Title

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Journal

Psychological Research, 87(4)

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Publication Date

2023-06-01

DOI

10.1007/s00426-022-01694-8

Peer reviewed

Working memory control predicts fixation duration in scene-viewing

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Abstract

When viewing scenes, observers differ in how long they linger at each fixation location and how far they move their eyes between fixations. What factors drive these differences in eye-movement behaviors? Previous work suggests individual differences in working memory capacity may influence fixation durations and saccade amplitudes. In the present study, participants (N = 98) performed two scene-viewing tasks, aesthetic judgement and memorization, while viewing 100 photographs of real-world scenes. Working memory capacity, working memory processing ability, and fluid intelligence were assessed with an operation span task, a memory updating task, and Raven's Advanced Progressive Matrices respectively. Across participants, we found significant effects of task on both fixation durations and saccade amplitudes. At the level of each individual participant, we also found a significant relationship between memory updating task performance and participants' fixation duration distributions. However, we found no effect of fluid intelligence and no effect of working memory capacity on fixation duration or saccade amplitude distributions, inconsistent with previous findings. These results suggest that the ability to flexibly maintain and update working memory is strongly related to fixation duration behavior.

Working memory control predicts fixation duration in scene-viewing

Due to the physiological structure of the eyes, visual acuity is highest at the fovea and decreases as you move out into the periphery (Anstis, 1974). When examining the visual world around us or viewing an image of a real-world scene, saccades improve processing by bringing peripheral image regions into foveal vision. Saccades are punctuated by fixations, which are crucial to obtaining visual information needed for cognitive processing of the visual scene (Henderson, 2007; Irwin & Zelinsky, 2002; Rayner et al., 2009). Both why we choose certain regions for fixation and how long we fixate those regions are interesting topics of research. While much previous work has focused on why we choose to fixate

certain regions over others (for a review, see Henderson, 2020), relatively less has focused on the factors influencing how long we fixate those regions. Evidence from reading and scene-viewing studies suggests that individual differences in cognitive processing capacities influence eye-movement behaviors. In the present work, we assess the extent to which individual differences in working memory influence fixation durations and saccade amplitudes during scene viewing.

Previous work suggests that, during scene viewing, the average fixation lasts between 250–300ms and the average saccade traverses approximately 4.5° of visual angle (Cronin et al., 2020; Rayner, 1998). Both the duration of individual fixations and the amplitude of saccadic eye movements are subject to influence by a multitude of factors. Fixation durations are influenced by participants' task (Cronin, et al., 2020; Mills et al., 2011; Nuthamn, 2017; but see Castelhano et al., 2009), the global and local complexity of the viewed stimulus (Einhäuser, Atzert, & Nuthmann, 2020; Ho-Phuoc et al., 2012; Nuthmann & Malcom, 2016, Mannan, Ruddock, & Wooding, 1995; Walshe & Nuthmann, 2015), and the characteristics of the preceding and outgoing saccades (Nuthmann, 2017; Smith & Henderson, 2009, 2011, Tatler & Vincent, 2008; Wilming et al., 2013). For example, fixation durations tend to be longer on regions containing more mid- and high-level feature complexity (e.g., edge density and clutter; Henderson et al., 2009; Nuthmann, 2017) and when the direction of the next saccade is extremely different from the direction of the preceding saccade (Smith & Henderson, 2011; Luke et al., 2014; Nuthmann, 2017). Saccade amplitudes during scene viewing also seem to be dependent on the complexity of the scene image, with shorter saccades tending to be directed towards higher-complexity scene regions (Tatler & Vincent, 2008; Tatler, Baddeley, & Vincent, 2006.

Both fixation durations and saccade amplitudes during scene viewing vary across individuals but seem to be relatively consistent across tasks within individuals. Individual viewers' fixation duration distributions tend to be stable regardless of the images they are viewing (Castelhano & Henderson, 2008) and fixation duration and saccade amplitudes tend to be stable regardless of the task a viewer is engaged in (Andrews & Coppola, 1999; Rayner et al., 2007). Individual differences in eye movement behavior have also been found in reading (Staub & Benatar, 2013), though these individual differences may be less stable than eye movement behaviors during scene viewing tasks (Rayner et al., 2007; Staub, 2021; but see Carter & Luke, 2018).

Why do fixation durations and saccade amplitudes vary across individuals? One possibility is that individual differences in cognitive capacities could influence eye movement behaviors. Working memory, a temporary memory store with limited capacity (Baddeley & Hitch, 1974; Bays & Husain, 2008; Ma et al., 2014), is one possible driver of individual differences in eye movement behavior. Working memory capacity varies across individuals (Conway, 1996; Jarrold & Towse, 2006) and is related to individual differences in other cognitive skills (Daneman & Carpenter, 1980; Hitch et al., 2001; Kane et al., 2004; Towse & Houston-Price, 2001; Unsworth & Engle, 2005; for a review, see Jarrold & Towse, 2006).

