, to address this, participants should be trained at suprathreshold to observe whether improvements are as a result of task practice. If improvements were due to task practice, then improvements on the task with suprathreshold stimuli should be observed.

An alternative to this explanation is that previous exposure to the neutral cues at pre-test may have enabled the improvements. Previous research observed that exposure to a stimulus is sufficient to observed learning effects (Zhang, Cong, Klein, Levi, & Yu, 2014; Zhang & Yang, 2014; Zhang, Zhang, Xiao, Klein, Levi & Yu, 2010). If this is correct, then participants trained with neutral cues would have exhibited greater learning relative to those trained with valid cues. Participants trained with neutral cues were consistently presented with neutral cues both at training and testing sessions. Therefore, participants trained with valid cues would have been at a disadvantage given that they were trained with valid cues but were tested with neutral cues.

Another plausible explanation is that the attentional enhancement observed during training sessions may just reflect two different learning processes; transient effects and sustained effects. These effects can be observed in performance for Studies 2 and 3. Specifically, performance during training sessions between valid and neutral cues indicate an attentional benefit of valid cues as compared to neutral cues. However, at post-test this attentional benefit is lost, and thus younger participants trained with valid cues or neutral cues have comparable performance following training. Attention is known to enhance perceptual processing and thus increases visual salience of a stimulus (Yeshurun & Carrasco, 1998; Yeshurun, Montagna & Carrasco, 2008). Furthermore, previous research has found an increased effect of attentional control signals on sensory gain in early visual areas during training (Mukai et al., 2011). From this, it can be speculated that there are two ways in which attention can improve performance. The first effect of attention is a transient change in performance (Xu, He, & Ooi, 2012; Xu, He, & Ooi, 2010) that may not be maintained at post-test. The second effect of attention is a sustained improvement that may be sustained at post-test (Mukai et al., 2011; Donovan & Carrasco, 2018). If this is correct, then it possible that these different types of attention (transient and sustained) may have differential effects on memory consolidation. Transient effects of attention may not involve memory consolidation. Sustained effects of attention may involve memory consolidation. This is merely speculative and future research may want to further investigate this issue.

The second hypothesis concerned the role of exogenous attention in TR-PL. According to Hypothesis 2, exogenous attention is not important for TR-PL. According to this hypothesis, performance will be comparable when participants are trained with exogenous attention. If this hypothesis is correct, then performance should not be impacted by cue-validity, but some learning may be observed due to task practice.

To assess Hypothesis 2, performance across different cue-validity conditions in the exogenous attention condition was examined. Significant learning was observed regardless of the cue-validity condition, which suggests improvements were comparable across groups. Furthermore, evaluation of training session performance for participants trained with endogenous attention, as compared to participants trained with exogenous attention, indicates that there was a greater effect of endogenous attention than exogenous attention on performance. This suggests that the results of Study 1 were consistent with Hypothesis 2.

However, a caveat of this study is that the task-relevant paradigm employed would have been sufficient to observe learning in both exogenous and endogenous attention. Furthermore, a review of magnitude of learning for pre-test and post-test performance suggests no significant differences between participants trained with endogenous attention or exogenous attention. This suggests that improvements in performance were comparable between exogenous and endogenous attention. According to the Dual-Plasticity model, TR-PL involves both feature-based plasticity and task-based plasticity. Given that feature-based plasticity may involve exogenous attention, it is possible that exogenous attention is also important to TR-PL. Future research should investigate this issue. For example, to evaluate whether exogenous attention is important to TR-PL, participants should be trained with exogenous attention either with near-threshold stimuli or supra-threshold stimuli. If exogenous attention is important to TR-PL, then learning should be observed when trained with near-threshold stimuli but not supra-threshold stimuli.

The Role of Attention in Generalized Learning

It has been proposed that attention mechanisms can expedite training and, as a consequence, can improve performance for a range of tasks (Green & Bavelier, 2003). Previous research has found that experience on a task can speed up learning of other related tasks (Green & Bavelier, 2003; 2012; Sowden, 2000). Therefore, attention can promote generalized learning. These attention-related learning effects could transfer broadly across task and stimulus features.

Understanding the precise conditions under which attention can induce transfer is important to the development of training protocols for visual rehabilitation. For instance, individuals with amblyopia experience a loss of critical information in early visual processing. These decrements in early-level visual areas can have significant effects on later visual information processing that receive output from these early-level visual areas. PL can be used to ameliorate this type of visual dysfunction (Levi & Li, 2009; Levi, 2005; Polat, Ma-Naim, Belkin, & Sagi 2004; Levi & Polat, 1996). Individuals with amblyopia can benefit from the type of training in PL that often use early-level visual stimuli (e.g., orientation, contrast, spatial frequency, etc.). However, an outcome of training with these types of visual stimuli is that performance tends to be specific to the trained task or stimulus feature. This specificity implies that extensive training would be required with every stimulus dimension in order to observe improvements on a variety of stimulus features or tasks. However, attention may attenuate specific learning. And so, attention-related training may be useful for promoting generalized learning for visual information specific to early visual processing. Therefore, an effective training protocol should (1) restrict the site of training to target those neural structures, (2) be broad enough to generalize learning, (3) require little intervention yet maximal benefit, and (4) require minimal effort from the individual.

To address the issue of the role of attention in generalized learning, the hypotheses reviewed here assessed the following; (1) whether the type of attention differentially modulates transfer of learning to untrained features and (2) whether there are age-related differences on the effect of attention on generalized learning. Hypotheses 3-4 were assessed in Study 1 (Chapter 1) and the study was designed to test the Dual-Plasticity model by assessing whether different forms of plasticity are involved in different types of attention, which may account for the type of transfer. According to Hypothesis 3, task-based plasticity involves endogenous attention. This assumes that task-based plasticity may be associated with higher-level cognitive processing or read-out from lower-level sensory processing areas and that endogenous attention may be primarily driven by higher-level cognitive processing. If this hypothesis is correct, then performance improvements for a trained stimulus feature will transfer to an untrained stimulus feature when participants have been trained with endogenous attention.

Hypothesis 3 was tested by evaluating pre-test and post-test performance of participants trained with endogenous attention. The results of Study 1 (Chapter 1) indicate that learning as a result of training with endogenous cues transferred to untrained features. However, local analyses separated by cue-validity condition for endogenous attention indicated that learning transferred to untrained features as a function of cue-validity. Specifically, performance improvements transferred to untrained features for the 80% cue-validity and neutral cue-validity conditions but not the 100% cue-validity condition. This suggests that the results for transfer-related benefits were not robust.

According to Hypothesis 4, feature-based plasticity involves exogenous attention. This hypothesis assumes feature-based plasticity reflects changes in lower-level sensory processing and that exogenous attention is primarily driven by lower-level sensory processes. If this hypothesis is correct, then performance improvements for a trained stimulus feature should be specific to the trained stimulus feature when trained with exogenous attention. However, feature transfer is possible due to varying target location. According to the Dual-Plasticity model, feature-based plasticity should be specific to the exposed feature or location the stimulus was presented during training (Watanabe & Sasaki, 2015). Given that the target stimulus location was varied, feature-based constraints should be eliminated. Thus, TR-PL should transfer to different locations/features (Harris et al. 2012).

Hypothesis 4 was tested by evaluating pre-test and post-test performance of participants with exogenous attention. The results of Study 1 indicate that learning as a result of training with exogenous cues transferred to untrained features. However, these results were not robust. Upon local analyses of exogenous attention---when separated by cue-validity conditions---performance improvements were found to be specific to the trained task across all cue-validity conditions. Therefore, these results indicate that there was not a reliable effect of exogenous attention on feature transfer. And so, with regard to Hypothesis 4, it could not be concluded that feature-based plasticity is important to exogenous attention.

Taken together, it is difficult to make a definitive conclusion about the results with regard to Hypotheses 3 and 4. The lack of reliable findings for feature transfer suggest that some caution should be considered when generalizing the results of Study 1 to generalized learning. It is possible that the nature of the task may have promoted generalized learning. The location of the target stimuli varied from trial-to-trial which may have resulted in transfer of training to an untrained feature. Thus, the training task employed may have partially accounted for the transfer effects.

Future research should investigate whether feature-based plasticity involves exogenous attention in paradigms commonly employed in PL. To examine this issue, a training paradigm that commonly observes specificity should be employed which include training the target stimulus in one location and utilizing a specific feature. Feature or location transfer could be evaluated by presenting the target stimulus in a new location or as a new feature and assess whether training-related improvements transfer to the untrained stimulus feature/location. If no transfer is observed, this suggests feature-based plasticity involves exogenous attention. An alternative is to train with exogenous attention and assess whether performance improvements transfer to an untrained task. Feature-based plasticity is constrained by the stimulus location/feature but not by the trained task. If feature-based plasticity involves exogenous attention, then training with exogenous attention should transfer to an untrained task.

Additionally, training sessions were carried out over 2 days which is comparatively fewer training sessions than typically employed in PL. PL is commonly administered over several days with extensive training sessions. Notably, rapid learning was found in a few as 2 days which may index an early component learning process that typically results in generalized learning. In contrast, the type of studies commonly employed in PL may index a later phase component process of learning. See Study 1 (Chapter 1) for a detailed discussion of rapid learning and slow learning in PL. It is likely that the results reported in Study 1 indexes the rapid learning component of PL.

Aging and Attention in PL

The effect of aging and attention in PL was assessed in Studies 2 and 3 and were reported in Chapters 2 and 3, respectively. In Study 2, older adults were trained with endogenous attention on a low-level perceptual task. In Study 3, older adults were trained with endogenous attention on a complex driving task. In both studies, training-related improvements were observed for older adults. This suggests that plasticity is well-preserved with advanced age. Several studies have investigated age-related differences in PL. Previous studies that examined aging and PL have concluded that the age-related declines are due to decreased inhibition (Schmolesky, Wang, Pu, & Leventhal, 2000). For example, one study found that older adults have higher internal noise and lower tolerance to external noise relative to younger adults (Bower & Andersen, 2012). This decreased tolerance to noise enabled generalized learning to different motion tasks.

Another study observed that older adults learned unimportant or irrelevant information that would otherwise be suppressed or ignored in younger adults (Chang, Shibata, Andersen, Sasaki, & Watanabe, 2014). If irrelevant signals compete with the relevant signals, then irrelevant signals are subject to attentional inhibition (Seitz & Watanabe, 2009). Therefore, supra-threshold task-irrelevant stimuli should engage the attentional system and be subsequently suppressed (Tsushima, Seitz & Watanabe, 2008). Engaging the attentional system this way should not lead to learning of the stimuli. It was observed in this study that older adults learned both the features that were sufficiently strong for younger adults to suppress as well as the features that were too weak for younger adults to learn (Chang, et al., 2014)

The process of attention involves selection and inhibition. The studies reviewed above suggest that age-related differences in learning may be due to declines in inhibition. In contrast, the results reported in Studies 2 and 3 (Chapters 2 & 3, respectively) suggests that age-related differences in learning could also be due to age-related declines in selective allocation of attention. Let us review this in detail.

Hypothesis 5 was tested in Study 2 (Chapter 2) and Study 3 (Chapter 3) and was intended to evaluate age-related differences in learning when trained with attentional cues. According to this hypothesis, the ability to learn increases with age. If this hypothesis is correct, then the presence of endogenous attention is likely to lead to learning for both older adults and younger adults. Given that older adults are less effective at processing endogenous cues and that initial task performance level is typically worse in older adults than younger adults (Ball et al., 1988; Sekuler & Ball, 1986), older adults should benefit more than younger adults from training with an endogenous cue. Thus, the magnitude of learning is predicted to be greater for older adults as compared to younger adults.

Comparing learning patterns between older and younger adults is informative for understanding the degree to which plasticity is retained throughout adulthood. And so, this hypothesis was evaluated via assessment of magnitude of learning between older and younger adults. Results for Study 2 indicate that learning rates for older and younger adults were comparable. This suggests that the results for Study 2 are inconsistent with Hypothesis 5. In contrast, the results reported for Study 3 indicate that a greater rate of learning observed for older drivers as compared to younger drivers. Thus, the results for Study 3 are consistent with Hypothesis 5.

Why was greater magnitude of learning for older adults observed in Study 3 but not in Study 2? The notable difference between performance of older adults in Studies 2 and 3 is that there appeared to be an attentional-benefit of valid cues as compared to neutral cues for older participants trained in a high-level perceptual task (Study 3) but no difference between older participants trained with valid or neutral cues in a low-level perceptual task (Study 2). This may be due to the type of task used which provides insight into what may be learned on these tasks. Study 2 observed attention-related differences in a low-level perceptual task whereas Study 3 observed attention-related differences in a high-level perceptual task. For Study 2, the finding of no attentional benefit between valid and neutral cues suggest that attentional processing may be compromised at this level of processing, presumably at a sensory level. In contrast, for Study 3, the finding an attentional benefit for valid cues as compared to neutral cues in older adults suggest attentional processing may have been relatively preserved at this level of information processing, presumably at a cognitive level. Furthermore, the improvements at this level of information processing suggests that these higher levels of processing (beyond early visual cortex) are receptive to training.

Hypothesis 6 examined whether attention-related training enables generalized learning in older adults. According to Hypothesis 6, older adults as compared to younger adults exhibit generalized learning. If Hypothesis 6 is correct, then transfer of learning to an untrained location should differ between older adults and younger adults. For older adults, performance improvements should transfer to an untrained location irrespective of being trained with a valid or neutral cue. For younger adults, performance improvements should transfer to an untrained location when trained with a valid cue but not with a neutral cue.

Hypothesis 6 was evaluated in Study 2. To test Hypothesis 6, transfer of training was assessed by examining changes in both contrast thresholds (α) and asymptote performance from pre-test to post-test for valid and neutral cues between older and younger adults. The results of Study 2 were separately assessed for contrast thresholds and asymptote performance. For contrast thresholds (α) for younger adults, improvements transferred to untrained locations when trained with valid cues but not with neutral cues. In contrast, contrast thresholds for older adults did not transfer, or generalize, to untrained locations when trained with valid or neutral cues.

For asymptote, performance improvements did not generalize to untrained locations when trained with the valid or neutral cues for younger adults. In contrast, improved asymptote performance transferred to untrained locations for older adults. This suggests that performance benefits can transfer to untrained locations for both age groups but are carried out via different mechanisms for younger and older adults. As reviewed in detail in Study 2 (Chapter 2), improvements in younger adults resembled changes in a contrast gain mechanism whereas improvements in older adults resembled changes in a response gain mechanism. Thus, different mechanisms may be engaged for older and younger adults.

Hypothesis 8 was concerned with age-related differences in learning when trained with endogenous attention. This hypothesis was assessed in Study 3 (Chapter 3). According to Hypothesis 8, processing efficiency of endogenous attention declines with age. If Hypothesis 8 is correct, then learning when trained with endogenous attention will differ for different age groups. For older adults, it was predicted that learning as a result of PL will not differ when trained with either valid or neutral cues. For younger adults, learning as a result of PL will be greater for those trained with valid cues than those trained with neutral cues.

Hypothesis 8 was tested by comparing change in performance for older and younger adults from pre-test to post-test for valid and neutral cues. The results reported in Study 3 (Chapter 3) suggest that younger adults benefit from training with valid cues as compared to neutral cues. In contrast, older adults benefited from training with neutral cues as compared to valid cues.

Altogether, the results reported for Studies 2 & 3 suggest that capacity for plasticity is well-preserved with age. But that plasticity may be modulated by attention. It is well-documented in the literature for age-related declines in sensory processing (see Andersen, 2012). It is likely that declines in sensory processing at the behavioral and neural level could impact the ability to perform any early-level perceptual task when attention is engaged. Endogenous attention could have an effect in early-level perceptual tasks. Thus, the degree to which endogenous attention is compromised, performance on an early-level perceptual task is likely to be affected as well.

PL Training and Improved Attentional Processing

An important question is whether task-related training generally improves attentional processing? This question was motivated by findings that similar mechanisms underlie attention and PL (see Byers & Serences, 2012). Previous studies have reported training-induced improvements associated with more efficient deployment of attention following PL training (Bays et al., 2015; Sireteanu & Rettenbach, 1995; 2000). Furthermore, training on action video game play, another type of high-level perceptual task, translated to improvements in UFOV (Green & Bavelier, 2003; 2006; Achtman, Green, & Bavelier, 2008; Belchior et al., 2014). The UFOV task has been found to be predictive of driving performance (Roenker, Cissell, Ball, Wadley & Edwards, 2003; Goode, Ball, Sloane, Roenker, Roth, Myers, & Owsley, 1998; Myers, Ball, Kalina, Roth, & Goode, 2000). If the UFOV task is predictive of driving performance, then improvements in driving performance should result in improved scores for the UFOV task. Extending these findings, it is possible that training on a high-level perceptual task such as driving may translate to improvements in attentional abilities as indexed by the UFOV task.

Hypothesis 7 was investigated to assess whether PL training with attention cues improves attentional processing. Hypothesis 7 was investigated in Studies 2 and 3. If Hypothesis 7 is correct, then improvements as a result of training with endogenous attention should transfer to improvements in UFOV. Improvements in UFOV should be reflected in pre-test and post-test UFOV measurements for both older and younger adults. But the magnitude of improvements in UFOV should be greater in older adults as compared to younger adults.

For both Studies 2 and 3, the results indicated no changes in attentional abilities as assessed by the UFOV following training in a low-level perceptual task (Study 2) or a high-level perceptual task (Study 3).