Working memory is also thought to be closely related to eye movement control. Many studies have found interference between working memory load and eye movements: a visual

working memory load disrupts detection of saccade-target displacements (Cronin & Irwin, 2018), saccades result in less precision in spatial working memory (Peterson et al., 2019), and saccades bias visual working memory towards information at the saccade target (Ohl & Rolfs, 2017). Further, items held in visual working memory strongly influence where gaze is directed (Van der Stigchel & Hollingworth, 2018). Cronin, Peacock, and Henderson (2020) found that maintaining a visual or a verbal working memory load changed eye movement behavior during scene-viewing: participants fixated longer and moved their eyes less far when maintaining a visual or verbal working memory load. Given that individuals differ in their working memory capacity (Conway, 1996; Jarrold & Towse, 2006) and working memory control (Salthouse et al., 1991), these results raise the possibility that individual differences in working memory capacity and control could influence eye movement behavior during scene viewing.

Recently, Luke and colleagues (2018) examined whether individual differences in working memory capacity and inhibitory executive control processes influenced eye movement behavior during scene viewing, visual search, and reading. They found that individuals with larger working memory capacity tended to make fewer long fixations when viewing scenes. This finding supports the hypothesis that individual differences in working memory capacity influence eye movement behavior. However, capacity is only one source of variance between individuals in working memory function. Salthouse and colleagues (1991) differentiate capacity from operational aspects of working memory. For example, memory updating describes the process of adding, removing, and manipulating contents of working memory to keep information current to the ongoing task (Hedden & Yoon, 2006). Tasks that require updating of working memory are temporarily disrupted by saccadic eye movements. For example, saccades hinder performance on mental rotation tasks (Irwin & Brockmole, 2000; Irwin & Carlson-Radvansky, 1996) and disrupt stimulus encoding (Sanders & Houtmans, 1985). Recent work in non-human primates also suggests a relationship between memory updating and the eye movement system. The superior colliculus, which plays a critical role in the initiation of saccades (e.g., Dorris et al., 1997; Schiller, et al., 1979), continuously updates visuospatial working memory during smooth-pursuit eye movements (Dash et al., 2015). Taken together, these results suggest individual differences in participants' ability to rapidly update and maintain working memory may influence the dynamics of eye movement behaviors during scene viewing.

Individual differences in executive control mechanisms like fluid intelligence, may also be related to individual differences in eye-movement behavior (Luke et al., 2018). Previous work suggests a strong relationship between working memory performance and fluid intelligence (Fry & Hale, 1996) and both working memory capacity and working memory processing (i.e., attention control) mediate this relationship (Unsworth et al., 2014). Fluid intelligence may be more closely tied to cognitive control processes in working memory than to working memory capacity (Engel de Abreu et al., 2010). Given the close relationship between working memory capacity, processing ability, and fluid intelligence, it is important to investigate the relative contributions of each factor towards individual differences in eye movement behavior.

In the present study, we assess the relative contributions of working memory capacity, processing ability, and fluid intelligence towards individual differences in eye movement behavior during scene-viewing. We assessed participant's working memory capacity using an operation span (OSPAN, Conway et al., 2005) task. We also included a measure of working memory processing abilities (memory updating; Lewandowsky et al., 2010) and a fluid intelligence measure (Raven's Advanced Progressive Matrices (short form), Bors & Stokes, 1998). By including a memory updating task and a fluid intelligence task, we can examine the extent to which individual differences in cognitive control processes and in working memory capacity influence eye movement behavior during scene viewing.

Studies on eye movement behavior have typically reported fixation durations with means and standard deviations and have looked at differences between participants or tasks through parametric analyses. However, histograms of fixation duration for a single participant or task show that the distribution of fixation duration lengths is not normally distributed, but instead heavily skewed to the right (Figure 1). As these distributions violate the assumption of normality, parametric analyses may not always be the best measure to quantify differences between conditions. Distribution-based analyses can be a better metric to study differences in fixation duration as the distributions do not need to be normally distributed in these analyses, and these analyses are more sensitive to differences that may be missed when averaging across the entire distribution. Ex-Gaussian modelling is a type of distribution-based analysis that separates a skewed distribution into three components: mu (μ, the mean of the normal part of the distribution), sigma (σ, the standard deviation of the normal part of the distribution), and tau (τ, the exponential part of the distribution that captures the rightward skew) (Figure 1; Lacouture & Cousineau, 2008). Previously, other studies have used ex-Gaussian fits of reaction time data to examine the relationship between τ and cognitive factors such as executive control (Unsworth et al., 2010) and working memory capacity (Schmiedek et al., 2007). Fixation durations are similar to reaction times as they both tend to have right-skewed distributions. Studies of fixation durations during reading and, more recently, during scene viewing, have taken advantage of ex-Gaussian modelling (Henderson et al., 2018; Luke et al., 2018; Staub & Benatar, 2013). In the present study, we fit each participants' fixation duration distribution with the ex-Gaussian distribution to better understand how fixation durations relate to working memory capacity, working memory control, and fluid intelligence across the distribution.

In the present study, we examined the relative contributions of individual differences in working memory capacity, working memory control, and fluid intelligence to individual differences in fixation durations and saccade amplitudes during scene viewing. As scene-viewing task is known to influence fixation durations and saccade amplitude, we used two scene-viewing tasks in our study. Additionally, unlike previous work, we included a measure of fluid intelligence to differentiate any effect of working memory capacity or control from an effect of general fluid intelligence. To preview the results, we found that scene-viewing task influences saccade amplitude and fixation durations. Importantly, we found evidence that working memory control is related to longer fixations during scene viewing but working memory capacity and fluid intelligence are not.

Methods

Participants

The participants for this study were 114 University of California, Davis undergraduate students who had normal or corrected-to-normal vision. The participants were compensated with course credit for taking part in the study. Fourteen participants' data were excluded due to poor eye tracking, quantified as 25% or greater signal loss over trials (Henderson & Hayes, 2017). Additionally, one participant's data was excluded due to having very few recorded fixations (<20 in either task condition). Another participant's data was excluded due to missing data files for one of the individual difference tasks. The remaining data from 98 participants were used in the analysis.

Apparatus and Stimuli

Participant eye movements were recorded using an EyeLink 1000 eye tracker with 0.01° spatial resolution, which sampled the right eye at 1000 Hz (SR Research, 2010). Participants were seated 85 cm away from a 21 in. CRT monitor. A chin and forehead rest were used to restrict head movements. Participants were presented with 100 images of real world scenes (1024 × 768 px) at 26.5 × 20 degrees of visual angle. The scenes were presented using SR Research Experiment Builder software.

The 100 images were selected from 100 different scene categories using online searches. Half of these scenes were indoors and half were outdoors. None of the images contained humans or legible text.

Scene Viewing Tasks

Participants had their eye movements tracked as they performed two types of tasks while viewing photographs of real world scenes. There were 100 scenes total, with 50 scenes in each task condition. Participants began each trial at a central fixation and viewed the scene for 12 seconds. For the Aesthetic Judgement task, participants were asked whether they liked, disliked, or felt neutral toward a scene. For the Memorization task, participants were instructed to memorize the images for a later test. The results of this memory test were not analyzed for this study.

Working Memory Tasks

Operation Span—The operation span task was presented using Py-Span Task software (von der Malsburg, 2015), following recommendations given in Conway and colleagues (2005). Participants were presented with simple mathematical operations and had to determine whether or not the problem had been solved correctly. In between these operations, an alphabetical letter was presented on screen. At the end of a trial, participants were asked to recall the letters they had seen in order. Participants could see and be tasked to remember between 3–5 letters in a given trial and completed three trials of each set size. Scoring was automated using the Levenshtein distance between the true sequence of letters and the sequence reported by the participant.

Memory Updating—Participants completed a memory updating task originally programmed in MATLAB (Lewandowsky et al., 2010) that was converted to Python. This memory updating task was proposed by Salthouse and colleagues (1991) and was adapted for psychometric purposes by Oberauer and colleagues (2000). In our task, participants were presented with an array of blank squares at the beginning of a trial. During the study phase of the task, numeric digits ranging from 1–9 appeared briefly in the squares, one at a time until a digit had appeared in each of the squares. During the update phase, operations (such as "+1") flashed in the squares. Throughout the update phase, participants were required to continuously apply the operations to the digits that had initially appeared in the squares. Each trial, a range of 3–5 squares would appear. Participants were tasked with completing 2–6 operations throughout a trial, and the operations had an equal probability of appearing in each square. It was therefore possible that participants could be asked to perform more than one update for a given square. After the update phase, participants were asked to report the most recently updated digit in each square. They completed seventeen trials in total.

Fluid Intelligence Task

Raven's Advanced Progressive Matrices (RAPM)—Participants completed the short form version of the Raven's Advanced Progressive Matrices (Bors & Stokes, 1998). In this task, participants were shown matrices that followed a certain pattern, with one entry missing. They were then given eight possible solutions to choose from. There were twelve trials total, with a time limit of ten minutes.

Data Analysis

Eye Movement Behavior—Fixation durations shorter than 50 ms and longer than 1400 ms were removed from the dataset to exclude outlier values. First fixations of a scene and null values for saccade amplitudes were also dropped. The dataset was then split by task condition; the Aesthetic Judgement trials were analyzed separately from the Memorization trials.

Each subject's fixation duration distribution was characterized using Ex-Gaussian modelling. Fixation durations tend to be right skewed, where a majority of fixation durations cluster toward the shorter end of the range. Using the GAMLSS package in R, the normal portion of the distribution was separated from the tail ((Rigby & Stasinopoulos, 2005). The specific parameters generated were μ (the center of the normal), σ (standard deviation of the normal), and τ (the tail).

Individual Difference Tasks—The Operation Span and Memory Updating tasks were partial scored, meaning that the score was the average accuracy rate across trials. The RAPM task was partial scored by dividing the total number of correct items by the number of trials since there was only one answer per trial. All scores were then standardized using z-scores.

Linear Mixed Effects Model—Linear mixed effects models were generated using lme4, a statistical package in R (Bates et al., 2020). Each eye movement parameter was predicted by a separate model with the three individual difference measure scores and task as fixed

effects with by-participant random intercepts. Interactions between the scene viewing tasks, the operation span task, the memory updating task, and the RAPM task were tested, and only the significant interactions were kept in the full model.

Bayesian hypothesis testing with Bayes factors was conducted in order to quantify evidence in support of the full model against the null (Andraszewicz et al., 2015). The scale for Bayes factor is defined according to the evidence categories from Andraszewicz and colleagues (2015). A Bayes factor of 1 is considered no evidence in support of either hypothesis. A Bayes factor between 0 and 1 suggests evidence in support of the null hypothesis, with values <1/100 considered extreme evidence in favor of the null. A Bayes factor above 1 is considered evidence in support of the full model, with values above 100 considered extreme evidence in favor of the full model.