An important question is what is being learned? Given that improvements can generalize to untrained stimulus features (Study 1) or untrained locations (Study 2), this suggests that the locus of learning is occurring at a high-level. Given that no improvements were observed in the UFOV task, this suggests that training does not involve learning to better allocate attention. However, the results reported in Studies 2 and 3 suggest that older adults may be learning to better allocate attention as a result of training. Let us review evidence for this in detail.

First, lower performance from pre-test to post-test as assessed by contrast thresholds (Study 2) was observed in older adults trained with valid cues. Second, greater performance was observed for older adults trained with neutral cues as compared to valid cues when assessing performance at pre-test and post-test. This is inconsistent with previous studies that have reported an attentional benefit of valid cues as compared to neutral cues (Posner, Nissen & Ogden,1978; Posner, 1980). As reviewed in detail in Studies 2 and 3, older adults may have been affected by the switch from valid cues during training to neutral cues at post-test. Specifically, the switch may have interfered with learning and suggests age-related declines in task-switching ability. Task-switching involves a shift of attention. The performance of older adults suggests that they were sensitive to this task-switch. It is possible that the training for older adults may be improving some aspect of attentional abilities. It is worth noting that despite no observed change in attentional abilities as indexed by the UFOV task for older adults, the UFOV task may be insensitive to the component process that may have been changed with training for older adults.

This suggests that older adults may not learn task-relevant information in the same way as younger adults. For younger adults, performance was comparable across the type of training task (i.e., low-level perceptual task in Study 2 or high-level perceptual task in Study 3) that was administered. Attentional processing may be optimal in younger adults. Therefore, it is likely that different processes may be modified with learning between older and younger adults. This explanation is consistent with the viewpoint that multiple components of PL may rely upon a distribution of plasticity across the brain- all of which are aimed to optimize performance (Maniglia & Seitz, 2017). Learning influences neural activity and connectivity across multiple levels of the visual cortex as well as parietal and frontal (Byers & Serences, 2012). In addition, maintaining stability while allowing for plasticity, constrains how the system learns perceptual tasks (Dosher & Lu, 2009). This may explain why older individuals show structural changes in association with PL because the system is no longer stable due to declines in sensory functioning. Much of the visual system evolved to support processing of important stimulus cues in the environment and continues to improve through development and experience (Lu & Dosher, 2017). Thus, PL could occur in a variety of ways all of which is to optimize visual processing. Future research may want to dissociate the component processes modified with learning between older and younger adults.

Hypothesis 9 was intended to assess whether performance varies as a function of number of objects in the scene. According to Hypothesis 9, performance declines with increased number of objects. If Hypothesis 9 is correct, then performance decrements should be observed with increased number of objects. It is well-known in the literature that there is a limit to the amount of information that can be actively maintained (Miller, 1956). Consistent with Hypothesis 9, results reported in Study 3 indicate performance declines with increased number of objects in the driving scene.

Notably, training with multiple objects in the driving scene can result in improved performance for both older and younger adults. This is important considering that older adults' performance on the secondary steering task was negatively affected by the number of objects in the scene. Specifically, there was greater steering error with high attentional load (e.g., 8 objects). This suggests that other skills relevant to driving performance may be affected by increased visual clutter in a driving scene for older drivers. An important issue to investigate in future research will be to assess what driving tasks may be affected by conditions of higher attention load. In addition, another related issue to investigate is whether training collision detection under conditions of high attentional load could mitigate decrements in other secondary driving tasks.

An important issue in human factors research is to identify the factors that influence and cause errors in vehicle motor crashes. The studies conducted in this dissertation are informative for the application and design of training protocols and driver assistance systems. Furthermore, the age-related differences in how older and younger drivers successfully perform relevant tasks is informative in approaching these issues. First, PL may be useful as a training method to mitigate crash risk. Given that improvements in detecting collisions with multiple objects in the scene can be improved with practice, this may translate to greater sensitivity to detecting collisions in real-world driving scenes. Incorporating this training as a methodology for driver training may be useful for older adults that experience age-related declines in collision detection performance. For younger adults, incorporating PL training as a method for graduated licensing may be useful for younger adults in gaining driving experience.

Second, performance in the secondary steering task for older drivers was affected by increased visual clutter in the driving scene. This occurred despite the presented attentional cues intended to aid performance. Thus, conditions under which drivers may be in cluttered driving environments may be appropriate for implementation of driver assistance systems that can be engaged to alleviate the attentional load on drivers. How and when to deploy driver assistance systems should be carefully considered. For instance, deploying driver assistance systems may be helpful to older drivers who are affected by declines in perceptual processing. However, the declines for younger adults are not due to perceptual processing but due to limited driving skill. Therefore, deploying driving assistance systems for younger drivers may not be beneficial.

In conclusion, the primary objective of this dissertation was to investigate the effect of attention and aging in perceptual learning in a theoretical and applied context. First, the present studies indicate that attention modulates learning. Second, these studies have found that attention promotes generalization. In addition, aging impacts attention and learning. Finally, this research indicates that PL training with attention cues improves driving performance. A greater understanding of how aging and attention modulates learning in different perceptual contexts is important to understanding how (1) attention modulates learning, (2) how perception changes with age and learning and (3) how plasticity is affected by aging and attention. These findings have implications for the development of new technologies to improve performance in real-world settings such as driving.

References

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience*, *26*(4–5), 435–446.

Andersen, G. J. (2012). Aging and vision: Changes in function and performance from optics to perception. *Wiley Interdisciplinary Reviews. Cognitive Science*, *3*(3), 403–410. https://doi.org/10.1002/wcs.1167.

Andersen, G. J., Ni, R., Bower, J. D., & Watanabe, T. (2010). Perceptual learning, aging, and improved visual performance in early stages of visual processing. *Journal of vision*, *10*(13), 4. https://doi.org/10.1167/10.13.4.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America. A, Optics and Image Science*, *5*(12), 2210–2219. https://doi.org/10.1364/josaa.5.002210.

Ball, K., & Sekuler, R. (1986). Improving visual perception in older observers. Journal of Gerontology, 41(2), 176–182. http://dx.doi.org/10.1093/geronj/41.2.176.

Ball, K., & Sekuler, R. (1981). Adaptive processing of visual motion. *J. Exp. Psychol. Hum. Percept. Perform.* 7, 780–794. doi: 10.1037/0096-1523.7.4.780.

Bays, B. C., Visscher, K. M., Le Dantec, C. C., & Seitz, A. R. (2015). Alpha-band EEG activity in perceptual learning. *Journal of Vision*, *15*(10), 7–7. PubMed. https://doi.org/10.1167/15.10.7.

Belchior, P., Marsiske, M., Sisco, S. M., Yam, A., Bavelier, D., Ball, K., & Mann, W. C. (2013). Video game training to improve selective visual attention in older adults. *Computers in Human Behavior*, *29*(4), 1318–1324. PubMed. https://doi.org/10.1016/j.chb.2013.01.034.

Bower, J. D., & Andersen, G. J. (2012). Aging, perceptual learning, and changes in efficiency of motion processing. *Vision Research, 61*, 144–156.

Bower, J. D., Watanabe, T., & Andersen, G. J. (2013). Perceptual learning and aging: Improved performance for low-contrast motion discrimination. *Frontiers in Psychology, 4*, 1–7.

Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012.

Chang, L.-H., Shibata, K., Andersen, G. J., Sasaki, Y., & Watanabe, T. (2014). Age-related declines of stability in visual perceptual learning. *Current Biology : CB*, *24*(24), 2926–2929. https://doi.org/10.1016/j.cub.2014.10.04.

Crist, R. E., Li, W., & Gilbert, C. D. (2001). Learning to see: Experience and attention in primary visual cortex. *Nature Neuroscience*, *4*(5), 519–525. https://doi.org/10.1038/87470.

DeLoss, D. J., Bian, Z., Watanabe, T., & Andersen, G. J. (2015). Behavioral training to improve collision detection. *Journal of Vision*, *15*(10), 2–2. https://doi.org/10.1167/15.10.2.

DeLoss, D. J., Watanabe, T., & Andersen, G. J. (2014). Optimization of perceptual learning: Effects of task difficulty and external noise in older adults. *Vision Research*, *99*, 37–45. https://doi.org/10.1016/j.visres.2013.11.003.

Donovan, I. & Carrasco, M. (2018). Endogenous attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7, 1-16.

Donovan, I., Szpiro, S., & Carrasco, M. (2015). Exogenous attention facilitates perceptual learning transfer within and across visual hemifields. *Journal of Vision*, *15*(10), Article 11. doi:10.1167/15.10.11.

Dosher B.A. & Lu Z.L. (2009) Hebbian reweighting on stable representations in perceptual learning. *Learning and Perception, 1*, 37–58

Evans, L. (2004). Overview of traffic fatalities. In Traffic safety (pp. 36–62). Bloomfield Hills, MI: Science Serving Society.

Fahle, M., Edelman, S., & Poggio, T. (1995). Fast perceptual learning in hyperacuity. *Vision Research, 35,* 3003–13.

Fahle, M, & Edelman, S. (1993). Long-term learning in vernier acuity: Effects of stimulus orientation, range and of feedback. *Vision Research*, *33*(3), 397–412. https://doi.org/10.1016/0042-6989(93)90094-d.

Fahle, M., & Henke-Fahle, S. (1996). Interobserver variance in perceptual performance and learning. *Investigative Ophthalmology & Visual Science*, 37 (5), 869– 877.

Fine, I., & Jacobs, R. A. (2002). Comparing perceptual learning tasks: A review. *Journal of Vision*, *2*(2), 190–203. https://doi.org/10.1167/2.2.5.

Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S. & Owsley, C. (1998). Useful field of view and other neurocognitive indicators of crash risk in older adults. Journal of Clinical Psychology in Medical Settings, 5(4), 425-440.

Green, C.S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current Biology : CB*, *22*(6), R197–R206. PubMed. https://doi.org/10.1016/j.cub.2012.02.012.

Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–537. https://doi.org/10.1038/nature01647.

Green, C Shawn, & Bavelier, D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(6), 1465–1478. PubMed. https://doi.org/10.1037/0096-1523.32.6.1465.

Harris H., Gliksberg M. & Sagi D. (2012). Generalized perceptual learning in the absence of sensory adaptation. *Curr Biol.* 22, 1813–17.

Hung, S. C., & Seitz, A. R. (2014). Prolonged training at threshold promotes robust retinotopic specificity in perceptual learning. *Journal of Neuroscience*, *34*(25), 8423-8431.

Jeter, P. E., Dosher, B. A., Petrov, A., & Lu, Z.-L. (2009). Task precision at transfer determines specificity of perceptual learning. *Journal of Vision*, *9*(3), 1–1. https://doi.org/10.1167/9.3.1.

Kramer, A.F., & Madden, D.J. (2008). Attention. In F.I.M. Craik & T.A. Salthouse (Eds.), *The handbook of aging and cognition* (3rd ed.). Mahwah, NJ: Erlbaum.

Kumar, T., & Glaser, D. A. (1993). Initial performance, learning and observer variability for hyperacuity tasks. *Vision research*, *33*(16), 2287–2300. https://doi.org/10.1016/0042-6989(93)90106-7.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2017). Training to improve collision detection in older adults. *Driving Assessment Conference.* DOI: 10.17077/drivingassessment.1651.

Levi, D. M., & Li, R. W. (2009). Improving the performance of the amblyopic visual system. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 364(*1515), 399–407.

Levi, D.M. (2005) Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Dev Psychobiol,46,* 222–232.

Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences of the United States of America, 93*(13), 6830–6834.

Lu, Z.L. & Dosher, B.A. (2017). Visual perceptual learning and models. *Annual Review of Vision Science, 3*(1), 343-363.

Madden, D. J. (2007). Aging and Visual Attention. *Current Directions in Psychological Science*, *16*(2), 70–74. PubMed. https://doi.org/10.1111/j.1467-8721.2007.00478.x.

Maniglia, M., & Seitz, A. R. (2017). Towards a whole brain model of Perceptual Learning. *Current Opinion in Behavioral Sciences*, *20*, 47–55. https://doi.org/10.1016/j.cobeha.2017.10.004.

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review, 63*(2), 81–97. https://doi.org/10.1037/h0043158.

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision*, *11*(1), 10.1167/11.1.25 25. PubMed. https://doi.org/10.1167/11.1.25.

Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience*, 27, 11401–11411.

Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., & Goode, K. T. (2000). Relation of useful field of view and other screening tests to on-road driving performance. Perceptual and Motor Skills, 91, 279-290.

Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences of the United States of America, 101*(17), 6692–6697.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Richards E, Bennett P., & Sekuler A. (2006) Age related differences in learning with the useful field of view. *Vision Research, 46* (25), 4217–4231. doi:10.1016/j.visres.2006.08.011.

Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V.G., & Edwards, J, D. (2003). Speed-of-processing and driving simulator training result in improved driving performance. Human factors, 45(2), 218-233.

Sagi, D., & Tanne, D. (1994). Perceptual learning: Learning to see. *Current Opinion in Neurobiology*, *4*(2), 195–199. https://doi.org/10.1016/0959-4388(94)90072-8.

Schmolesky, M. T., Wang, Y., Pu, M., & Leventhal, A. G. (2000). Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, *3*(4), 384–390. https://doi.org/10.1038/73957.

Seitz, A. R., & Watanabe, T. (2009). The phenomenon of task-irrelevant perceptual learning. *Vision Research, 49*, 2604–2610.

Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America. A, Optics and image science*, *3*(6), 864–867. https://doi.org/10.1364/josaa.3.000864.

Sims, R. V, McGwin Jr, G., Allman, R. M., Ball, K. K., & Owsley, C. (2000). Exploratory study of incident vehicle crashes among older drivers. *Journal of Gerontology, 55*(1), M22–M27. doi:10.1093/gerona/55.1.M22.

Sireteanu, R., & Rettenbach, R. (*2000*). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research*, 40(21), 2925-2949.

Sireteanu, R., & Rettenbach, R. (1995). Perceptual learning in visual search: Fast, enduring, but non-specific. Vision Research, 35, 2037–2043.

Shibata, K., Sagi, D., & Watanabe, T. (2014) Two stage model of perceptual learning, *the Year in Cognitive Neuroscience, Annual Review of New York Academy of Sciences, 1316*, 18-28.

Sowden, P. T., Davies, I. R., & Roling, P. (2000). Perceptual learning of the detection of features in X-ray images: a functional role for improvements in adults' visual sensitivity?. *Journal of experimental psychology. Human perception and performance*, *26*(1), 379–390. https://doi.org/10.1037//0096-1523.26.1.379.

Szpiro, S. F., & Carrasco, M. (2015). Exogenous Attention Enables Perceptual Learning. *Psychological science*, *26*(12), 1854–1862. https://doi.org/10.1177/0956797615598976.

Tefft, B. C. (2008). Risks older drivers pose to themselves and to other road users. *Journal of Safety Research, 39*(6), 577–82. doi:10.1016/j.jsr.2008.10.002.

Tsushima, Y., Seitz, A. R., & Watanabe, T. (2008). Task-irrelevant learning occurs only when the irrelevant feature is weak. *Current Biology : CB*, *18*(12), R516–R517. PubMed. https://doi.org/10.1016/j.cub.2008.04.029.

Watanabe, T., & Sasaki, Y. (2015). Perceptual learning: toward a comprehensive theory. *Annual review of psychology*, *66*, 197–221. https://doi.org/10.1146/annurev-psych-010814-015214.

Williams, A., & Carsten, O. (1989). Driver age and crash involvement. *American Journal of Public Health, 79*(3), 326–327.

Xu, J. P., He, Z. J., & Ooi, T. L. (2012). Perceptual learning to reduce sensory eye dominance beyond the focus of top-down visual attention. *Perceptual Learning - Mechanisms and Manifestations*, *61*, 39–47. https://doi.org/10.1016/j.visres.2011.05.013.

Xu, J. P., He, Z. J., & Ooi, T. L. (2010). Effectively Reducing Sensory Eye Dominance with a Push-Pull Perceptual Learning Protocol. *Current Biology*, *20*(20), 1864–1868. https://doi.org/10.1016/j.cub.2010.09.043.

Yeshurun, Y., Montagna, B., & Carrasco, M. (2008). On the flexibility of sustained attention and its effects on a texture segmentation task. *Vision Research, 48*(1), 80–95.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution, *Nature, 396* (6706), 72–75.

Yotsumoto Y., Chang L., Ni R., Pierce R., Andersen G.J., Watanabe T., Sasaki Y. (2014) White matter in the older brain is more plastic than in the younger brain. *Nature Comm.*

Yotsumoto Y., Watanabe T., & Sasaki Y. (2008) Different dynamics of performance and brain activation in the time course of perceptual learning. *Neuron*, 57, 827–33.

Zhang J. Y., & Yang Y. X. (2014). Perception learning of motion direction discrimination transfers to an opposite direction with TPE training. *Vision Research*, 99, 93–98.

Zhang J. Y., Zhang G. L., Xiao L. Q., Klein S. A., Levi D. M. & Yu C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *Journal of Neuroscience*, 30 (37), 12323–12328.

Zhang J. Y., Cong L. J., Klein S. A., Levi D. M., & Yu C. (2014). Perceptual learning improves adult amblyopic vision through rule-based cognitive compensation. *Investigative Ophthalmology & Visual Science*, 55 (4), 2020–2030.

Complete List of References

Aberg, K. C., & Herzog, M. H. (2009). Interleaving bisection stimuli—Randomly or in sequence—Does not disrupt perceptual learning, it just makes it more difficult. *Vision Research*, *49*(21), 2591–2598. https://doi.org/10.1016/j.visres.2009.07.006.