Results

Based on the close relationship between eye movements and working memory, and between working memory and fluid intelligence, we hypothesized that our individual difference measures would be predictive of individual differences in eye movement parameters. To assess the potential relationships between scene-viewing task, individual differences in cognitive capacity, and individual differences in eye movements, we employed linear mixed effects models. Separate models were run for each eye movement parameter of interest.

Task Influences Eye-Movement Behavior During Scene-Viewing

Participants had slightly longer fixation durations on average in the memorization task ($M = 291.37$, SD = 35.63) than in the aesthetic judgement task ($M = 289.05$, SD = 33.34), though this difference is not significant (two-tailed independent t-test: $t(194) = 0.48$, p > .05). When accounting for the non-normal distribution of fixation durations, we find that the fitted ex-gaussian mean, μ, of fixation duration *was significantly higher* in the aesthetic judgement task ($M = 158.94$, $SD = 19.24$) than in the memorization task ($M = 150.56$, $SD = 20.22$), $b = -8.38$, $SE = 1.49$, $t = -5.63$, $p < .001$, $BF_{JZS} = 9.50$[1]. Furthermore, the memorization task had a significantly higher average τ ($M = 141.32$, $SD = 34.32$) than the aesthetic judgment task ($M = 130.36$, $SD = 31.11$), $b = 10.96$, $SE = 2.10$, $t = 5.23$, $p < .001$, $BF_{JZS} = 1.01$, suggesting that the longer fixation duration averages for the memorization task were due to participants having more very long fixations than participants in the aesthetic judgement task.

Additionally, the average mean saccade amplitude was significantly higher in the aesthetic judgment task ($M = 4.64$, $SD = 0.74$) than in the memorization task ($M = 4.49$, $SD = 0.77$) $b = -0.15$, $SE = 0.05$, $t = -3.11$, $p = 0.002$, $BF_{JZS} = 0.36$. While the frequentist p-value for the task parameter is significant, the Bayes Factor suggests some evidence in favor of the null model. This could be due in part to the small size of the effect of task on mean saccade amplitude and should be noted if future studies should seek to replicate this effect. However, both the aesthetic judgement task (($M = 47.64$, $SD = 9.46$) and memorization task had similar averages for σ ($M = 46.97$, $SD = 8.99$), and there was no significant effect in our model, $b = -0.67$, $SE = 0.57$, $t = -1.17$, $p = 0.242$, $BF_{JZS} = 0.18$. The Bayes Factor suggests moderate evidence in favor of the null.

Consistent with previous studies, we find that task influences eye-movement behavior during scene viewing. While there was no significant difference between raw mean fixation durations between tasks, when looking at the differences using the means fitted to an ex-gaussian distribution, we find that participants made longer fixations on average and longer saccades between fixations during the aesthetic judgment task compared to the memorization task. Participants in the aesthetic judgement task also tended to make fewer very long fixations than those in the memorization task. We found no evidence that task influences the variability of the fixation duration distribution.

Individual Differences in Memory Updating Influence Fixation Durations

Performance on the Operation Span (OSPAN) task and the Memory Updating task was moderately correlated ($r = 0.33$, $p < 0.001$). Of the two working memory measures, only the Memory Updating task was significantly predictive of participant eye movement behavior. In the present study, OSPAN (M = 0.87, SD = 0.10) did not significantly predict μ ($b = -1.34$, $SE = 1.98$, $t = -0.68$, $p = 0.500$; $BF_{JZS} = 0.39$), σ ($b = 0.01$, $SE = 0.89$, $t = -1.17$, $p = 0.242$; $BF_{JZS} = 0.27$), τ ($b = 1.15$, $SE = 3.29$, $t = 0.35$, $p = 0.727$; $BF_{JZS} = 0.31$), or mean saccade amplitude ($b = 0.05$, $SE = 0.08$, $t = 0.70$, $p = 0.485$; $BF_{JZS} = 0.44$). The Bayes Factor suggests anecdotal evidence in favor of the null for for μ and mean saccade amplitude, and moderate evidence in favor of the null for σ and τ. These results suggest that working memory capacity (as assessed by OSPAN) is not related to individual differences in eye movement behavior during scene viewing.

Performance on the memory updating task was significantly predictive of τ, $b = -5.04$, $SE = 3.53$, $t = -1.43$, $p = 0.030$; $BF_{JZS} = 1.01$. The Bayes Factor suggests anecdotal evidence in favor of the alternative. Interaction between performance on the memory updating task and scene-viewing task was also predictive of τ, $b = -4.55$, $SE = 2.10$, $t = -2.17$, $p = 0.030$; $BF_{JZS} = 0.48$, though the Bayes Factor suggests some anecdotal evidence in favor of the null. While better performance on the memory updating task trends with fewer long fixations in both the memorization and aesthetic judgment scene-viewing tasks, there is a slightly steeper slope in the memorization task for the effect, suggesting the effect of working memory ability on fixation duration is stronger for memorization tasks than for aesthetic judgement scene-viewing tasks (Figure 4a).

Memory updating (M = 0.50, SD = 0.17) did not significantly predict μ ($b = 1.58$, $SE = 2.03$, $t = 0.78$, $p = 0.436$; $BF_{JZS} = 0.46$), σ ($b = -1.12$, $SE = 0.91$, $t = -1.22$, $p = 0.222$; $BF_{JZS} = 0.98$), and mean saccade amplitude ($b = -0.09$, $SE = 0.08$, $t = -1.07$, $p = 0.283$; $BF_{JZS} = 0.73$). The Bayes Factor suggests anecdotal evidence in favor of the null for σ, μ, and mean saccade amplitude.

Our results suggest that participants' fixation duration variability is related to their working memory processing ability rather than to their working memory capacity. Participants who performed better on our memory updating task tended to make fewer very long fixations during the two scene-viewing tasks.

Earlier work found a negative relationship between working memory span and τ and positive relationships between working memory span and μ and σ (Luke et al., 2018). We did not

find evidence of these relationships. Instead, we found a significant negative relationship between working memory *processing* (memory updating) and τ. There was a small, nonsignificant positive relationship between participants' working memory span (OSPAN) and τ. Our results suggest that participants with better working memory processing abilities, as assessed by our memory updating task, tended to make fewer long fixations during the two scene-viewing tasks. We also did not find evidence for a positive relationship between working memory span and μ or a positive relationship between working memory span and σ. Participants had similar average fixation durations and similar variance in their fixation durations regardless of their performance on the working memory processing (memory updating) and span (OSPAN) tasks.

Fluid Intelligence Does Not Influence Eye-Movement Behavior

Finally, we examined the relationship between fluid intelligence and individual differences in eye movement behavior as previous work has found a strong relationship between working memory performance and fluid intelligence (Fry & Hale, 1996). Performance on the RAPM task and the memory updating task was moderately correlated ($r = 0.27$, $p = 0.007$), while performance on the RAPM task and OSPAN was slightly correlated ($r = 0.16$, $p = 0.107$). Performance on the RAPM task was not significantly predictive of μ ($b = 1.75$, $SE = 2.03$, $t = 0.78$, $p = 0.436$; $BF_{JZS} = 0.53$), σ ($b = 0.47$, $SE = 0.87$, $t = 0.54$, $p = 0.591$; $BF_{JZS} = 0.32$), τ ($b = -0.65$, $SE = 3.22$, $t = -0.20$, $p = 0.840$; $BF_{JZS} = 0.30$), or mean saccade amplitude ($b = 0.06$, $SE = 0.08$, $t = 0.82$, $p = 0.414$; $BF_{JZS} = 0.48$). The Bayes Factor suggests that there is anecdotal evidence in favor of the null for μ and mean saccade amplitude, and moderate evidence in favor of the null for σ and τ. We did not find a relationship between participant performance on the fluid intelligence task (RAPM) and eye movement parameters during scene viewing.

Discussion

Previous work has shown that scene-viewing task (e.g., Castelhano et al., 2009) and individual differences in working memory span (Luke et al., 2018) both influence eye movement behavior. In the present study, we examined how task, working memory span and processing ability, and fluid intelligence influence individual participants' distribution of fixation durations and the amplitude of their saccades during scene-viewing. We found an effect of scene-viewing task on participants' eye movement behavior. Task influenced both the central tendency (μ) and the skewness (τ) of participants' fixation duration distributions. Participants tended to make more long fixations during the memorization task than during the aesthetic judgement task. Task also influenced the amplitude of participants' saccades: participants tended to make longer eye movements in the aesthetic judgement task than in the memorization task.

We found that participants with worse working memory processing (as assessed by a memory updating task) tended to have a higher τ, meaning they made more long fixations during scene-viewing. We also found a significant interaction effect between scene-viewing task and working memory processing ability. Poor working memory ability more strongly trended with higher τ for fixations collected from the memorization task than for those from

the aesthetic judgement task. We found no effect of working memory span (OSPAN) or fluid intelligence (RAPM) on eye movement parameters.

Scene-Viewing Task Effect

Cognitive guidance theories of attention suggest that we move our eyes to scene locations most relevant to our current goals (Henderson, 2003, 2007; Henderson et al., 2009). Much research has supported this assertion. For example, eye movements tend to be directed to highly-meaningful scene locations (Henderson & Hayes, 2017, 2018) and participants' task can influence which objects they attend in a scene (Castelhano et al., 2009). However, substantially less research has focused on understanding how an observer's goals influence the mechanics of their eye movements through a scene—can task not only influence where we look, but how long we look at a certain location? Or, how far we move our eyes from one fixation to the next?

Previous studies have found evidence of task-driven differences in eye movement behavior (Mills et al., 2011; Henderson et al., 1999). Recently, Cronin and colleagues (2020) found that eye movement behavior between two scene-viewing tasks was relatively similar at the level of participant means but found significant differences at the level of the distribution. Therefore, analyses using only means may be less sensitive to differences in fixation durations and saccade amplitudes when comparing between scene-viewing tasks. Indeed, in the present study, we found differences in participant fixation durations between the two scene-viewing tasks using Ex-Gaussian fits of participants' distributions. Our findings suggest that our goals influence not only where we look in a scene, but how long we look at a certain location and how far we move our eyes between fixations. These results provide evidence in support of top-down (higher level or cognitive) control of eye movements as opposed to guidance by bottom-up (low level) processes in scene-viewing (e.g., Henderson, 2003, 2007; Henderson & Hollingworth, 1999).