Aberg, K. C., Tartaglia, E. M., & Herzog, M. H. (2009). Perceptual learning with Chevrons requires a minimal number of trials, transfers to untrained directions, but does not require sleep. *Vision Research, 49*(16), 2087–2094.

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience*, *26*(4–5), 435–446.

Adini, Y., Sagi, D., & Tsodyks, M. (2002). Context-enabled learning in the human visual system. *Nature*, *415*(6873), 790–793. https://doi.org/10.1038/415790a.

Ahissar, M., & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences, 8*, 457–464.

Ahissar, M, & Hochstein, S. (1997). Task difficulty and the specificity of perceptual learning. *Nature*, *387*(6631), 401–406. https://doi.org/10.1038/387401a0.

Ahissar, Merav, & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences*, *8*(10), 457–464. https://doi.org/10.1016/j.tics.2004.08.011.

Albrecht, D.G. & Hamilton, D.B. (1982) Striate cortex of monkey and cat: contrast response function. Journal of Neurophysiology, 48(1), 217-237.

Andersen, G. J. (2012). Aging and vision: Changes in function and performance from optics to perception. *Wiley Interdisciplinary Reviews. Cognitive Science*, *3*(3), 403–410. https://doi.org/10.1002/wcs.1167.

Andersen G.J. & Atchley P. (1995). Age-related differences in the detection of three-dimensional surfaces from optic flow. *Psychology and Aging. 10*(4):650–658. doi:10.1037/0882-7974.10.4.650.

Andersen, G. J., Cisneros, J., Atchley, P., & Saidpour, A. (1999). Speed, size, and edge-rate information for the detection of collision events. Journal of Experimental Psychology. Human Perception and Performance, 25(1), 256–269.

Andersen, G. J., & Enriquez, A. (2006). Aging and the detection of observer and moving object collisions. *Psychology and Aging, 21*(1), 74-85.

Andersen, G. J., & Kim, R. D. (2001). Perceptual information and attentional constraints in visual search of collision events. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(5), 1039.

Andersen, G. J., Ni, R., Bower, J. D., & Watanabe, T. (2010). Perceptual learning, aging, and improved visual performance in early stages of visual processing. *Journal of vision*, *10*(13), 4. https://doi.org/10.1167/10.13.4.

Andersen G.J. & Sauer C.W. (2004) Optical information for collision detection during deceleration. In: Hecht H, Savelsbergh G, editors. Advances in Psychology Volume 135: Time to Contact. Elsevier; Amsterdam, Netherlands, 93–108.

Astle A.T., Blighe A.J., Webb B.S. & McGraw P.V. (2015) The effect of aging on crowded letter recognition in the peripheral visual field. Investig Ophthalmol Vision Science, 55, 5039-5045.

Baker, C. I., Peli, E., Knouf, N., & Kanwisher, N. G. (2005). Reorganization of visual processing in macular degeneration. *J. Neurosci.* 25, 614–618. doi: 10.1523/JNEUROSCI.3476-04.2005.

Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America. A, Optics and Image Science*, *5*(12), 2210–2219. https://doi.org/10.1364/josaa.5.002210.

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., (2002). Effects of cognitive training interventions with older adults: a randomized controlled trial. *Journal of the American Medical Association, 208*, 2271–2281.

Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*, *33*(5), 583–595. https://doi.org/10.1177/001872089103300509.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology & Visual Science*, *34*(11), 3110–3123.

Ball, K., & Sekuler, R. (1987). Direction-specific improvement in motion discrimination. *Vision Research, 27*, 953–65.

Ball, K., & Sekuler, R. (1986). Improving visual perception in older observers. Journal of Gerontology, 41(2), 176–182. http://dx.doi.org/10.1093/geronj/41.2.176.

Ball, K., & Sekuler, R. (1982) A specific and enduring improvement in motion discrimination. *Science, 218,* 697-698.

Ball, K., & Sekuler, R. (1981). Adaptive processing of visual motion. *J. Exp. Psychol. Hum. Percept. Perform.* 7, 780–794. doi: 10.1037/0096-1523.7.4.780.

Bates D, Mächler M, Bolker B, Walker S (2015). "Fitting Linear Mixed-Effects Models Using lme4." *Journal of Statistical Software*, *67*(1), 1–48. doi: 10.18637/jss.v067.i01.

Bartolucci, M., & Smith, A. T. (2011). Attentional modulation in visual cortex is modified during perceptual learning. *Neuropsychologia*, *49*(14), 3898–3907. https://doi.org/10.1016/j.neuropsychologia.2011.10.007.

Bays, B. C., Visscher, K. M., Le Dantec, C. C., & Seitz, A. R. (2015). Alpha-band EEG activity in perceptual learning. *Journal of Vision*, *15*(10), 7–7. PubMed. https://doi.org/10.1167/15.10.7.

Bedard, A.-C., Nichols, S., Barbosa, J.A., Schachar, R., Logan, G.D., & Tannock, R., (2002) The development of selective inhibitory control across the life span. *Developmental Neuropsychology, 21,* 93–111.

Belchior, P., Marsiske, M., Sisco, S. M., Yam, A., Bavelier, D., Ball, K., & Mann, W. C. (2013). Video game training to improve selective visual attention in older adults. *Computers in Human Behavior*, *29*(4), 1318–1324. PubMed. https://doi.org/10.1016/j.chb.2013.01.034.

Betts, L. R., Sekuler, A. B., & Bennett, P. J. (2007). The effects of aging on orientation discrimination. Vision Research, 47(13), 1769–1780. http://dx.doi.org/10.1016/j.visres.2007.02.016.

Betts, L. R., Taylor, C. P., Sekuler, A. B., & Bennett, P. J. (2005). Aging reduces Center-surround antagonism in visual motion processing. *Neuron, 45,* 361-366.

Bower, J. D., Watanabe, T., & Andersen, G. J. (2013). Perceptual learning and aging: Improved performance for low-contrast motion discrimination. *Frontiers in Psychology, 4*, 1–7.

Bower, J. D., & Andersen, G. J. (2012). Aging, perceptual learning, and changes in efficiency of motion processing. *Vision Research, 61*, 144–156.

Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 51*(1), 20–35. https://doi.org/10.1037/1196-1961.51.1.20.

Burnett, K. E., Close, A. C., d'Avossa, G., & Sapir, A. (2016). Spatial attention can be biased towards an expected dimension. *Quarterly Journal of Experimental Psychology, 69*(11), 2218–2232, https://doi.org/10.1080/17470218.2015.1111916.

Byers, A. & Serences, J.T. (2012). Exploring the relationship between perceptual learning and top-down attentional control. *Vision Research, 74*, 30–39.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012.

Cassavaugh, N. D., Kramer, A. F., & Irwin, D. E. (2003) Influence of task- irrelevant onset distractors on the visual search performance of young and old adults, *Aging, Neuropsychology* & *Cognition,* 10, 44-60.

Chang, L.-H., Shibata, K., Andersen, G. J., Sasaki, Y., & Watanabe, T. (2014). Age-related declines of stability in visual perceptual learning. *Current Biology : CB*, *24*(24), 2926–2929. https://doi.org/10.1016/j.cub.2014.10.04.

Cheal M., Lyon D. (1991) Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*. *43*(4), 859–880.

Cheal, M., Lyon, D. R., & Hubbard, D. C. (1991). Does attention have different effects on line orientation and line arrangement discrimination? *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *43*(4), 825–857. https://doi.org/10.1080/14640749108400959.

Chica, A. B., Bartolomeo, P., & Lupiáñez, J. (2013). Two cognitive and neural systems for endogenous and exogenous spatial attention. *Behavioural Brain Research*, *237*, 107–123. https://doi.org/10.1016/j.bbr.2012.09.027.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews. Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755.

Craik, F. I. M., & Byrd, M. (1982a). Aging and Cognitive Deficits. In F. I. M. Craik & S. Trehub (Eds.), *Aging and Cognitive Processes* (pp. 191–211). Springer US. https://doi.org/10.1007/978-1-4684-4178-9_11.

Craik, Fergus I M, & Byrd, M. (1982b). *Aging and Cognitive Deficits BT - Aging and Cognitive Processes* (F I M Craik & S. Trehub, Eds.; pp. 191–211). Springer US. https://doi.org/10.1007/978-1-4684-4178-9_11.

Crist, R. E., Li, W., & Gilbert, C. D. (2001). Learning to see: Experience and attention in primary visual cortex. *Nature Neuroscience*, *4*(5), 519–525. https://doi.org/10.1038/87470.

DeLoss, D. J., Bian, Z., Watanabe, T., & Andersen, G. J. (2015). Behavioral training to improve collision detection. *Journal of Vision*, *15*(10), 2–2. https://doi.org/10.1167/15.10.2.

DeLoss, D. J., Watanabe, T., & Andersen, G. J. (2014). Optimization of perceptual learning: Effects of task difficulty and external noise in older adults. *Vision Research*, *99*, 37–45. https://doi.org/10.1016/j.visres.2013.11.003.

Deveau, J., & Seitz, A. R. (2014). Applying perceptual learning to achieve practical changes in vision. *Frontiers in Psychology, 5,* 1–6.

Desimone R. & Duncan J. (1995) Neural mechanisms of selective visual attention. Annual Review of Neuroscience,18:193–222.

Donovan, I. & Carrasco, M. (2018). Endogenous attention during perceptual learning facilitates location transfer. *Journal of Vision*, *18*(11):7, 1-16.

Donovan, I., Shen, A., Barbot, A., & Carrasco, M. (2019, May). Does exogenous spatial attention facilitate perceptual learning transfer in acuity and hyperacuity tasks? *Journal of Vision*, *19*(10):26d. doi: https://doi.org/10.1167/19.10.26d.

Donovan, I., Szpiro, S., & Carrasco, M. (2015). Exogenous attention facilitates perceptual learning transfer within and across visual hemifields. *Journal of Vision*, *15*(10), Article 11. doi:10.1167/15.10.11.

Dosher, B.A., Jeter, P., Liu, J., & Lu, Z.L. (2013). An integrated reweighting theory of perceptual learning. *Proc. Natl. Acad. Sci.* USA, *110*, 13678–83.

Dosher B.A. & Lu Z.L. (2009) Hebbian reweighting on stable representations in perceptual learning. *Learning and Perception, 1*, 37–58.

Dosher, B A, & Lu, Z. L. (2000). Noise exclusion in spatial attention. *Psychological Science*, *11*(2), 139–146. https://doi.org/10.1111/1467-9280.00229.

Dosher, B A, & Lu, Z. L. (1999). Mechanisms of perceptual learning. *Vision Research*, *39*(19), 3197–3221. https://doi.org/10.1016/s0042-6989(99)00059-0.

Dosher, B.A., & Lu, Z.-L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proceedings of the National Academy of Sciences*, *95*(23), 13988. https://doi.org/10.1073/pnas.95.23.13988.

Durrie, D., & McMinn, P. S. (2007). Computer-based primary visual cortex training for treatment of low myopia and early presbyopia. *Transactions of the American Ophthalmological Society, 105,* 132–140.

Eriksen, C. W. & Yeh, Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 583-597.

Evans, L. (2004). Overview of traffic fatalities. In Traffic safety (pp. 36–62). Bloomfield Hills, MI: Science Serving Society.

Fahle, M. (2005). Perceptual learning: Specificity versus generalization. *Current Opinion in Neurobiology*, *15*(2), 154–160. https://doi.org/10.1016/j.conb.2005.03.010.

Fahle, M. (2004). Perceptual learning: A case for early selection. *Journal of Vision*, *4*(10), 879–890. https://doi.org/10.1167/4.10.4.

Fahle, M. (1997). Specificity of learning curvature, orientation, and vernier discriminations. *Vision Research*, *37*(14), 1885–1895. https://doi.org/10.1016/s0042-6989(96)00308-2.

Fahle, M, & Edelman, S. (1993). Long-term learning in vernier acuity: Effects of stimulus orientation, range and of feedback. *Vision Research*, *33*(3), 397–412. https://doi.org/10.1016/0042-6989(93)90094-d.

Fahle, M., Edelman, S., & Poggio, T. (1995). Fast perceptual learning in hyperacuity. *Vision Research, 35,* 3003–13.

Fahle, M., & Henke-Fahle, S. (1996). Interobserver variance in perceptual performance and learning. *Investigative Ophthalmology & Visual Science*, 37 (5), 869– 877.

Fine, I., & Jacobs, R. A. (2002). Comparing perceptual learning tasks: A review. *Journal of Vision*, *2*(2), 190–203. https://doi.org/10.1167/2.2.5.

Fiorentini, A., & Berardi, N. (1981). Learning in grating waveform discrimination: Specificity for orientation and spatial frequency. *Vision Research*, *21*(7), 1149–1158. https://doi.org/10.1016/0042-6989(81)90017-1.

Fiorentini A., & Berardi N. (1980). Perceptual learning specific for orientation and spatial frequency. *Nature, 287*, 43–44.

Folk, C. L., & Hoyer, W. J. (1992). Aging and shifts of visual spatial attention. *Psychology and aging*, *7*(3), 453–465. https://doi.org/10.1037//0882-7974.7.3.453.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*(4), 1030−1044.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*(3), 189–198. https://doi.org/10.1016/0022-3956(75)90026-6.

Gibson E. J. (1953). Improvements in perceptual judgement as a function of controlled practice of training. Psychological Bulletin, 50, 402-431.

Gibson, J.J (1947). Motion picture testing and research. AAF Aviation Psychology program report 7; U.S. Government Printing Office.

Gilbert, *C*.D. & Li, W. (2012). Adult Visual Cortical Plasticity. *Neuron, 75*(2), 250–264.

Gilbert, C. D., Sigman, M., & Crist, R. E. (2001). The neural basis of perceptual learning. *Neuron*, *31*(5), 681–697. https://doi.org/10.1016/s0896-6273(01)00424-x.

Giordano, A. M., McElree, B., & Carrasco, M. (2009). On the automaticity and flexibility of covert attention: A speed-accuracy trade-off analysis. *Journal of Vision, 9*(3), 10–31.

Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S. & Owsley, C. (1998). Useful field of view and other neurocognitive indicators of crash risk in older adults. Journal of Clinical Psychology in Medical Settings, 5(4), 425-440.

Green, C.S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current Biology : CB*, *22*(6), R197–R206. PubMed. https://doi.org/10.1016/j.cub.2012.02.012.

Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–537. https://doi.org/10.1038/nature01647.

Green, C.S., Li, R. & Bavelier, D. (2010). Perceptual learning during action video game playing. *Topic in Cognitive Science 2*, 202-16.

Green, C Shawn, & Bavelier, D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology. Human Perception and Performance*, *32*(6), 1465–1478. PubMed. https://doi.org/10.1037/0096-1523.32.6.1465.

Gutnisky, D.A., Hansen, B.J., Iliescu, B.F., & Dragoi, V. (2009). Attention alters visual plasticity during exposure-based learning. *Current Biology*, 19, 555–60.

Harris H., Gliksberg M. & Sagi D. (2012). Generalized perceptual learning in the absence of sensory adaptation. *Curr Biol.* 22, 1813–17.

Hartley, A.A., (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychol. Aging, 8*, 371–379.

Hartley, A. A., & Kieley, J. M. (1995). Adult age differences in the inhibition of return of visual attention. *Psychology and Aging, 10*(4), 670–683. https://doi.org/10.1037/0882-7974.10.4.670.

Hartley A.A. & Little D.M. (1999) Age-related differences and similarities in dual-task interference. Journal of Experimental Psychology. 128, 416–449.

Hautus, M.J. (1995). Corrections for extreme proportions and their biasing effects on estimated values of d'. *Behavior Research, Methods, Instruments & Computers, 27*, 46-51. https://doi.org/10.3758/BF03203619.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Focal visual attention produces illusory temporal order and motion sensation. *Vision Research, 33*(9), 1219–1240.

Hochstein, S., & Ahissar, M. (2002). View from the top: hierarchies and reverse hierarchies in the visual system. *Neuron, 36,* 791–804.

Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage, 31*(2), 774–789.

Horn, J. L., & Blankson, N. (2005). *Foundations for Better Understanding of Cognitive Abilities.* In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (p. 41–68). The Guilford Press.

Houser, A., Fox-Grage, W., and Ujvari, K., (2012). Across the States 2013: Profiles of Long-Term Services and Supports [WWW Document]. AARP Public Policy Inst. http://www.aarp.org/content/dam/aarp/research/public_policy_institute/ltc/2012/across-the-states-2012-full-report-AARP-ppi-ltc.pdf.

Hua, T., Bao, P., Huang, C.B., Wang, Z., Xu, J., Zhou, Y., & Lu, Z.L. (2010). Perceptual learning improves contrast sensitivity of V1 neurons in cats. *Current Biology, 20*, 887–94.

Hua, T., Kao, C., Sun, Q., Li, X., & Zhou, Y. (2008). Decreased proportion of GABA neurons accompanies age-related degradation of neuronal function in cat striate cortex. *Brain research bulletin*, *75*(1), 119–125. https://doi.org/10.1016/j.brainresbull.2007.08.001.

Huang, L., & Dobkins, K. R. (2005). Attentional effects on contrast discrimination in humans: Evidence for both contrast gain and response gain. *Vision Research*, *45*(9), 1201–1212. https://doi.org/10.1016/j.visres.2004.10.024.

Hubel, D.H. & Wiesel, T.N. (1970). Period of susceptibility to physiological effects of unilateral eye closure in kittens. *Journal of Physiology-London, 206*, 419–436.