Relationship Between Working Memory and Eye Movement Behavior

Previous work suggests working memory and eye-movement behavior are closely related (Cronin & Irwin, 2018; Cronin, Peacock, & Henderson, 2020; Hollingworth, Matsukura, & Luck, 2013; Hollingworth, Richard, & Luck, 2008; Ohl & Rolfs, 2017; Peterson et al., 2019; van der Stigchel & Hollingworth, 2018). Given the variance in individuals' working memory capacities, it is reasonable to think variance in working memory capacity could contribute to differences in eye-movement behavior during scene-viewing and previous work has suggested this sort of a relationship exists (Luke et al., 2018). We did not find evidence of this relationship between capacity and eye-movement behavior. Instead, we found evidence that participants' working memory processing abilities were related to fixation durations, with participants with poorer working memory processing abilities tending to make more very long fixations. Like working memory capacity, working memory processing abilities vary among individuals (e.g., Salthouse et al., 1991).

Why did we find evidence for a relationship between working memory ability and eye-movement behaviors, but no relationship between working memory capacity and eye-movements? One possibility is that our OSPAN test was not difficult enough to elicit a

greater range of scores, and that the smaller variance in our scores would weaken the correlation with eye-movement behaviors. Luke et al. (2018) used 3–7 length sequences in their OSPAN task and reported a lower average score with greater variance (M = 0.77, SD = 0.15, MIN = 0.24, MAX = 1), while we used 3–5 length sequences and found high average scores, with a small range (M = .87, SD = .10, MIN = 0.48, MAX = 1). Similarly, we found a weaker correlation between our OSPAN and RAPM scores (0.16) than the range reported in other studies (0.20–0.34; Engle et al., 1999; Conway et al., 2002; Kane et al., 2004). It might therefore be necessary to increase the length of the sequences in the OSPAN task to get a greater range of scores. Given more sensitivity in OSPAN scores, it may be possible for both working memory control and working memory capacity to explain variance in eye-movement behaviors. Ultimately, it can be difficult to ensure that different cognitive tasks are equally sensitive measures. Future studies will need to be carefully designed if we seek to understand to what degree eye-movement behaviors can be explained by underlying cognitive abilities, and not just a difference in sensitivity between the measures.

It is also possible that working memory processing and working memory span interact to drive participants' performance in these individual difference tasks. When only one facet of working memory is assessed (e.g., span), a relationship between that factor and behavior may appear that is actually driven by another aspect of working memory (e.g., processing ability). For example, previous work in reading by Traxler and colleagues (2005) initially revealed a relationship between working memory capacity and fixation durations in reading. However, a subsequent analysis of the same data suggested that the relationship between working memory capacity and fixation durations was actually driven by participants' global processing speed (Traxler et al., 2012). It is possible that the relationship between working memory span and fixation durations reported by Luke and colleagues (2018) was also driven by individual differences in their working memory or global processing speeds, neither of which were assessed in their study. In our study, participants' performance on OSPAN and memory updating (a measure of working memory processing) was moderately correlated (0.33) and both factors were included as predictors in our models. When both factors were included in our model, we only found a relationship between working memory processing and fixation durations.

Why would working memory processing ability influence eye movement behavior during scene viewing? Previous work suggests that stimulus complexity influences fixation durations. Regions of a scene that contain more mid- and high-level features tend to be fixated for longer, as are regions that are low in luminance or low in contrast (Henderson et al., 1999; Henderson & Hayes, 2017; Nuthmann, 2017). Low-luminance levels at the upcoming fixation location can also influence the duration of the current fixation (Einhäuser, Atzert, & Nuthmann, 2020; Nuthmann, 2017). Observers with higher working memory processing abilities may be able to more efficiently process these semantically and/or visually complex scene regions, while observers with poorer working memory processing abilities may rely on very long fixations to compensate for less efficient processing of the visual information at fixation. It is especially interesting that we find that this relationship is significantly stronger in a memorization scene-viewing task than an aesthetic-judgement task. In memorization, participants may be more heavily influenced to explore new details of the scene to see and store in memory and would therefore need to continuously update a

working memory store of what areas of the scene they have already explored and what areas they have yet to fixate.

Future research should examine the relationship between visual/spatial working memory span versus verbal working memory span on eye movement behavior during scene viewing. Future studies would also benefit from assessing both working memory span and working memory processing speed to further examine the relationship between both facets of working memory and individual differences in eye movement behavior.

Acknowledgements:

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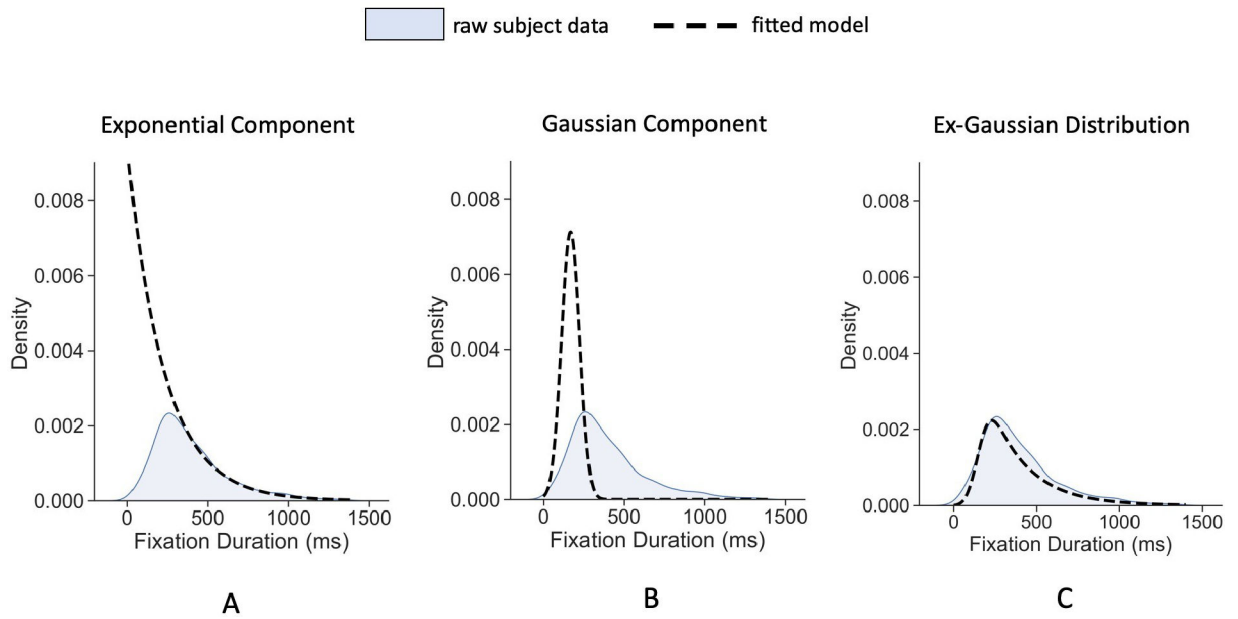
Figure 1: Components of the Ex-Gaussian Function.
The calculated Ex-Gaussian function combines the fitted exponential distribution (A) and the fitted Gaussian distribution (B) to find the Ex-Gaussian distribution (C). Each participant's raw data (e.g., the blue distribution in A-C) was fitted with an Ex-Gaussian distribution. Fixation duration length is on the x-axis while frequency is on the y-axis.
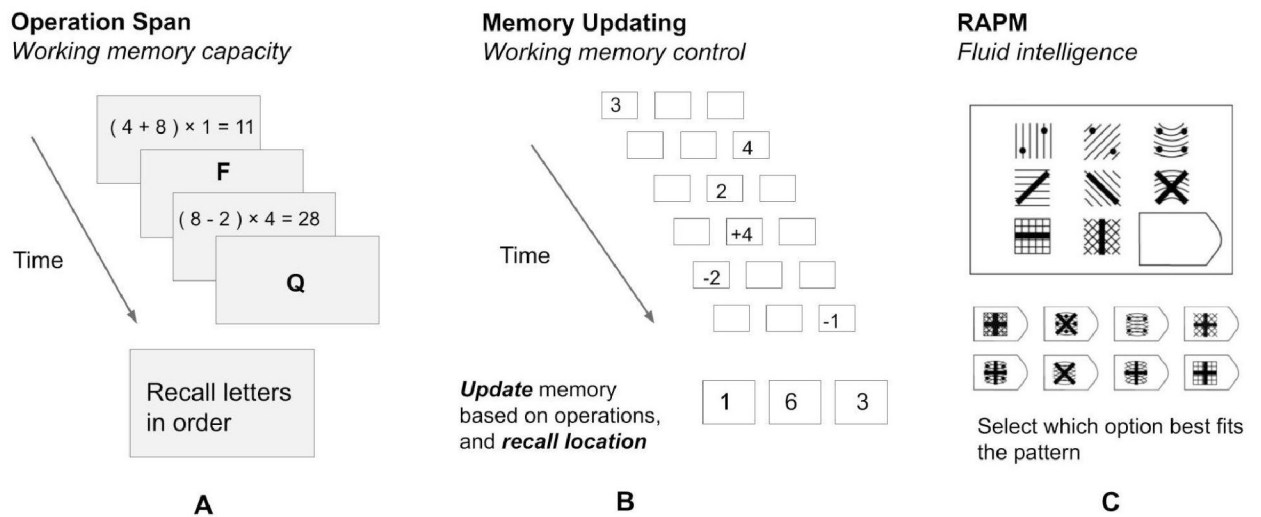
Figure 2: Operation Span, Memory Updating, and RAPM tasks.
Format of the tasks used in the study. A. Operation Span, a measure of working memory capacity. B. Memory Updating, a measure of working memory control. C. RAPM, a measure of fluid intelligence (matrices in figure adapted from Pearson, 2018 for visualization).
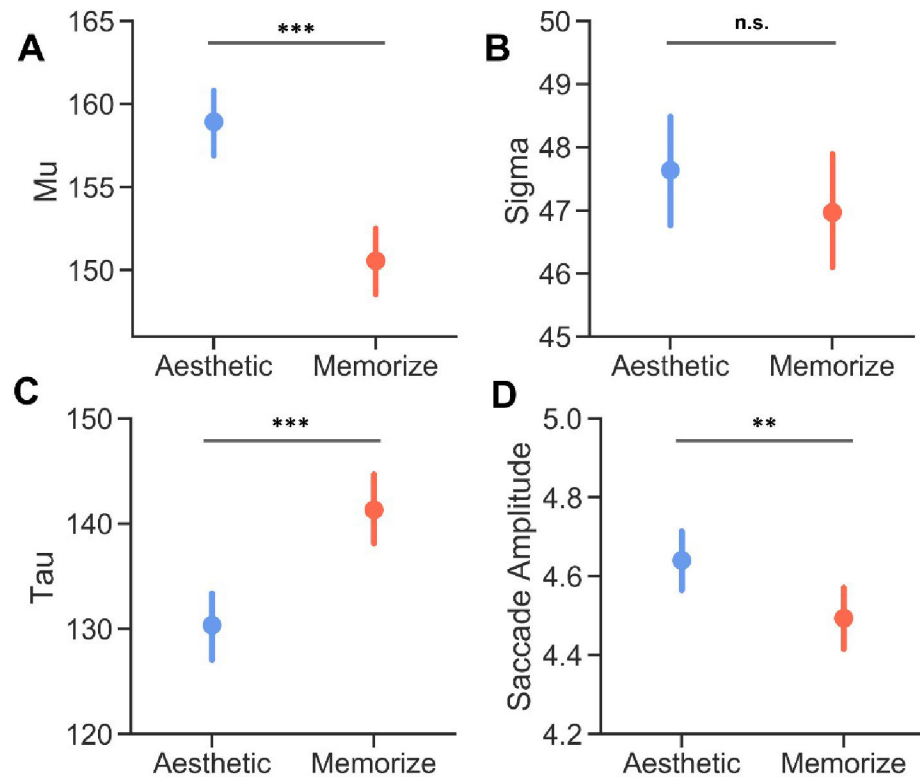
Figure 3: Relationship Between Scene-Viewing Task and Eye Movement Parameters.
Plots of the Ex-Gaussian and Saccade Amplitude means by task. Error bars are standard error of the mean. Significant differences between tasks are indicated, as assessed by linear mixed effects models with by-participant intercepts. A. Ex-gaussian μ of fixation duration. B. Ex-gaussian σ of fixation duration. C. Ex-gaussian τ of fixation duration. D. Mean Saccade Amplitude.
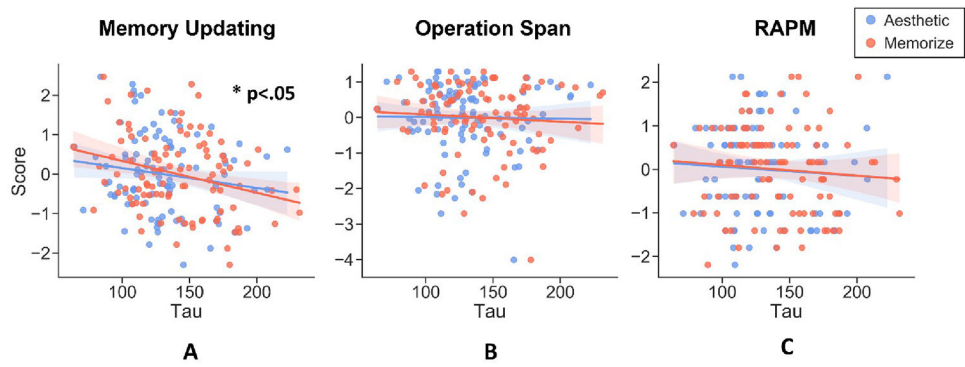
Figure 4: Relationship Between Individual Difference Measures and τ.
Scatterplots with τ on the x-axis and individual difference measure scores on the y-axisfor the two scene-viewing tasks. Shading on the regression line represents the 95% confidence interval for each individual difference measure score. Memory Updating score significantly predicted tau in a linear mixed effect model with by-participant intercepts. A. Memory updating task scores on the y-axis. B. Operation span task scores on the y-axis. C. RAPM scores on the y-axis.