Hung, S. C., & Seitz, A. R. (2014). Prolonged training at threshold promotes robust retinotopic specificity in perceptual learning. *Journal of Neuroscience*, *34*(25), 8423-8431.

Iarocci, G., Enns, J. T., Randolph, B., & Burack, J. A. (2009). The modulation of visual orienting reflexes across the lifespan. *Developmental Science, 12*(5), 715–724. https://doi.org/10.1111/j.1467-7687.2009.00810.x.

Ito, M., Westheimer, G. & Gilbert, C. D. (1998). Attention and perceptual learning modulate con- textual influences on visual perception. *Neuron, 20*(6), 1191–1197, https://doi.org/S0896- 6273(00)80499-7.

Jeter, P. E., Dosher, B. A., Liu, S.-H., & Lu, Z.-L. (2010). Specificity of perceptual learning increases with increased training. *Vision Research*, *50*(19), 1928–1940. PubMed. https://doi.org/10.1016/j.visres.2010.06.016.

Jeter, P. E., Dosher, B. A., Petrov, A., & Lu, Z.-L. (2009). Task precision at transfer determines specificity of perceptual learning. *Journal of Vision*, *9*(3), 1–1. https://doi.org/10.1167/9.3.1.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In: Long, JB.; Baddeley, AD., editors. Attention & performance IX. Erlbaum; Hillsdale, NJ: 187-203.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, *43*(4), 346–354. https://doi.org/10.3758/bf03208805.

Kahneman, D. 1973. Attention and Effort. Englewood Cliffs, NJ: Prentice-Hall.

Kaiser, M. K., & Mowafy, L. (1993). Optical specification of time-to- passage: Observers' sensitivity to global tau. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1028-1040.

Karni, A., & Sagi, D. (1993). The time course of learning a visual skill. *Nature, 365*, 250–52.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Sciences of the United States of America*, *88*(11), 4966–4970. https://doi.org/10.1073/pnas.88.11.4966.

Koenderink, J. J. (1986). Optic flow. *Vision Research, 26*(1), 161–179.

Kramer A.F., Hahn S., Irwin D.E. & Theeuwes J. (1999). Attentional capture and aging: Implications for visual search performance and oculomotor control. Psychology and aging. 14, 135–154.

Kramer, A.F., Humphrey, D.G., Larish, J.F., Logan, G.D., & Strayer, D.L. (1994) Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychological Aging, 9,* 491–512.

Kramer, A.F., & Madden, D.J. (2008). Attention. In F.I.M. Craik & T.A. Salthouse (Eds.), *The handbook of aging and cognition* (3rd ed.). Mahwah, NJ: Erlbaum.

Kumar, T., & Glaser, D. A. (1993). Initial performance, learning and observer variability for hyperacuity tasks. *Vision research*, *33*(16), 2287–2300. https://doi.org/10.1016/0042-6989(93)90106-7.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 371-379.

Lam, L. T. (2002). Distractions and the risk of car crash injury: The effect of drivers' age. *Journal of Safety Research, 33*(3), 411–419. https://doi.org/10.1016/S0022-4375(02) 00034-8.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2017). Training to improve collision detection in older adults. *Driving Assessment Conference.* DOI: 10.17077/drivingassessment.1651.

Lemon, C.M., Deloss, D.J. & Andersen G.J. (2015). Collision detection in cluttered driving scenes. In: Proceedings of the Eighth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, June 22-25, 2015, Salt Lake City, Utah. Iowa City, IA: Public Policy Center, University of Iowa, 2015: 233-239. https://doi.org/10.17077/drivingassessment.1577.

Leventhal, A. G., Wang, Y., Pu, M., Zhou, Y., & Ma, M. (2003). GABA and its agonists improved visual cortical function in senescent monkeys. *Science, 300*, 812-815.

Levi, D. M., & Li, R. W. (2009). Improving the performance of the amblyopic visual system. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 364(*1515), 399–407.

Levi, D.M. (2005) Perceptual learning in adults with amblyopia: A reevaluation of critical periods in human vision. *Dev Psychobiol,46,* 222–232.

Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences of the United States of America, 93*(13), 6830–6834.

Li, W., Piëch, V., & Gilbert, C. D. (2004). Perceptual learning and top-down influences in primary visual cortex. *Nature Neuroscience*, *7*(6), 651–657. https://doi.org/10.1038/nn1255.

Lien, M. C., Gemperle, A., & Ruthruff, E. (2011). Aging and involuntary attention capture: electrophysiological evidence for preserved attentional control with advanced age. *Psychology and aging*, *26*(1), 188–202. https://doi.org/10.1037/a0021073.

Ling, S., & Carrasco, M. (2006). Sustained and transient covert attention enhance the signal via different contrast response functions. *Vision Research, 46*(8-9), 1210–1220. https://doi.org/10.1016/j.visres.2005.05.008.

Liu, Z. (1999). Perceptual learning in motion discrimination that generalizes across motion directions. *Proc. Natl. Acad. Sci.* USA, *96*, 14085–87.

Liu, J., Lu, Z.L., & Dosher, B.A. (2010). Augmented Hebbian reweighting: interactions between feedback and training accuracy in perceptual learning. *Journal of Vision, 10*, 29.

Liu, Z., & Weinshall, D. (2000). Mechanisms of generalization in perceptual learning. *Vision Research*, *40*(1), 97–109.

Lord, S. & Dayhew, J. (2001). Visual Risk Factors for Falls in Older People. Journal of the American Geriatrics Society. 49. 508-15. 10.1093/ageing/afl085.

Lord S.R., Dayhew J. & Howland A. (2002). Multifocal glasses impair edge-contrast sensitivity and depth perception and increase the risk of falls in older people. *J Am Geriatr Society* 50(11):1760–1766. doi:10.1046/j.1532-5415.2002.50502.x. [PubMed: 12410892].

Lu, Z.L. & Dosher, B.A. (2017). Visual perceptual learning and models. *Annual Review of Vision Science, 3*(1), 343-363.

Lu, Z. L., & Dosher, B. A. (2000). Spatial attention: Different mechanisms for central and peripheral temporal precues? *Journal of Experimental Psychology: Human Perception and Performance, 26*(5), 1534–1548.

Lu, Z.L., & Dosher, B.A. (1998) External noise distinguishes attention mechanisms. *Vision Research, 38*,1183–1198.

Ma, L., & Yan, X. (2014). Examining the nonparametric effect of drivers' age in rear-end accidents through an additive logistic regression model. A*ccident Analysis and Prevention, 67*, 129–136. https://doi.org/10.1016/j.aap.2014.02.021.

Madden, D. J. (2007). Aging and Visual Attention. *Current Directions in Psychological Science*, *16*(2), 70–74. PubMed. https://doi.org/10.1111/j.1467-8721.2007.00478.x.

Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., White, L. E., & Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging*, *28*(3), 459–476. https://doi.org/10.1016/j.neurobiolaging.2006.01.005.

Madden, D.J. & Whiting, W.L. (2004) Age-related changes in visual attention. In: Costa, PT.; Siegler, IC., editors. *Recent advances in psychology and aging*. Amsterdam: Elsevier, 41-88.

Maniglia, M., & Seitz, A. R. (2017). Towards a whole brain model of Perceptual Learning. *Current Opinion in Behavioral Sciences*, *20*, 47–55. https://doi.org/10.1016/j.cobeha.2017.10.004.

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology : CB*, *14*(9), 744–751. https://doi.org/10.1016/j.cub.2004.04.028.

Mayfrank, L., Kimmig, H., & Fischer, B. (1987). The role of attention in the preparation of visually guided saccadic eye movements in man. In J. K. O'Reganm & A. Levy-Schoen (Eds.), Eye movements: From physiology to cognition (pp. 37–45). NY: North-Holland.

McAndrews, C., Beyer, K., Guse, C. E., & Layde, P. (2013). Revisiting exposure: Fatal and non-fatal traffic injury risk across different populations of travelers in Wisconsin, 2001–2009. *Accident Analysis and Prevention, 60*, 103–112. https://doi.org/10.1016/j.aap.2013.08.005.

McDowd, J.M., & Craik, F.I.M. (1988) Effects of aging and task difficulty on divided attention performance. *J. Exp. Psychol. Hum. Percept. Perform*., *14*, 267–280.

Menz, H. B., Morris, M. E., & Lord, S. R. (2005). Foot and ankle characteristics associated with impaired balance and functional ability in older people. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *60*(12), 1546–1552. https://doi.org/10.1093/gerona/60.12.1546.

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review, 63*(2), 81–97. https://doi.org/10.1037/h0043158

Monsell S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134–140. https://doi.org/10.1016/s1364-6613(03)00028-7.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science (New York, N.Y.)*, *229*(4715), 782–784. https://doi.org/10.1126/science.4023713.

Mukai, I., Bahadur, K., Kesavabhotla, K., & Ungerleider, L. G. (2011). Exogenous and endogenous attention during perceptual learning differentially affect post-training target thresholds. *Journal of Vision*, *11*(1), 10.1167/11.1.25 25. PubMed. https://doi.org/10.1167/11.1.25.

Mukai, I., Kim, D., Fukunaga, M., Japee, S., Marrett, S., & Ungerleider, L. G. (2007). Activations in visual and attention-related areas predict and correlate with the degree of perceptual learning. *The Journal of Neuroscience*, 27, 11401–11411.

Muller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*(2), 315–330.

Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., & Goode, K. T. (2000). Relation of useful field of view and other screening tests to on-road driving performance. Perceptual and Motor Skills, 91, 279-290.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*(11), 1631–1647. https://doi.org/10.1016/0042-6989(89)90144-2.

Ni, R. & Andersen, G.J (2006). Age Related Performance in Driving: Steering and Collision Detection. *Vision in Vehicles 11*, Dublin, Ireland.

Ni, R., Bian, Z. & Andersen, G.J. (2009) Age-related differences in using optical flow and landmark information for steering control, *2009 IEEE Intelligent Vehicles Symposium*, Xi'an, 691-694, doi: 10.1109/IVS.2009.5164360.

Owsley, C. (2013). Visual processing speed. *Vision Research*, *90*, 52–56. https://doi.org/10.1016/j.visres.2012.11.014.

Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, *6*(3), 403–415. https://doi.org/10.1037//0882-7974.6.3.403.

Owsley, C. & Mcgwin, G. (2004). Association Between Visual Attention and Mobility in Older Adults. Journal of the American Geriatrics Society. 52. 1901-6. 10.1111/j.1532-5415.2004.52516.x.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision research*, *23*(7), 689–699. https://doi.org/10.1016/0042-6989(83)90210-9.

Peli, E. (1990). Contrast in complex images. *J. Opt. Soc. Am. A., 7*(10), 2032-2040.

Petrov, A.A., Dosher, B.A., & Lu, Z.L. (2005). The dynamics of perceptual learning: an incremental reweighting model. *Psychol. Rev., 112*, 715–43.

Plude, D. J., & Doussard-Roosevelt, J. A. (1989). Aging, selective attention, and feature integration. *Psychology and Aging, 4*(1), 98-105.

Polat, U. (2009) Making perceptual learning practical to improve visual functions. *Vision Research, 49*, 2566–2573.

Polat, U., Schor, C., Tong, J.-L., Zomet, A., Lev, M., Yehezkel, O., Sterkin, A. & Levi, D. M. (2012). Training the brain to overcome the effect of aging on the human eye. *Scientific Reports*, 2: 278.

Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences of the United States of America, 101*(17), 6692–6697.

Poggio, T., Fahle, M., & Edelman, S. (1992) Fast perceptual learning in visual hyperacuity. *Science. 256*, 1018–1021.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3−25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. Bonwhuis (Eds.), *Attention and performance X: Control of language processes*, 551–556. Hillsdale, NJ: Erlbaum.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Pierce, R.S. & Andersen, G.J. (2014) The effects of age and workload on 3D spatial attention in dual-task driving, *Accident Analysis and Prevention, 67*, 96–104.

R Foundation for Statistical Computing (2020). R: A language and environment for statistical computing. Vienna, Austria.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., & Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex (New York, N.Y. : 1991)*, *15*(11), 1676–1689. https://doi.org/10.1093/cercor/bhi044.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron, 61*(2), 168–185. https://doi.org/10.1016/j.neuron.2009.01.002.

Reuter-Lorenz, P. A., & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral precues. *Perception & Psychophysics, 52*(3), 336–344. https://doi.org/10.3758/BF03209150.

Richards, O, W. (1977). Effects of luminance and contrast on visual acuity, ages 16 to 90 years. *American Journal of Optometry and Physiological Optics, 54,* 178-184.

Richards E, Bennett P., & Sekuler A. (2006) Age related differences in learning with the useful field of view. *Vision Research, 46* (25), 4217–4231. doi:10.1016/j.visres.2006.08.011.

Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V.G., & Edwards, J, D. (2003). Speed-of- processing and driving simulator training result in improved driving performance. Human factors, 45(2), 218-233.

Rohenkohl, G., Coull, J. T., & Nobre, A. C. (2011). Behavioural Dissociation between Exogenous and Endogenous Temporal Orienting of Attention. *PLOS ONE*, *6*(1), e14620. https://doi.org/10.1371/journal.pone.0014620.

Rosen, A. C., Rao, S. M., Caffarra, P., Scaglioni, A., Bobholz, J. A., Woodley, S. J., Hammeke, T. A., Cunningham, J. M., Prieto, T. E., & Binder, J. R. (1999). Neural basis of endogenous and exogenous spatial orienting. A functional MRI study. *Journal of Cognitive Neuroscience*, *11*(2), 135–152. https://doi.org/10.1162/089892999563283.

Roudaia, E., Bennett, P. J., & Sekuler, A. B. (2008). The effect of aging on contour integration. *Vision research*, *48*(28), 2767–2774. https://doi.org/10.1016/j.visres.2008.07.026.

Sagi, D., & Tanne, D. (1994). Perceptual learning: Learning to see. *Current Opinion in Neurobiology*, *4*(2), 195–199. https://doi.org/10.1016/0959-4388(94)90072-8.

Salat, D. H., Tuch, D. S., Hevelone, N. D., Fischl, B., Corkin, S., Rosas, H. D., & Dale, A. M. (2005). Age-related changes in prefrontal white matter measured by diffusion tensor imaging. *Annals of the New York Academy of Sciences*, *1064*, 37–49. https://doi.org/10.1196/annals.1340.009.

Salthouse, T.A. (1996). The processing-speed theory of adult age differences in cognition*. Psychol. Rev. 103*, 403–428.

Salthouse, T. A. (1991). *Theoretical perspectives on cognitive aging.* Lawrence Erlbaum Associates, Inc.

Salthouse, T.A., Fristoe, N.M., Lineweaver, T.T., & Coon, V.E. (1995) Aging of attention: Does the ability to divide decline*? Mem. Cognit., 23*, 59–71.

Sanders, M. S., & McCormick, E. J. (1993). *Human factors in engineering and design* (7th ed.). Mcgraw-Hill Book Company.

Schiff, W., Oldak, R., & Shah, V. (1992). Aging persons' estimates of vehicular motion. *Psychology and Aging, 7*(4), 518–525. https://doi.org/10.1037/0882 7974.7.4.518.

Schmolesky, M. T., Wang, Y., Pu, M., & Leventhal, A. G. (2000). Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, *3*(4), 384–390. https://doi.org/10.1038/73957.

Schoups A.A., Vogels, R. & Orban, G.A. (1995). Human perceptual learning in identifying the oblique orientation: retinotopy, orientation specificity and monocularity. *Journal of Physiology, 483,* 797– 810.

Schoups, A., Vogels, R., Qian, N., & Orban, G. (2001). Practising orientation identification improves orientation coding in V1 neurons. *Nature*, *412*(6846), 549–553. https://doi.org/10.1038/35087601.

Scialfa, C. T., Kline, D. W., & Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging*, *2*(1), 14–19. https://doi.org/10.1037//0882-7974.2.1.14.

Seitz, A. R., & Watanabe, T. (2009). The phenomenon of task-irrelevant perceptual learning. *Vision Research, 49*, 2604–2610.

Seitz, A., & Watanabe, T. (2005). A unified model for perceptual learning. *Trends Cogn. Sci.* 9:329–34.

Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America. A, Optics and image science*, *3*(6), 864–867. https://doi.org/10.1364/josaa.3.000864.

Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research*, *26*(2), 103–120. https://doi.org/10.1080/036107300243588.

Sekuler, R., Owsley, C., & Hutman, L. (1982). Assessing spatial vision of older people. *American Journal of Optometry and Physiological Optics*, *59*(12), 961–968. https://doi.org/10.1097/00006324-198212000-00005.

Shibata, K., Sasaki, Y., Kawato, M., & Watanabe, T. (2016) Neuroimaging evidence for two types of plasticity in association with visual perceptual learning. *Cerebral Cortex*, 26 (9): 3681-3689.

Shibata, K., Sagi, D., & Watanabe, T. (2014) Two stage model of perceptual learning, *the Year in Cognitive Neuroscience, Annual Review of New York Academy of Sciences, 1316*, 18-28.

Shibata, K., Watanabe, T., Sasaki, Y. & Kawato, M.(2011) Perceptual learning incepted by decoded fMRI neurofeedback without stimulus presentation. *Science*, *334*(6061), 1413-1415.

Shibata, K., Yamagishi, N., Ishii, S., & Kawato, M. (2009). Boosting perceptual learning by fake feedback. *Vision Research, 49*, 2574–2585.

Shiu, L., Pashler, H. (1992) Improvement in line orientation discrimination is retinally local but dependent on cognitive set. *Perception & Psychophysics 52***,** 582–588. https://doi.org/10.3758/BF03206720.

Sigman, M., Pan, H., Yang, Y., Stern, E., Silbersweig, D., & Gilbert, C. D. (2005). Top-down reorganization of activity in the visual pathway after learning a shape identification task. *Neuron*, *46*(5), 823–835. https://doi.org/10.1016/j.neuron.2005.05.014.

Sims, R. V, McGwin Jr, G., Allman, R. M., Ball, K. K., & Owsley, C. (2000). Exploratory study of incident vehicle crashes among older drivers. *Journal of Gerontology, 55*(1), M22–M27. doi:10.1093/gerona/55.1.M22.

Sims R.V., Owsley C., Allman R.M., Ball K. & Smoot T.M. (1998) A preliminary assessment of the medical and functional factors associated with vehicle crashes in older adults. *Journal of the American Geriatrics Society, 46*, 556–561. [PubMed: 9588367].

Sireteanu, R., & Rettenbach, R. (2000). Perceptual learning in visual search generalizes over tasks, locations, and eyes. *Vision Research*, 40(21), 2925-2949.

Sireteanu, R., & Rettenbach, R. (1995). Perceptual learning in visual search: Fast, enduring, but non-specific. Vision Research, 35, 2037–2043.

Sokal, R. R., & Rohlf, J. F. (1981). Biometry: The principles and practice of statistics in biological research (2nd ed.). San Francisco: W.H. Freeman.

Son, J. & Suh, J. (2011) Design considerations for the older population: A human-vehicle interface perspective. SHUSER 2011 - 2011 International Symposium on Humanities, Science and Engineering Research. 10.1109/SHUSER.2011.6008506.

Sowden, P.T., Davies, I.R.L., & Roling, P. (2000). Perceptual learning of the detection of features in X-ray images: A functional role for improvements in adults' visual sensitivity? *Journal of Experimental Psychology: Human Perception and Performance, 26*(1), 379-390.

Spieler, DH., Balota, D.A., & Faust, M.E. (1996) Stroop performance in healthy younger and older adults and in Individuals with dementia of the alzheimer's type. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 461-479.

Stalvey, B.T., Owsley, C., Sloane, M.E., & Ball, K. (1999). The life space questionnaire: A measure of the extent of mobility of older adults. *Journal of Applied Gerontology*, *18(4)*, 460-478.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*. *18*(6): 643–662.

Suzuki, S., & Cavanagh, P. (1997). Focused attention distorts visual space: An attentional repulsion effect. *Journal of Experimental Psychology: Human Perception and Performance, 23*(2), 443–463.

Szpiro, S. F., & Carrasco, M. (2015). Exogenous Attention Enables Perceptual Learning. *Psychological science*, *26*(12), 1854–1862. https://doi.org/10.1177/0956797615598976.

Tartaglia, E. M., Bamert, L., Mast, F. W., & Herzog, M. H. (2009). Human perceptual learning by mental imagery. *Current Biology : CB*, *19*(24), 2081–2085. https://doi.org/10.1016/j.cub.2009.10.060.

Tefft, B. C. (2008). Risks older drivers pose to themselves and to other road users. *Journal of Safety Research, 39*(6), 577–82. doi:10.1016/j.jsr.2008.10.002.

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135*(2), 77–99. https://doi.org/10.1016/j.actpsy.2010.02.006.

Treisman, A. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.

Tsushima, Y., Seitz, A. R., & Watanabe, T. (2008). Task-irrelevant learning occurs only when the irrelevant feature is weak. *Current Biology : CB*, *18*(12), R516–R517. PubMed. https://doi.org/10.1016/j.cub.2008.04.029.

Tsushima, Y., & Watanabe, T. (2009). Roles of attention in perceptual learning from perspectives of psychophysics and animal learning. *Learning & Behavior*, *37*(2), 126–132. https://doi.org/10.3758/LB.37.2.126.

US Census (2014), https://www.census.gov/newsroom/press-releases/2014/cb14-84.html.

Vogels, R. & Orban, G. A. (1985). The effect of practice on the oblique effect in line orientation of perceptual learning across retinal locations enabled by double training. *Current biology, 18,* 1922–6.

Wahl H.W., Schilling O., Oswald F., & Heyl V. (1999) Psychosocial consequences of age-related visual impairment: comparison with mobility-impaired older adults and long-term outcome. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 54*(5): P304–316.

Wang R., Zhang J. Y., Klein S. A., Levi D. M., Yu C. (2014). Vernier perceptual learning transfers to completely untrained retinal locations after double training: A "piggybacking" effect. *Journal of Vision*, 14 (13): 12, 1–12, doi:10.1167/14.13.12.

Wang, R., Zhang, J. Y., Klein, S. A., Levi, D. M., & Yu C. (2012). Task relevancy and demand modulate double-training enabled transfer of perceptual learning. *Vision Research*, *61,* 33–38.

Wasylyshyn, C., Verhaeghen, P., & Sliwinski, M. J. (2011). Aging and task switching: a meta-analysis. *Psychology and aging*, *26*(1), 15–20. https://doi.org/10.1037/a0020912.

Watson, A. A. B., & Pelli, D. G. D. (1983). QUEST: A Bayesian adaptive psychometric method. *Attention, Perception, & Psychophysics, 33*(2), 113–120.

Watanabe, T., Nanez, J.E., & Sasaki, Y. (2001). Perceptual learning without perception. *Nature, 413*, 844–48.

Watanabe, T., & Sasaki, Y. (2015). Perceptual learning: toward a comprehensive theory. *Annual review of psychology*, *66*, 197–221. https://doi.org/10.1146/annurev-psych-010814-015214.

Watson, A. A. B., & Pelli, D. G. D. (1983). QUEST: A Bayesian adaptive psychometric method. Attention, *Perception, & Psychophysics, 33*(2), 113–120.

Wechsler, D. (1997). *WAIS-III Administration and scoring manual*. San Antonio, TX: The Psychological Association.

White, A. L., Lunau, R., & Carrasco, M. (2014). The attentional effects of single cues and color singletons on visual sensitivity. *Journal of Experimental Psychology: Human Perception and Performance, 40*(2), 639–652, https://doi.org/10.1037/a0033775.

Whiting, W.L., Madden, D.J., Pierce, T.W. & Allen, P.A. (2005). Searching from the top down: Ageing and attentional guidance during singleton detection. *Quarterly Journal Experimental Psychology A, 58*(1), 72–97.

Williams, A., & Carsten, O. (1989). Driver age and crash involvement. *American Journal of Public Health, 79*(3), 326–327.

Williams, A. F., & Shabanova, V. I. (2003). Responsibility of drivers, by age and gender, for motor-vehicle crash deaths. *Journal of Safety Research, 34*(5), 527–531. https://doi.org/10.1016/j.jsr.2003.03.001.

World Health Organization (2015). Global status report on road safety 2015. https://www.who.int/violence_injury_prevention/road_safety_status/2015/en/.

Xiao, L. Q., Zhang, J. Y., Wang, R., Klein, S. A., Levi, D. M., & Yu, C. (2008). Complete transfer of perceptual learning across retinal locations enabled by double training. *Current biology: CB*, *18*(24), 1922–1926. https://doi.org/10.1016/j.cub.2008.10.030.

Xu, J. P., He, Z. J., & Ooi, T. L. (2012). Perceptual learning to reduce sensory eye dominance beyond the focus of top-down visual attention. *Perceptual Learning - Mechanisms and Manifestations*, *61*, 39–47. https://doi.org/10.1016/j.visres.2011.05.013.

Xu, J. P., He, Z. J., & Ooi, T. L. (2010). Effectively Reducing Sensory Eye Dominance with a Push-Pull Perceptual Learning Protocol. *Current Biology*, *20*(20), 1864–1868. https://doi.org/10.1016/j.cub.2010.09.043.

Yan, F.F., Zhou, J., Zhao, W., Li, M., Xi, J., Lu Z.L. & Huang C.B. (2015). Perceptual learning improves neural processing in myopic vision. *Journal of Vision, 15*(10):12, 1-14.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 676−681.

Yantis, S., & Hillstrom, A. P. (1994). Stimulus-driven attentional capture: Evidence from equiluminant visual objects. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 95−107.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 121−134.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10*(5):601-21.

Yehezkel, O., Sterkin, A., Lev, M., Levi, D. M., & Polat, U. (2016). Gains following perceptual learning are closely linked to the initial visual acuity. *Scientific Reports*, 6, 25188.

Yeshurun, Y., Montagna, B., & Carrasco, M. (2008). On the flexibility of sustained attention and its effects on a texture segmentation task. *Vision Research, 48*(1), 80–95.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution, *Nature, 396* (6706), 72–75.

Yotsumoto Y., Chang L., Ni R., Pierce R., Andersen G.J., Watanabe T., Sasaki Y. (2014) White matter in the older brain is more plastic than in the younger brain. *Nature Comm.*

Yotsumoto, Y. & Watanabe, T. (2008). Defining a link between perceptual learning and Attention. *PLoS Biology,* 6(8), e221.

Yotsumoto Y., Watanabe T., & Sasaki Y. (2008) Different dynamics of performance and brain activation in the time course of perceptual learning. *Neuron*, 57, 827–33.

Yu C., Klein S.A., Levi D.M. (2004) Perceptual learning in contrast discrimination and the (minimal) role of context. *J. Vis. 4*:169–182.

Zanto T.P. & Gazzaley A. (2014) Attention and ageing. In: Nobre AC, Kastner S, editors. The Oxford Handbook of Attention. Oxford University Press, 927–971.

Zhang J. Y., Cong L. J., Klein S. A., Levi D. M., & Yu C. (2014). Perceptual learning improves adult amblyopic vision through rule-based cognitive compensation. *Investigative Ophthalmology & Visual Science*, 55 (4), 2020–2030.

Zhang J. Y. & Yang Y. X. (2014). Perception learning of motion direction discrimination transfers to an opposite direction with TPE training. *Vision Research*, *99*, 93–98.

Zhang, T., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Decoupling location specificity from perceptual learning of orientation discrimination. *Vision Research, 50*(4), 368–374, https://doi.org/10. 1016/j.visres.2009.08.024.

Zhang, J. Y., Zhang, G. L., Xiao, L. Q., Klein, S. A., Levi, D. M., & Yu, C. (2010). Rule-based learning explains visual perceptual learning and its specificity and transfer. *The Journal of neuroscience: the official journal of the Society for Neuroscience*, *30*(37), 12323–12328. https://doi.org/10.1523/JNEUROSCI.0704-10.2010.

Appendix A

Demographics	N	Mean	SD
Age (years)	60	19.9833	2.3542
Far Acuity LogMAR [Left Eye]	60	0.0597	0.1187
Far Acuity LogMAR [Right Eye]	60	0.0610	0.1144
Far Acuity LogMAR [Both Eyes]	60	-0.0027	0.0927
Near Acuity LogMAR [Left Eye]	60	0.0087	0.1027
Near Acuity LogMAR [Right Eye]	60	0.0083	0.1126
Near Acuity LogMAR [Both Eyes]	60	-0.0483	0.0846
Contrast Sensitivity [Left Eye]	60	1.2725	0.1014
Contrast Sensitivity [Right Eye]	60	1.2675	0.1049
Contrast Sensitivity [Both Eyes]	60	1.4025	0.0950

Attention group	Contrast Thresholds											
	Trained Orientation						**Untrained Orientation**					
	Pre-Test Threshold			**Post-Test Threshold**			**Pre-Test Threshold**			**Post-Test Threshold**		
	n	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Exogenous Attention	**30**	**.3002**	**.1128**	**30**	**.1841**	**.0565**	**30**	**.2733**	**.1243**	**30**	**.1997**	**.0767**
100% cue-validity	10	.3263	.1143	10	.1781	.0567	10	.2996	.1313	10	.2054	.0828
80% cue-validity	10	.2745	.9368	10	.1787	.0559	10	.2391	.0713	10	.2225	.0825
Neutral cue-validity	10	.2999	.1331	10	.1954	.0612	10	.2812	.1592	10	.1712	.0617
Endogenous Attention	**30**	**.2837**	**.1269**	**30**	**.1673**	**.0601**	**30**	**.2492**	**.1137**	**30**	**.1788**	**.0470**
100% cue-validity	10	.2700	.1210	10	.1767	.0746	10	.2508	.1375	10	.1733	.0351
80% cue-validity	10	.2587	.1189	10	.1673	.0664	10	.2149	.0594	10	.1814	.0520
Neutral cue-validity	10	.3225	.1434	10	.1579	.0382	10	.2820	.1294	10	.1817	.0559

Magnitude of Learning						
Attention group	**Trained Orientation**			**Untrained Orientation**		
	n	**Mean**	**SD**	**n**	**Mean**	**SD**
Exogenous Attention	**30**	**-.3537**	**.1687**	**30**	**-.1934**	**.3385**
100% cue-validity	10	-.4270	.1498	10	-.2346	.3936
80% cue-validity	10	-.3231	.1879	10	-.0361	.3319
Neutral cue-validity	10	-.3109	.1580	10	-.3095	.2447
Endogenous Attention	**30**	**-.3531**	**.1997**	**30**	**-.2087**	**.2700**
100% cue-validity	10	-.3326	.1350	10	-.1968	.3419
80% cue-validity	10	-.2814	.2338	10	-.1455	.1607
Neutral cue-validity	10	-.4399	.2025	10	-.2839	.2851

Correct Response Times (RT)												
	Trained Orientation						**Untrained Orientation**					
Attention group	**Pre-Test**			**Post-Test**			**Pre-Test**			**Post-Test**		
	n	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Exogenous Attention	**30**	**.7278**	**.1782**	**30**	**.5975**	**.0861**	**30**	**.7281**	**.2783**	**30**	**.6055**	**.1026**
100% cue-validity	10	.7412	.1380	10	.6153	.0828	10	.7176	.1457	10	.6175	.0872
80% cue-validity	10	.7274	.2417	10	.581	.0938	10	.7878	.4505	10	.5843	.1215
Neutral cue-validity	10	.7148	.1565	10	.5960	.0870	10	.6789	.1363	10	.6147	.1037
Endogenous Attention	**30**	**.8308**	**.8431**	**30**	**.5772**	**.0960**	**30**	**.6935**	**.1651**	**30**	**.5734**	**.0715**
100% cue-validity	10	.6733	.1121	10	.5569	.0909	10	.6829	.0968	10	.5801	.0751
80% cue-validity	10	.7141	.2088	10	.5968	.1122	10	.7450	.2362	10	.5696	.0710
Neutral cue-validity	10	1.1050	1.4519	10	.5781	.0893	10	.6526	.1330	10	.5705	.0757

Attention group	d' (sensitivity)											
	Trained Orientation						**Untrained Orientation**					
	Pre-Test			**Post-Test**			**Pre-Test**			**Post-Test**		
	n	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Exogenous Attention	**30**	**1.6086**	**.4934**	**30**	**1.7125**	**.5944**	**30**	**1.5436**	**.5427**	**30**	**1.5327**	**.6410**
100% cue-validity	10	1.5450	.3361	10	1.8876	.7008	10	1.6488	.3951	10	1.8009	.5800
80% cue-validity	10	1.4993	.4549	10	1.6938	.5162	10	1.3025	.5887	10	1.4632	.7149
Neutral cue-validity	10	1.7815	.6431	10	1.5561	.5650	10	1.6796	.5909	10	1.3340	.5895
Endogenous Attention	**30**	**1.8036**	**.5433**	**30**	**1.7591**	**.5242**	**30**	**1.6289**	**.5149**	**30**	**1.6747**	**.5436**
100% cue-validity	10	1.8950	.6318	10	1.7655	.5352	10	1.8498	.4222	10	1.8538	.6896
80% cue-validity	10	1.7130	.4318	10	1.8379	.5912	10	1.5361	.4949	10	1.7115	.3710
Neutral cue-validity	10	1.8027	.5890	10	1.6740	0.4841	10	1.5009	.5909	10	1.4589	.5002

Training Sessions: Contrast Thresholds						
	Attention group					
	Exogenous attention			Endogenous attention		
Training Day	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Day 1						
block 1	30	.2351	.1005	30	.2238	.0961
block 2	30	.233	.0751	30	.1943	.0587
block 3	30	.2272	.0651	30	.1919	.0606
block 4	30	.2211	.0606	30	.1895	.0681
block 5	30	.2181	.0557	30	.1847	.0660
block 6	30	.2159	.0567	30	.1811	.0640
Day 2						
block 1	30	.1909	.0790	30	.1671	.0664
block 2	30	.1801	.0648	30	.1485	.0598
block 3	30	.1792	.0605	30	.1462	.0554
block 4	30	.1751	.0541	30	.1439	.0546
block 5	30	.1728	.0531	30	.1422	.0529
block 6	30	.1710	.0523	30	.1416	.0531
100 % cue-validity condition						
Day 1						
block 1	10	.2329	.0378	10	.1969	.0940
block 2	10	.2380	.0747	10	.1792	.0564
block 3	10	.2389	.0624	10	.1735	.0589
block 4	10	.2286	.0572	10	.1721	.0671
block 5	10	.2211	.0531	10	.1680	.0623
block 6	10	.2171	.0489	10	.1679	.0600
Day 2						
block 1	10	.1903	.1050	10	.1673	.0785
block 2	10	.1805	.0740	10	.1437	.0607
block 3	10	.1877	.0671	10	.1381	.0513
block 4	10	.1791	.0605	10	.1342	.0526
block 5	10	.1742	.0572	10	.1359	.0549
block 6	10	.1745	.0598	10	.1382	.0604
80 % cue-validity condition						
Day 1						
block 1	10	.2129	.0444	10	.2268	.1015
block 2	10	.2126	.0518	10	.2035	.0696
block 3	10	.2112	.0596	10	.2058	.0769
block 4	10	.2086	.0588	10	.2060	.0895
block 5	10	.2114	.0554	10	.2013	.0903
block 6	10	.2052	.0548	10	.1948	.0844