Table 1

Intercorrelations of Individual Difference Measures

Individual Difference Measure	1	2	3
1. Memory Updating	-		
2. Operation Span	0.33*	-	
3. RAPM	0.27*	0.16	-

*
$p < .01$

Table 2

Mean and Standard Deviation for Eye Movement Parameters

	Aesthetic Task		Memorize Task	
	M	*SD*	*M*	*SD*
μ	158.94	19.24	150.56	20.22
σ	47.64	8.46	46.97	8.99
τ	130.36	31.11	141.32	34.32
Mean Saccade Amplitude	4.64	0.74	4.49	0.77

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Table 3

Linear Mixed Effects Model for μ

	b	*SE*	*t* value	*p* value
Task	−8.38	1.49	−5.63	< 0.001
Operation Span	−1.34	1.98	−0.68	0.500
Memory Updating	1.58	2.03	0.78	0.436
RAPM	1.75	1.94	0.90	0.366

Table 4

Linear Mixed Effects Model for σ

	b	*SE*	*t* value	*p* value
Task	−0.67	0.57	−1.17	0.242
Operation Span	0.01	0.89	0.01	0.989
Memory Updating	−1.12	0.91	−1.22	0.222
RAPM	0.47	0.87	0.54	0.591

Table 5

Linear Mixed Effects Model for τ

	b	*SE*	*t* value	*p* value
Task	10.96	2.10	5.23	< .001
Operation Span	1.15	3.29	0.35	0.727
Memory Updating	−5.04	3.53	−1.43	0.030
RAPM	−0.65	3.22	−0.20	0.840
Memory Updating: Task	−4.55	2.10	−2.17	0.030

Table 6

Linear Mixed Effects Model for Mean Saccade Amplitude

	b	*SE*	*t* value	*p* value
Task	−0.15	0.05	−3.11	0.002
Operation Span	0.05	0.08	0.70	0.485
Memory Updating	−0.09	0.08	−1.07	0.283
RAPM	0.06	0.08	0.82	0.414