Day 2						
block 1	10	.1707	.0285	10	.1751	.0660
block 2	10	.1607	.0383	10	.1583	.0746
block 3	10	.1595	.0377	10	.1604	.0733
block 4	10	.1572	.0411	10	.1599	.0714
block 5	10	.1579	.0460	10	.1573	.0655
block 6	10	.1570	.0441	10	.1533	.0624
Neutral cue-validity condition						
Day 1						
block 1	10	.2596	.1672	10	.2477	.0956
block 2	10	.2508	.0953	10	.2003	.0518
block 3	10	.2316	.0759	10	.1963	.0429
block 4	10	.2262	.0695	10	.1905	.0422
block 5	10	.2217	.0637	10	.1847	.0374
block 6	10	.2253	.0688	10	.1807	.0456
Day 2						
block 1	10	.2117	.0856	10	.1589	.0595
block 2	10	.1991	.0759	10	.1434	.0460
block 3	10	.1914	.0721	10	.1402	.0392
block 4	10	.1891	.0592	10	.1375	.0364
block 5	10	.1863	.0569	10	.1336	.0363
block 6	10	.1813	.0542	10	.1333	.0361

Appendix B

Demographics for Younger Adults

Younger Adults	Mean	SD
Age (years)	20.3750	1.2091

Visual Assessments for Younger Adults

Younger Adults	Mean	SD
Far Acuity: Left Eye (LogMAR)	0.0908	0.1244
Far Acuity: Right Eye (LogMAR)	0.1025	0.1309
Far Acuity: Both Eyes (LogMAR)	-0.0125	0.1030
Near Acuity: Left Eye (LogMAR)	-0.0342	0.0818
Near Acuity: Right Eye (LogMAR)	-0.0308	0.0748
Near Acuity: Both Eyes (LogMAR)	-0.0783	0.0757
Contrast Sensitivity: Left Eye	1.27	0.1124
Contrast Sensitivity: Right Eye	1.26	0.1120
Contrast Sensitivity: Both Eyes	1.37	0.0604

Overall Accuracy for Younger Adults

Younger Adults			Mean	SD
Overall Accuracy				
Trained Location				
	Pre-Test		**72.6042**	**6.3153**
		Attention Cue	74.2448	5.3986
		Neutral Cue	70.9635	6.9552
	Post-Test		**79.7396**	**7.4811**
		Attention Cue	79.9740	7.1404
		Neutral Cue	79.5052	8.1189
Untrained Location				
	Pre-Test		**70.7031**	**6.1922**
		Attention Cue	72.3177	5.9524
		Neutral Cue	69.0885	6.2492
	Post-Test		**75.4557**	**8.4604**
		Attention Cue	75.4427	8.9511
		Neutral Cue	75.4688	8.3391

Magnitude Overall Accuracy for Younger Adults

Younger Adults			Mean	SD
Magnitude Overall Accuracy				
	Trained Location		**0.1003**	**0.0801**
		Attention Cue	0.0779	0.0754
		Neutral Cue	0.1226	0.0814
	Trained Location		**0.0678**	**0.0835**
		Attention Cue	0.0429	0.0892
		Neutral Cue	0.0927	0.0726

Correct Response Times (RT) for Younger Adults

Younger Adults			Mean	SD
Correct RT				
Trained Location				
	Pre-Test		**0.2700**	**0.1128**
		Attention Cue	0.2484	0.0697
		Neutral Cue	0.2917	0.1439
	Post-Test		**0.1698**	**0.0393**
		Attention Cue	0.1632	0.0329
		Neutral Cue	0.1764	0.0453
Untrained Location				
	Pre-Test		**0.2741**	**0.1116**
		Attention Cue	0.2501	0.0602
		Neutral Cue	0.2981	0.1455
	Post-Test		**0.1863**	**0.0601**
		Attention Cue	0.1695	0.0403
		Neutral Cue	0.2031	0.0729

d’ (sensitivity) for Younger Adults

Younger Adults			Mean	SD
d' (sensitivity)				
Trained Location				
	Pre-Test		**0.8846**	**0.2787**
		Attention Cue	0.9606	0.2593
		Neutral Cue	0.8086	0.2873
	Post-Test		**1.2490**	**0.3944**
		Attention Cue	1.2722	0.3703
		Neutral Cue	1.2258	0.4323
Untrained Location				
	Pre-Test		**0.8115**	**0.2718**
		Attention Cue	0.8733	0.2555
		Neutral Cue	0.7496	0.2843
	Post-Test		**1.0582**	**0.4186**
		Attention Cue	1.0515	0.4249
		Neutral Cue	1.0649	0.4310

Psychometric Function for Younger Adults

Younger Adults			Mean	SD
Psychometric Function				
Pre-Test (Trained Location)				
	Contrast 2%		**20.7917**	**2.4844**
		Attention Cue	21.6667	2.7414
		Neutral Cue	19.9167	1.9287
	Contrast 4%		**22.5000**	**4.1284**
		Attention Cue	21.5000	3.4245
		Neutral Cue	23.5000	4.6613
	Contrast 8%		**28.2917**	**4.3984**
		Attention Cue	29.5000	3.4510
		Neutral Cue	27.0833	5.0355
	Contrast 12%		**29.5000**	**4.4331**
		Attention Cue	31.4167	3.3967
		Neutral Cue	27.5833	4.6409
	Contrast 16%		**32.0000**	**3.1623**
		Attention Cue	32.9167	3.0588
		Neutral Cue	31.0833	3.1176
	Contrast 24%		**31.6667**	**4.0611**
		Attention Cue	32.3333	4.1414
		Neutral Cue	31.0000	4.0452
	Contrast 32%		**33.3750**	**4.6514**
		Attention Cue	33.5000	3.3710
		Neutral Cue	33.2500	5.8173
	Contrast 64%		**34.2083**	**3.0357**
		Attention Cue	34.7500	2.8959
		Neutral Cue	33.6667	3.2004
Post-Test (Trained Location)				
	Contrast 2%		**21.0417**	**3.2233**
		Attention Cue	21.1667	3.0401
		Neutral Cue	20.9167	3.5280

Contrast 4%		**24.8333**	**4.2290**
	Attention Cue	23.6667	4.1414
	Neutral Cue	26.0000	4.1560
Contrast 8%		**30.2917**	**4.9209**
	Attention Cue	30.0000	4.0000
	Neutral Cue	30.5833	5.8692
Contrast 12%		**34.0000**	**4.0860**
	Attention Cue	34.5833	4.0555
	Neutral Cue	33.4167	4.2095
Contrast 16%		**34.7083**	**4.4671**
	Attention Cue	35.5000	3.5032
	Neutral Cue	33.9167	5.2994
Contrast 24%		**35.9167**	**3.9882**
	Attention Cue	36.0000	4.2853
	Neutral Cue	35.8333	3.8573
Contrast 32%		**37.0000**	**3.2571**
	Attention Cue	37.5833	3.4761
	Neutral Cue	36.4167	3.0588
Contrast 64%		**37.3750**	**3.3338**
	Attention Cue	37.4167	3.6045
	Neutral Cue	37.3333	3.2004
Pre-Test (Untrained Location)			
Contrast 2%		**20.4583**	**3.2434**
	Attention Cue	20.3333	2.6054
	Neutral Cue	20.5833	3.8954
Contrast 4%		**22.2500**	**3.8022**
	Attention Cue	22.2500	2.4909
	Neutral Cue	22.2500	4.9013
Contrast 8%		**27.5833**	**4.6711**
	Attention Cue	28.1667	4.4279
	Neutral Cue	27.0000	5.0272
Contrast 12%		**28.5000**	**4.6718**
	Attention Cue	30.0000	3.9312
	Neutral Cue	27.0000	5.0272

Contrast 16%		**30.4167**	**3.8552**
	Attention Cue	31.8333	3.5119
	Neutral Cue	29.0000	3.7899
Contrast 24%		**31.3333**	**3.6673**
	Attention Cue	32.0833	3.7040
	Neutral Cue	30.5833	3.6296
Contrast 32%		**32.3750**	**3.7742**
	Attention Cue	33.0833	3.9187
	Neutral Cue	31.6667	3.6515
Contrast 64%		**33.3333**	**3.3579**
	Attention Cue	33.6667	3.3121
	Neutral Cue	33.0000	3.5162
Post-Test (Untrained Location)			
Contrast 2%		**19.4583**	**3.2165**
	Attention Cue	19.1667	3.2983
	Neutral Cue	19.7500	3.2509
Contrast 4%		**24.3333**	**4.9137**
	Attention Cue	22.2500	4.4133
	Neutral Cue	26.4167	4.6409
Contrast 8%		**30.2500**	**4.9541**
	Attention Cue	31.4167	3.6794
	Neutral Cue	29.0833	5.9001
Contrast 12%		**31.8750**	**4.7210**
	Attention Cue	32.4167	5.1250
	Neutral Cue	31.3333	4.4381
Contrast 16%		**32.3333**	**4.4980**
	Attention Cue	32.8333	4.1084
	Neutral Cue	31.8333	4.9879
Contrast 24%		**33.2083**	**5.3241**
	Attention Cue	33.1667	6.1472
	Neutral Cue	33.2500	4.6344
Contrast 32%		**34.5833**	**3.4631**
	Attention Cue	34.5833	3.9187
	Neutral Cue	34.5833	3.1176

Contrast 64%	**35.4167**	**3.3869**
Attention Cue	35.5833	3.4761
Neutral Cue	35.2500	3.4411

Contrast Threshold (α) for Younger Adults

Younger Adults			Mean	SD
Contrast Threshold [α]%				
	Trained Location			
	Pre-Test		**20.1667**	**15.7139**
		Attention Cue	21.0000	16.2816
		Neutral Cue	19.3333	15.8018
	Post-Test		**14.0833**	**12.8331**
		Attention Cue	13.0000	8.0227
		Neutral Cue	15.1667	16.6561
	Untrained Location			
	Pre-Test		**21.1667**	**13.6148**
		Attention Cue	19.6667	8.9375
		Neutral Cue	22.6667	17.4008
	Post-Test		**18.0000**	**16.0867**
		Attention Cue	13.0000	4.8617
		Neutral Cue	23.0000	21.5153

Asymptote for Younger Adults

Younger Adults			Mean	SD
Asymptote				
Trained Location				
	Pre-Test		**1.2625**	**0.1338**
		Attention Cue	1.2881	0.1498
		Neutral Cue	1.2370	0.1165
	Post-Test		**1.4127**	**0.1576**
		Attention Cue	1.4178	0.1746
		Neutral Cue	1.4077	0.1462
Untrained Location				
	Pre-Test		**1.2303**	**0.1333**
		Attention Cue	1.2435	0.1430
		Neutral Cue	1.2170	0.1278
	Post-Test		**1.2933**	**0.1429**
		Attention Cue	1.2928	0.1377
		Neutral Cue	1.2938	0.1542

Useful Field of View (UFOV) for Younger Adults

Younger Adults			Mean	SD
UFOV				
Processing Speed				
	Pre-Test		**17.6667**	**3.2660**
		Attention Cue	17.0000	0.0000
		Neutral Cue	18.3333	4.6188
	Post-Test		**18.0833**	**4.7081**
		Attention Cue	17.2500	0.8660
		Neutral Cue	18.9167	6.6395
Divided Attention				
	Pre-Test		**31.2083**	**32.2018**
		Attention Cue	23.2500	19.8363
		Neutral Cue	39.1667	40.4539
	Post-Test		**21.7917**	**13.4034**
		Attention Cue	18.8333	4.6090
		Neutral Cue	24.7500	18.3111
Selective Attention				
	Pre-Test		**57.1250**	**32.4845**
		Attention Cue	55.6667	22.8048
		Neutral Cue	58.5833	41.0088
	Post-Test		**61.3750**	**43.1386**
		Attention Cue	52.1667	24.6312
		Neutral Cue	70.5833	55.6719

Training Sessions: Overall Accuracy for Younger Adults

Younger Adults		Mean	SD
Overall Accuracy (Training Sessions)			
Day 2: 1st Session		**76.4844**	**7.3717**
	Attention Cue	78.0208	7.6539
	Neutral Cue	74.9479	7.0633
Day 2: 2nd Session		**76.4323**	**9.2381**
	Attention Cue	77.7604	9.9981
	Neutral Cue	75.1042	8.6390
Day 2: 3rd Session		**77.0052**	**8.8138**
	Attention Cue	76.6667	9.6027
	Neutral Cue	77.3438	8.3646
Day 2: 4th Session		**77.6302**	**7.4248**
	Attention Cue	78.5417	7.8667
	Neutral Cue	76.7188	7.1813
Day 3: 1st Session		**78.8021**	**7.0661**
	Attention Cue	80.0521	6.3540
	Neutral Cue	77.5521	7.7856
Day 3: 2nd Session		**79.0625**	**8.1219**
	Attention Cue	80.9375	7.8358
	Neutral Cue	77.1875	8.2980
Day 3: 3rd Session		**78.3073**	**7.9517**
	Attention Cue	80.5729	8.1554
	Neutral Cue	76.0417	7.3823
Day 3: 4th Session		**78.6979**	**7.6323**
	Attention Cue	81.6667	6.6483
	Neutral Cue	75.7292	7.6400
Day 4: 1st Session		**82.3698**	**8.6012**
	Attention Cue	83.5417	8.0496
	Neutral Cue	81.1979	9.3217
Day 4: 2nd Session		**79.5313**	**9.3709**
	Attention Cue	82.4479	8.3149
	Neutral Cue	76.6146	9.7935

Day 4: 3rd Session		**79.7396**	**8.3648**
	Attention Cue	81.7188	8.7505
	Neutral Cue	77.7604	7.8220
Day 4: 4th Session		**77.8125**	**11.1026**
	Attention Cue	80.3646	12.9396
	Neutral Cue	75.2604	8.7234

Demographics for Older Adults

Older Adults	Mean	SD
Age (years)	75.5417	3.7761
Education (years)	15.8636	2.4161
Digit Span Forward - [out of 16]	9.3181	2.3580
Digit Span Backward - [out of 14]	7.1818	2.0385
Total Digit Span - [out of 30]	15.7826	5.1694

Visual Assessments for Older Adults

Older Adults	Mean	SD
Far Acuity: Left Eye (LogMAR)	0.2300	0.1386
Far Acuity: Right Eye (LogMAR)	0.2200	0.1645
Far Acuity: Both Eyes (LogMAR)	0.1417	0.1236
Near Acuity: Left Eye (LogMAR)	0.3900	0.1935
Near Acuity: Right Eye (LogMAR)	0.3258	0.2379
Near Acuity: Both Eyes (LogMAR)	0.2500	0.1612
Contrast Sensitivity: Left Eye	1.11	0.1454
Contrast Sensitivity: Right Eye	1.15	0.1511
Contrast Sensitivity: Both Eyes	1.30	0.0950

Overall Accuracy for Older Adults

Older Adults			Mean	SD
Overall Accuracy				
Trained Location				
	Pre-Test		**61.0938**	**6.9999**
		Attention Cue	59.8958	5.9805
		Neutral Cue	62.2917	7.9720
	Post-Test		**67.9818**	**6.4729**
		Attention Cue	65.8594	6.1687
		Neutral Cue	70.1042	6.3028
Untrained Location				
	Pre-Test		**61.2370**	**6.9502**
		Attention Cue	58.5417	5.5461
		Neutral Cue	63.9323	7.3752
	Post-Test		**65.0521**	**7.6783**
		Attention Cue	62.4740	6.9001
		Neutral Cue	67.6302	7.8204

Magnitude Overall Accuracy for Older Adults

Older Adults			Mean	SD
Magnitude Overall Accuracy				
	Trained Location		**0.1200**	**0.1107**
		Attention Cue	0.1064	0.1267
		Neutral Cue	0.1336	0.0958
	Untrained Location		**0.0644**	**0.0768**
		Attention Cue	0.0690	0.0905
		Neutral Cue	0.0598	0.0642

Correct Response Times (RT) for Older Adults

Older Adults				Mean	SD
Correct RT					
	Trained Location				
		Pre-Test		**1.0476**	**0.5555**
			Attention Cue	1.2352	0.7022
			Neutral Cue	0.8600	0.2746
		Post-Test		**0.6228**	**0.3372**
			Attention Cue	0.7639	0.4187
			Neutral Cue	0.4816	0.1379
	Untrained Location				
		Pre-Test		**1.0582**	**0.5061**
			Attention Cue	1.2801	0.5805
			Neutral Cue	0.8364	0.3020
		Post-Test		**0.6520**	**0.2962**
			Attention Cue	0.8032	0.3349
			Neutral Cue	0.5007	0.1461

d’ (sensitivity) for Older Adults

Older Adults				Mean	SD
d' (sensitivity)					
	Trained Location				
		Pre-Test		**0.4121**	**0.2626**
			Attention Cue	0.3674	0.2227
			Neutral Cue	0.4569	0.3003
		Post-Test		**0.6934**	**0.2829**
			Attention Cue	0.6159	0.2904
			Neutral Cue	0.7710	0.2643
	Untrained Location				
		Pre-Test		**0.4277**	**0.2784**
			Attention Cue	0.3301	0.2392
			Neutral Cue	0.5253	0.2898
		Post-Test		**0.6013**	**0.3103**
			Attention Cue	0.5182	0.2988
			Neutral Cue	0.6844	0.3114

Psychometric Function for Older Adults

Older Adults		Mean	SD
Psychometric Function			
Pre-Test (Trained Location)			
Contrast 2%		**18.9583**	**2.5956**
	Attention Cue	18.4167	2.6785
	Neutral Cue	19.5000	2.5045
Contrast 4%		**20.1667**	**2.9587**
	Attention Cue	21.0833	3.2602
	Neutral Cue	19.2500	2.4168
Contrast 8%		**21.1250**	**3.1251**
	Attention Cue	20.5000	2.6458
	Neutral Cue	21.7500	3.5452
Contrast 12%		**22.2917**	**4.1753**
	Attention Cue	20.9167	4.0555
	Neutral Cue	23.6667	3.9848
Contrast 16%		**24.7917**	**5.4452**
	Attention Cue	22.9167	3.7040
	Neutral Cue	26.6667	6.3723
Contrast 24%		**27.5000**	**5.1160**
	Attention Cue	27.0833	4.2738
	Neutral Cue	27.9167	6.0069
Contrast 32%		**29.3333**	**5.0014**
	Attention Cue	29.0833	5.0894
	Neutral Cue	29.5833	5.1250
Contrast 64%		**31.3333**	**5.0014**
	Attention Cue	31.6667	4.4992
	Neutral Cue	31.0000	5.6408
Post-Test (Trained Location)			
Contrast 2%		**18.4583**	**3.0784**
	Attention Cue	18.8333	3.8099
	Neutral Cue	18.0833	2.2344

Contrast 4%		**20.0000**	**3.3101**
	Attention Cue	19.3333	3.5505
	Neutral Cue	20.6667	3.0551
Contrast 8%		23.0417	4.2781
	Attention Cue	21.9167	3.2322
	Neutral Cue	24.1667	5.0061
Contrast 12%		**26.0000**	**5.4931**
	Attention Cue	23.7500	4.7697
	Neutral Cue	28.2500	5.4125
Contrast 16%		**27.4583**	**5.2501**
	Attention Cue	25.5833	5.4349
	Neutral Cue	29.3333	4.5193
Contrast 24%		**32.6667**	**4.1668**
	Attention Cue	32.8333	3.9734
	Neutral Cue	32.5000	4.5227
Contrast 32%		**33.7500**	**5.2357**
	Attention Cue	32.5833	5.3336
	Neutral Cue	34.9167	5.0894
Contrast 64%		**36.1667**	**2.8079**
	Attention Cue	35.9167	2.7784
	Neutral Cue	36.4167	2.9375
Pre-Test (Untrained Location)			
Contrast 2%		**20.7083**	**3.0995**
	Attention Cue	20.2500	2.5981
	Neutral Cue	21.1667	3.5887
Contrast 4%		**20.2917**	**4.1544**
	Attention Cue	20.5833	4.1001
	Neutral Cue	20.0000	4.3693
Contrast 8%		**21.4167**	**4.3129**
	Attention Cue	20.8333	3.7376
	Neutral Cue	22.0000	4.9175
Contrast 12%		**23.0833**	**4.4907**
	Attention Cue	22.0833	3.7285
	Neutral Cue	24.0833	5.1072

Contrast 16%		**25.0417**	**5.3445**
	Attention Cue	23.5833	5.1603
	Neutral Cue	26.5000	5.3343
Contrast 24%		**27.2083**	**5.4612**
	Attention Cue	25.3333	4.0527
	Neutral Cue	29.0833	6.1859
Contrast 32%		**28.7083**	**5.4890**
	Attention Cue	27.5000	5.2657
	Neutral Cue	29.9167	5.6642
Contrast 64%		**29.5000**	**5.4693**
	Attention Cue	27.1667	4.8399
	Neutral Cue	31.8333	5.2194
Post-Test (Untrained Location)			
Contrast 2%		**19.4167**	**3.0633**
	Attention Cue	19.8333	2.1249
	Neutral Cue	19.0000	3.8376
Contrast 4%		**19.0417**	**3.5567**
	Attention Cue	20.0000	3.5675
	Neutral Cue	18.0833	3.4234
Contrast 8%		**22.2500**	**4.9012**
	Attention Cue	21.0833	4.6604
	Neutral Cue	23.4167	5.0535
Contrast 12%		**24.7500**	**5.8995**
	Attention Cue	22.6667	5.3824
	Neutral Cue	26.8333	5.8595
Contrast 16%		**26.8333**	**6.3634**
	Attention Cue	25.0000	4.9360
	Neutral Cue	28.6667	7.2780
Contrast 24%		**30.0000**	**6.0577**
	Attention Cue	27.4167	6.8018
	Neutral Cue	32.5833	3.9877
Contrast 32%		**32.0417**	**4.2578**
	Attention Cue	31.0000	4.1121
	Neutral Cue	33.0833	4.3161

Contrast 64%		**33.8333**	**4.3805**
	Attention Cue	32.9167	4.3788
	Neutral Cue	34.7500	4.3719

Contrast Threshold (α) for Older Adults

Older Adults			Mean	SD
Contrast Threshold [α] %				
	Trained Location			
	Pre-Test		**27.0833**	**16.3013**
		Attention Cue	35.6667	18.0067
		Neutral Cue	18.5000	8.4045
	Post-Test		**15.7500**	**8.9891**
		Attention Cue	19.0000	10.2514
		Neutral Cue	12.5000	6.3889
	Untrained Location			
	Pre-Test		**18.3333**	**13.6371**
		Attention Cue	17.5000	9.8396
		Neutral Cue	19.1667	17.0445
	Post-Test		**22.0000**	**15.9019**
		Attention Cue	26.6667	19.3970
		Neutral Cue	17.3333	10.2455

Asymptote for Older Adults

Older Adults			Mean	SD
Asymptote				
	Trained Location			
	Pre-Test		**1.1378**	**0.1407**
		Attention Cue	1.1432	0.1472
		Neutral Cue	1.1324	0.1403
	Post-Test		**1.3105**	**0.1561**
		Attention Cue	1.2973	0.1623
		Neutral Cue	1.3236	0.1557
	Untrained Location			
	Pre-Test		**1.0965**	**0.1552**
		Attention Cue	1.0445	0.1124
		Neutral Cue	1.1484	0.1784
	Post-Test		**1.2372**	**0.1744**
		Attention Cue	1.1953	0.1526
		Neutral Cue	1.2792	0.1909

Useful Field of View (UFOV) for Older Adults

Older Adults			Mean	SD
UFOV				
Processing Speed				
	Pre-Test		**20.0833**	**7.5695**
		Attention Cue	21.0000	8.6129
		Neutral Cue	19.1667	6.6172
	Post-Test		**20.1250**	**11.7337**
		Attention Cue	17.2500	0.8660
		Neutral Cue	23.0000	16.4040
Divided Attention				
	Pre-Test		**67.6667**	**54.2167**
		Attention Cue	56.4167	43.4479
		Neutral Cue	78.9167	63.1052
	Post-Test		**53.0833**	**53.4203**
		Attention Cue	60.4167	55.2851
		Neutral Cue	45.7500	52.8499
Selective Attention				
	Pre-Test		**177.5833**	**52.8418**
		Attention Cue	203.1667	54.1963
		Neutral Cue	152.0000	38.3809
	Post-Test		**169.8333**	**69.1989**
		Attention Cue	178.0000	59.9833
		Neutral Cue	161.6667	79.1757

Training Sessions: Overall Accuracy for Older Adults

Older Adults		Mean	SD
Overall Accuracy (Training Sessions)			
Day 2: 1st Session		**65.6250**	**7.5474**
	Attention Cue	64.3229	6.0329
	Neutral Cue	66.9271	8.8887
Day 2: 2nd Session		**67.5000**	**6.4321**
	Attention Cue	67.5000	6.6519
	Neutral Cue	67.5000	6.5007
Day 2: 3rd Session		**66.9271**	**8.0439**
	Attention Cue	66.6667	7.6840
	Neutral Cue	67.1875	8.7236
Day 2: 4th Session		**67.5521**	**6.3869**
	Attention Cue	67.0313	6.5503
	Neutral Cue	68.0729	6.4648
Day 3: 1st Session		**68.9063**	**7.5906**
	Attention Cue	68.5938	7.7291
	Neutral Cue	69.2188	7.7795
Day 3: 2nd Session		**67.0833**	**7.2012**
	Attention Cue	66.6667	6.8119
	Neutral Cue	67.5000	7.8516
Day 3: 3rd Session		**70.1042**	**7.2739**
	Attention Cue	68.7500	7.3033
	Neutral Cue	71.4583	7.3000
Day 3: 4th Session		**69.3750**	**5.6356**
	Attention Cue	68.6979	5.4581
	Neutral Cue	70.0521	5.9678
Day 4: 1st Session		**69.4271**	**7.2394**
	Attention Cue	68.1771	6.8333
	Neutral Cue	70.6771	7.7122
Day 4: 2nd Session		**69.3490**	**7.4123**
	Attention Cue	67.9688	8.2921
	Neutral Cue	70.7292	6.4779

Day 4: 3rd Session		**70.2604**	**8.0355**
	Attention Cue	67.7083	9.1675
	Neutral Cue	72.8125	6.0625
Day 4: 4th Session		**69.7396**	**7.0757**
	Attention Cue	68.8021	7.6984
	Neutral Cue	70.6771	6.5953

Appendix C

Demographics for Younger Drivers

Younger Drivers	Mean	SD
Age (years)	20.7917	2.7502
Education (years)	14.8333	2.4257
Driving Experience (years)	3.5833	3.1021
Driving frequency (days per week)	4.1875	2.2302
Average freeway speed (mph)	70.1666	5.5455

Visual Assessments for Younger Drivers

Younger Drivers	Mean	SD
Far Acuity: Left Eye (LogMAR)	0.0783	0.1052
Far Acuity: Right Eye (LogMAR)	0.0758	0.1580
Far Acuity: Both Eyes (LogMAR)	-0.0150	0.0721
Near Acuity: Left Eye (LogMAR)	-0.0250	0.0942
Near Acuity: Right Eye (LogMAR)	0.0108	0.1734
Near Acuity: Both Eyes (LogMAR)	-0.0958	0.0806
Contrast Sensitivity: Left Eye	1.32	0.0847
Contrast Sensitivity: Right Eye	1.31	0.0912
Contrast Sensitivity: Both Eyes	1.44	0.1155

Cognitive Assessments for Younger Drivers

Younger Drivers	Mean	SD
WAIS: Digit Symbol - Coding - [out of 133]	91.0833	13.0148
WAIS: Digit Symbol - Copy - [out of 133]	128.2500	9.6875
WAIS: Digit Span Forward - [out of 16]	10.1250	2.0283
WAIS: Digit Span Backward - [out of 14]	7.7500	1.8238
WAIS: Total Digit Span - [out of 30]	17.8750	3.3791
WAIS: Matrix Reasoning - [out of 26]	18.6667	4.1980
Mini-Mental State Examination (MMSE) - [out of 30]	29.0417	0.9079

Accuracy (% Correct) for Younger Drivers

Younger Drivers		Mean	SD
Pre-Test: 2 Objects		**87.1528**	**9.14661**
	Valid Cue	86.6319	9.16573
	Neutral Cue	87.6736	9.50388
Post-Test: 2 Objects		**89.2361**	**9.64862**
	Valid Cue	88.8889	8.71898
	Neutral Cue	89.5833	10.87985
Pre-Test: 4 Objects		**68.3160**	**15.11054**
	Valid Cue	67.5347	12.79508
	Neutral Cue	69.0972	17.67395
Post-Test: 4 Objects		**72.6563**	**18.50497**
	Valid Cue	74.4792	17.18248
	Neutral Cue	70.8333	20.33495
Pre-Test: 8 Objects		**40.6250**	**13.36104**
	Valid Cue	40.1042	10.13346
	Neutral Cue	41.1458	16.43122
Post-Test: 8 Objects		**46.2674**	**19.90674**
	Valid Cue	45.1389	18.44947
	Neutral Cue	47.3958	22.03226

Correct RT for Younger Drivers

Younger Drivers		Mean	SD
Pre-Test: 2 Objects		**5.6067**	**1.34875**
	Valid Cue	5.5934	0.91515
	Neutral Cue	5.6201	1.72213
Post-Test: 2 Objects		**4.3889**	**1.63736**
	Valid Cue	3.9151	1.08424
	Neutral Cue	4.8627	1.98499
Pre-Test: 4 Objects		**6.0762**	**1.11725**
	Valid Cue	6.1159	0.81235
	Neutral Cue	6.0364	1.39521
Post-Test: 4 Objects		**5.3047**	**1.35669**
	Valid Cue	4.9884	1.14580
	Neutral Cue	5.6211	1.52229
Pre-Test: 8 Objects		**6.2601**	**1.05615**
	Valid Cue	6.1942	0.78901
	Neutral Cue	6.3260	1.30395
Post-Test: 8 Objects		**5.4855**	**1.24518**
	Valid Cue	5.0924	0.90317
	Neutral Cue	5.8785	1.44537

Incorrect RT Younger Drivers

Younger Drivers		Mean	SD
Pre-Test: 2 Objects		**6.5961**	**1.54353**
	Valid Cue	6.8898	1.42964
	Neutral Cue	6.3025	1.65817
Post-Test: 2 Objects		**4.7709**	**2.25520**
	Valid Cue	4.1469	2.16949
	Neutral Cue	5.3949	2.25344
Pre-Test: 4 Objects		**6.4195**	**1.09677**
	Valid Cue	6.5480	0.81899
	Neutral Cue	6.2910	1.34477
Post-Test: 4 Objects		**5.5041**	**1.48428**
	Valid Cue	5.0703	1.41043
	Neutral Cue	5.9379	1.48544
Pre-Test: 8 Objects		**6.6437**	**1.07323**
	Valid Cue	6.7101	0.81854
	Neutral Cue	6.5773	1.31481
Post-Test: 8 Objects		**5.8181**	**1.30933**
	Valid Cue	5.5384	1.24407
	Neutral Cue	6.0979	1.36604

Root Mean Square Error (RMSE) for Younger Drivers

Younger Drivers		Mean	SD
Pre-Test: 2 Objects (Pre-Onset)		**0.1919**	**0.07109**
	Valid Cue	0.1967	0.07052
	Neutral Cue	0.1871	0.07446
Post-Test: 2 Objects (Pre-Onset)		**0.2042**	**0.06955**
	Valid Cue	0.2147	0.07062
	Neutral Cue	0.1937	0.06991
Pre-Test: 2 Objects (Post-Onset)		**0.1977**	**0.06649**
	Valid Cue	0.2065	0.06825
	Neutral Cue	0.1889	0.06645
Post-Test: 2 Objects (Post-Onset)		**0.2106**	**0.06340**
	Valid Cue	0.2254	0.06669
	Neutral Cue	0.1958	0.05897
Pre-Test: 4 Objects (Pre-Onset)		**0.2289**	**0.17584**
	Valid Cue	0.1976	0.04905
	Neutral Cue	0.2602	0.24517
Post-Test: 4 Objects (Pre-Onset)		**0.2281**	**0.09181**
	Valid Cue	0.2202	0.06149
	Neutral Cue	0.2360	0.11709
Pre-Test: 4 Objects (Post-Onset)		**0.2268**	**0.16846**
	Valid Cue	0.1976	0.05140
	Neutral Cue	0.2559	0.23419
Post-Test: 4 Objects (Post-Onset)		**0.2113**	**0.07858**
	Valid Cue	0.2190	0.06686
	Neutral Cue	0.2037	0.09118
Pre-Test: 8 Objects (Pre-Onset)		**0.2060**	**0.05867**
	Valid Cue	0.2155	0.05530
	Neutral Cue	0.1965	0.06277
Post-Test: 8 Objects (Pre-Onset)		**0.2260**	**0.11718**
	Valid Cue	0.2107	0.06194
	Neutral Cue	0.2413	0.15609
Pre-Test: 8 Objects (Post-Onset)		**0.2117**	**0.06640**
	Valid Cue	0.2279	0.07498
	Neutral Cue	0.1954	0.05497
Post-Test: 8 Objects (Post-Onset)		**0.2238**	**0.08695**
	Valid Cue	0.2225	0.08763
	Neutral Cue	0.2251	0.09015

Useful Field of View (UFOV) for Younger Drivers

Younger Drivers			Mean	SD
UFOV				
Processing Speed				
	Pre-Test		**17.1250**	**0.6124**
		Valid Cue	17.2500	0.8660
		Neutral Cue	17.0000	0.0000
	Post-Test		**17.0000**	**0.0000**
		Valid Cue	17.0000	0.0000
		Neutral Cue	17.0000	0.0000
Divided Attention				
	Pre-Test		**20.0000**	**7.7963**
		Valid Cue	17.2500	0.8660
		Neutral Cue	22.7500	10.4805
	Post-Test		**18.3333**	**4.2290**
		Valid Cue	17.7500	1.8650
		Neutral Cue	18.9167	5.7597
Selective Attention				
	Pre-Test		**83.2500**	**27.7132**
		Valid Cue	75.2500	21.0760
		Neutral Cue	91.2500	31.9691
	Post-Test		**77.6667**	**32.9739**
		Valid Cue	78.8300	38.9050
		Neutral Cue	76.5000	27.5103

Training Sessions: Accuracy (% Correct) for Younger Drivers

Younger Drivers		Mean	SD
2 Objects (Block 1)		**93.4028**	**9.2899**
	Valid Cue	99.1319	2.4260
	Neutral Cue	87.6736	10.1464
2 Objects (Block 2)		**94.7917**	**7.2690**
	Valid Cue	98.4375	4.7941
	Neutral Cue	91.1458	7.6482
2 Objects (Block 3)		**94.0972**	**8.3484**
	Valid Cue	99.4792	0.9422
	Neutral Cue	88.7153	9.0357
4 Objects (Block 1)		**76.1285**	**15.5293**
	Valid Cue	83.6806	11.2659
	Neutral Cue	68.5764	15.9024
4 Objects (Block 2)		**75.4340**	**14.5895**
	Valid Cue	81.0764	11.9994
	Neutral Cue	69.7917	15.2188
4 Objects (Block 3)		**77.4306**	**15.0189**
	Valid Cue	83.1597	14.5280
	Neutral Cue	71.7014	13.7465
8 Objects (Block 1)		**59.3750**	**17.2782**
	Valid Cue	66.8403	16.3429
	Neutral Cue	51.9097	15.3469
8 Objects (Block 2)		**54.3403**	**17.0795**
	Valid Cue	59.8958	18.0121
	Neutral Cue	48.7847	14.7704
8 Objects (Block 3)		**57.5521**	**17.5148**
	Valid Cue	64.9306	17.9618
	Neutral Cue	50.1736	14.1426

Training Sessions: Correct RT for Younger Drivers

Younger Drivers		Mean	SD
2 Objects (Block 1)		**3.9247**	**1.8350**
	Valid Cue	3.0005	1.8167
	Neutral Cue	4.8490	1.3698
2 Objects (Block 2)		**3.6400**	**1.8265**
	Valid Cue	2.8511	1.9467
	Neutral Cue	4.4288	1.3521
2 Objects (Block 3)		**3.3674**	**1.6269**
	Valid Cue	2.5861	1.5678
	Neutral Cue	4.1486	1.3208
4 Objects (Block 1)		**5.2115**	**1.3628**
	Valid Cue	4.8154	1.6379
	Neutral Cue	5.6076	0.9265
4 Objects (Block 2)		**5.0188**	**1.4207**
	Valid Cue	4.4722	1.5718
	Neutral Cue	5.5654	1.0477
4 Objects (Block 3)		**5.0013**	**1.5092**
	Valid Cue	4.5709	1.8099
	Neutral Cue	5.4317	1.0403
8 Objects (Block 1)		**5.9005**	**1.6871**
	Valid Cue	5.1400	1.4407
	Neutral Cue	6.6610	1.6166
8 Objects (Block 2)		**5.9903**	**1.8617**
	Valid Cue	5.1088	1.5456
	Neutral Cue	6.8718	1.7784
8 Objects (Block 3)		**6.0283**	**1.7215**
	Valid Cue	5.1825	1.4376
	Neutral Cue	6.8741	1.6028

Training Sessions: Incorrect RT for Younger Drivers

Younger Drivers		Mean	SD
2 Objects (Block 1)		**3.1612**	**2.8582**
	Valid Cue	1.1162	2.6140
	Neutral Cue	5.2063	1.0600
2 Objects (Block 2)		**2.6205**	**2.5526**
	Valid Cue	0.7182	1.7865
	Neutral Cue	4.5228	1.5927
2 Objects (Block 3)		**3.8191**	**6.4124**
	Valid Cue	3.0082	9.1194
	Neutral Cue	4.6300	1.1740
4 Objects (Block 1)		**5.0624**	**1.2757**
	Valid Cue	4.9647	1.6870
	Neutral Cue	5.1601	0.7321
4 Objects (Block 2)		**5.7320**	**3.9362**
	Valid Cue	6.3128	5.5913
	Neutral Cue	5.1512	0.6301
4 Objects (Block 3)		**5.0298**	**2.5106**
	Valid Cue	4.9509	3.5264
	Neutral Cue	5.1086	0.8547
8 Objects (Block 1)		**5.6653**	**1.2881**
	Valid Cue	5.1611	1.1906
	Neutral Cue	6.1696	1.2236
8 Objects (Block 2)		**5.5839**	**1.3772**
	Valid Cue	5.0531	1.0918
	Neutral Cue	6.1147	1.4693
8 Objects (Block 3)		**5.4467**	**1.4079**
	Valid Cue	4.9465	1.1709
	Neutral Cue	5.9469	1.4926

Demographics for Older Drivers

Older Drivers	Mean	SD
Age (years)	73.7500	4.6552
Education (years)	15.45	4.0324
Driving Experience (years)	56.65	5.7241
Driving Frequency (days per week)	5.775	1.2510
Average freeway speed (mph)	67.65	5.1224

Visual Assessments for Older Drivers

Older Drivers	Mean	SD
Far Acuity: Left Eye (LogMAR)	0.3450	0.2042
Far Acuity: Right Eye (LogMAR)	0.3168	0.2166
Far Acuity: Both Eyes (LogMAR)	0.1960	0.1360
Near Acuity: Left Eye (LogMAR)	0.4510	0.2548
Near Acuity: Right Eye (LogMAR)	0.3705	0.2610
Near Acuity: Both Eyes (LogMAR)	0.2260	0.1722
Contrast Sensitivity: Left Eye	0.95	0.5202
Contrast Sensitivity: Right Eye	1.12	0.2311
Contrast Sensitivity: Both Eyes	1.12	0.5093

Cognitive Assessments for Older Drivers

Older Drivers	Mean	SD
WAIS: Digit Symbol - Coding - [out of 133]	58.2105	12.7435
WAIS: Digit Symbol - Copy - [out of 133]	92.7895	18.2744
WAIS: Digit Span Forward - [out of 16]	9.9474	1.9285
WAIS: Digit Span Backward - [out of 14]	6.4211	1.8048
WAIS: Total Digit Span - [out of 30]	16.3684	3.0223
WAIS: Matrix Reasoning - [out of 26]	15.0526	5.2649
Mini-Mental State Examination (MMSE) - [out of 30]	28.4211	1.7738

Accuracy (% Correct) for Older Drivers

Older Drivers		Mean	SD
Pre-Test: 2 Objects		**75.8929**	**13.7703**
	Valid Cue	78.1385	12.1976
	Neutral Cue	73.1481	15.7786
Post-Test: 2 Objects		**80.3125**	**10.5901**
	Valid Cue	82.9545	6.8982
	Neutral Cue	77.0833	13.6216
Pre-Test: 4 Objects		**42.8571**	**14.3414**
	Valid Cue	44.9675	15.5245
	Neutral Cue	40.2778	13.1762
Post-Test: 4 Objects		**55.2083**	**15.5682**
	Valid Cue	59.4697	13.8620
	Neutral Cue	50.0000	16.7316
Pre-Test: 8 Objects		**16.3690**	**11.5336**
	Valid Cue	16.1255	8.3851
	Neutral Cue	16.6667	15.0952
Post-Test: 8 Objects		**25.3125**	**13.2328**
	Valid Cue	27.4621	13.0377
	Neutral Cue	22.6852	13.7581

Correct Response Times (RT) for Older Drivers

Older Drivers		Mean	SD
Pre-Test: 2 Objects		**6.0658**	**0.8908**
	Valid Cue	6.0527	1.0351
	Neutral Cue	6.0818	0.7381
Post-Test: 2 Objects		**5.4510**	**0.8607**
	Valid Cue	5.4573	0.8792
	Neutral Cue	5.4434	0.8904
Pre-Test: 4 Objects		**6.5301**	**0.8369**
	Valid Cue	6.2948	0.8336
	Neutral Cue	6.8176	0.7912
Post-Test: 4 Objects		**5.8929**	**0.7563**
	Valid Cue	5.9744	0.7351
	Neutral Cue	5.7932	0.8142
Pre-Test: 8 Objects		**6.8360**	**0.9599**
	Valid Cue	6.8082	1.1813
	Neutral Cue	6.8699	0.6644
Post-Test: 8 Objects		**5.9566**	**0.8473**
	Valid Cue	6.1035	0.7042
	Neutral Cue	5.7770	1.0096

Incorrect Response Times (RT) for Older Drivers

Older Drivers		Mean	SD
Pre-Test: 2 Objects		**6.3642**	**0.9669**
	Valid Cue	6.3240	1.0424
	Neutral Cue	6.4134	0.9257
Post-Test: 2 Objects		**5.8468**	**0.9308**
	Valid Cue	5.8799	0.9266
	Neutral Cue	5.8064	0.9904
Pre-Test: 4 Objects		**6.6670**	**0.8216**
	Valid Cue	6.4641	0.8411
	Neutral Cue	6.9151	0.7700
Post-Test: 4 Objects		**6.0430**	**0.8455**
	Valid Cue	6.1375	0.8843
	Neutral Cue	5.9276	0.8326
Pre-Test: 8 Objects		**6.8007**	**1.0629**
	Valid Cue	6.8000	1.2445
	Neutral Cue	6.8016	0.8644
Post-Test: 8 Objects		**6.2748**	**0.8082**
	Valid Cue	6.4450	0.7781
	Neutral Cue	6.0667	0.8403

Root-Mean-Squares Error (RMSE) for Older Drivers

Older Drivers RMSE steering control		Mean	SD
Pre-Test: 2 Objects (Pre-Onset)		**0.1839**	**0.0455**
	Valid Cue	0.1869	0.0384
	Neutral Cue	0.1802	0.0553
Post-Test: 2 Objects (Pre-Onset)		**0.1849**	**0.1163**
	Valid Cue	0.1882	0.1457
	Neutral Cue	0.1808	0.0748
Pre-Test: 2 Objects (Post-Onset)		**0.2094**	**0.0465**
	Valid Cue	0.2149	0.0361
	Neutral Cue	0.2028	0.0585
Post-Test: 2 Objects (Post-Onset)		**0.2040**	**0.1033**
	Valid Cue	0.2027	0.1241
	Neutral Cue	0.2055	0.0781
Pre-Test: 4 Objects (Pre-Onset)		**0.2011**	**0.0903**
	Valid Cue	0.2234	0.1120
	Neutral Cue	0.1738	0.0468
Post-Test: 4 Objects (Pre-Onset)		**0.1888**	**0.1330**
	Valid Cue	0.2019	0.1763
	Neutral Cue	0.1728	0.0515
Pre-Test: 4 Objects (Post-Onset)		**0.2180**	**0.0814**
	Valid Cue	0.2222	0.0961
	Neutral Cue	0.2128	0.0643
Post-Test: 4 Objects (Post-Onset)		**0.2056**	**0.1280**
	Valid Cue	0.2121	0.1655
	Neutral Cue	0.1976	0.0675
Pre-Test: 8 Objects (Pre-Onset)		**0.2006**	**0.0396**
	Valid Cue	0.2053	0.0389
	Neutral Cue	0.1948	0.0419
Post-Test: 8 Objects (Pre-Onset)		**0.1868**	**0.0869**
	Valid Cue	0.1866	0.1009
	Neutral Cue	0.1871	0.0722
Pre-Test: 8 Objects (Post-Onset)		**0.2350**	**0.0478**
	Valid Cue	0.2306	0.0420
	Neutral Cue	0.2404	0.0563
Post-Test: 8 Objects (Post-Onset)		**0.2216**	**0.0904**
	Valid Cue	0.2135	0.0954
	Neutral Cue	0.2315	0.0883

Useful Field of View (UFOV) for Older Drivers

Older Drivers			Mean	SD
UFOV				
Processing Speed				
	Pre-Test		**20.9000**	**14.7002**
		Valid Cue	17.0000	0.0000
		Neutral Cue	25.6667	21.6044
	Post-Test		**18.4000**	**3.7753**
		Valid Cue	17.2727	0.9045
		Neutral Cue	19.7778	5.3800
Divided Attention				
	Pre-Test		**85.9000**	**79.9828**
		Valid Cue	87.3636	90.3352
		Neutral Cue	84.1111	70.6142
	Post-Test		**64.1500**	**67.5934**
		Valid Cue	66.3636	66.4715
		Neutral Cue	61.4444	72.8905
Selective Attention				
	Pre-Test		**287.1000**	**105.2195**
		Valid Cue	295.2727	102.6958
		Neutral Cue	277.1111	113.6084
	Post-Test		**259.1000**	**117.2514**
		Valid Cue	286.6364	100.0892
		Neutral Cue	225.4444	133.4617

Training Sessions: Accuracy (% Correct) for Older Drivers

Older Drivers		Mean	SD
2 Objects (Block 1)		**89.8958**	**13.6743**
	Valid Cue	98.6742	2.6798
	Neutral Cue	79.1667	14.1299
2 Objects (Block 2)		**89.5833**	**16.0380**
	Valid Cue	99.4318	0.9731
	Neutral Cue	77.5463	17.7015
2 Objects (Block 3)		**90.9375**	**15.2086**
	Valid Cue	99.0530	2.5282
	Neutral Cue	81.0185	18.4420
4 Objects (Block 1)		**70.4167**	**23.2049**
	Valid Cue	87.3106	7.5951
	Neutral Cue	49.7685	18.2944
4 Objects (Block 2)		**66.9792**	**17.7714**
	Valid Cue	78.7879	7.5587
	Neutral Cue	52.5463	15.8928
4 Objects (Block 3)		**71.8750**	**19.4673**
	Valid Cue	84.6591	7.6418
	Neutral Cue	56.2500	18.1022
8 Objects (Block 1)		**46.7708**	**18.4426**
	Valid Cue	58.7121	8.8789
	Neutral Cue	32.1759	16.5396
8 Objects (Block 2)		**42.6042**	**14.2181**
	Valid Cue	48.4848	11.8619
	Neutral Cue	35.4167	14.0914
8 Objects (Block 3)		**50.1042**	**17.8893**
	Valid Cue	59.8485	11.0668
	Neutral Cue	38.1944	17.8000

Training Sessions: Correct RT for Older Drivers

Older Drivers		Mean	SD
2 Objects (Block 1)		**5.2399**	**2.0555**
	Valid Cue	4.4600	1.9724
	Neutral Cue	6.1930	1.8202
2 Objects (Block 2)		**4.6421**	**2.1150**
	Valid Cue	3.6470	1.5919
	Neutral Cue	5.8583	2.1049
2 Objects (Block 3)		**4.6560**	**2.0406**
	Valid Cue	3.6669	1.5107
	Neutral Cue	5.8648	2.0119
4 Objects (Block 1)		**6.3317**	**1.7463**
	Valid Cue	5.5789	0.9311
	Neutral Cue	7.2517	2.1042
4 Objects (Block 2)		**6.0555**	**1.6096**
	Valid Cue	5.4619	1.0230
	Neutral Cue	6.7810	1.9413
4 Objects (Block 3)		**6.1294**	**1.6044**
	Valid Cue	5.5004	1.1887
	Neutral Cue	6.8983	1.7715
8 Objects (Block 1)		**6.6013**	**1.1431**
	Valid Cue	6.2116	1.1871
	Neutral Cue	7.0776	0.9368
8 Objects (Block 2)		**6.7698**	**0.9958**
	Valid Cue	6.4953	0.9853
	Neutral Cue	7.1053	0.9545
8 Objects (Block 3)		**6.7791**	**0.9341**
	Valid Cue	6.4964	0.9599
	Neutral Cue	7.1245	0.8225

Training Sessions: Incorrect RT for Older Drivers

Older Drivers		Mean	SD
2 Objects (Block 1)		**3.7198**	**3.3180**
	Valid Cue	1.8496	3.1724
	Neutral Cue	6.0056	1.6969
2 Objects (Block 2)		**3.3125**	**3.0650**
	Valid Cue	1.3057	2.5066
	Neutral Cue	5.7652	1.4671
2 Objects (Block 3)		**2.9337**	**3.0575**
	Valid Cue	0.7073	1.7797
	Neutral Cue	5.6549	1.7599
4 Objects (Block 1)		**5.9046**	**1.2666**
	Valid Cue	5.4308	0.6279
	Neutral Cue	6.4836	1.6221
4 Objects (Block 2)		**5.8522**	**1.2456**
	Valid Cue	5.5034	0.9400
	Neutral Cue	6.2785	1.4862
4 Objects (Block 3)		**5.8284**	**1.2111**
	Valid Cue	5.4260	0.6280
	Neutral Cue	6.3201	1.5799
8 Objects (Block 1)		**5.9817**	**0.8849**
	Valid Cue	5.7739	1.0281
	Neutral Cue	6.2355	0.6379
8 Objects (Block 2)		**5.9862**	**0.7499**
	Valid Cue	5.8814	0.7362
	Neutral Cue	6.1143	0.7904
8 Objects (Block 3)		**5.8802**	**0.7342**
	Valid Cue	5.7909	0.6907
	Neutral Cue	5.9892	0.8122

Magnitude of Learning

Younger Drivers	Mean	SD
Magnitude Accuracy (% Correct)	**0.0765**	**0.2709**
Valid Cue	0.1025	0.3180
Neutral Cue	0.0505	0.2154
Magnitude Correct RT	**-0.1441**	**0.2256**
Valid Cue	-0.2182	0.1696
Neutral Cue	-0.0700	0.2514

Older Drivers	Mean	SD
Magnitude Accuracy (% Correct)	**0.4235**	**0.6685**
Valid Cue	0.4460	0.6335
Neutral Cue	0.3960	0.7202
Magnitude Correct RT	**-0.1020**	**0.1204**
Valid Cue	-0.0766	0.1037
Neutral Cue	-0.1332	0.1336