Title

Understanding the Plasticity, Motor Deficits and Possible Adaptations Associated with Poor Stereopsis

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Understanding the Plasticity, Motor Deficits and

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By

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requirements for the degree of

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Professor Dennis M. Levi, Chair

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By Angelica Godinez

Abstract

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The experience of stereovision is something that those of us who have it, can never image a life without it, but those who don't have it, may become keenly aware that they are missing something else everyone has. The experience of stereovision has been overlooked – with some people arguing that it may not even be a necessary function. However, in this dissertation I show evidence that stereovision is important for everyday visuomotor tasks, those who have impaired stereovision show deficits in the motor movements most dependent on binocular vision and visual feedback. Indeed, the model that best predicts the relationship between stereoacuity and reaching-and-grasping movement kinematics is a linear sum of the peak velocity and the time it takes to for the grip. In particular, the time it takes to form the grip is a movement parameter that reflects the certainty of the intrinsic 3-dimensional properties of the target.

In addition, a lifetime of experience with impaired stereovision does not result in functional adaptations in motor movement that are better than adaptations from people with stereo-loss in adulthood. But rather, the experience of stereovision seems to provide some benefit or stability when binocular vision is artificially disrupted.

Furthermore, we provide evidence that stereovision can be strengthened in adulthood vis direct training using perceptual learning and scaffolding cues in virtual reality. We conclude that the experience of stereovision is indeed an important function in everyday visuomotor tasks and that direct stereo training can be a good tool restore stereovision in children and adults alike.

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Dedication

To my family- Familia Godinez Velasco. This dissertation would not have been possible without the unwavering support and encouragement from my parents. Even though they still have no idea what it is I do, they have always encouraged me to follow my curious and creative desires. *Gracias mama Toña y papa Jose por siempre creer en mi y por darme amor y apoyo incodicional*. Thank you to my siblings (Tony, Nacho, Claudia, Lupe, Vero and Caro) for all the many weekends at the house with endless laughter and constant banter. You all helped me stay grounded and focused.

Most importantly, I dedicate this dissertation to the little ones – my nieces and nephews (Angel, Alexis, Izel, Manny, Antonio, Julian, Alex, Adrian, Evelyn, Jesus and the ones to come). I embarked on this journey to fuel my intellectual curiosity but also to pave a new way for you all. My hope is not that you all become scientists, but rather that you find your passion and run with it. I love you all.

Chapter 1

Introduction

The goal of this dissertation was to generate a better understanding of (1) the plasticity of stereopsis, (2) the relationship between stereoacuity and prehension kinematics and (3) the possible adaptations to motor movement as a result of a lifetime with impaired or nil stereopsis.

Humans have at their disposal a variety of cues to infer depth. Of those cues, most are non-binocular, meaning they require only one eye: overlapping (interposition), perspective (conical projection), lighting-shading, chromatic attenuation, focus and motion parallax (created by the motion between an observer's head and the perceived scene). However, the most compelling cue to depth, stereopsis, requires the functional coordination of both eyes. Stereopsis plays a critical role in extracting depth information from natural scenes[1], breaking camouflage and planning and executing everyday visuomotor tasks[2–4].

However, not everyone has the ability to functionally coordinate their eyes and thus lack the experience of stereovision. Among the famous examples of Bruce Bridgeman and Sue Barry— both scientist who recovered stereovision and have given colorful accounts of their new visual experience[5,6], an estimated 3-40% of the population are stereo-deficient and 7% are stereo-blind[7].

A big culprit of impaired stereopsis is amblyopia. Amblyopia is a neuro-developmental condition that arises from unequal inputs to the brain. The most common causes of unequal inputs are: a misalignment of the visual axis (strabismus) and/ or unequal refractive error between the two eyes (anisometropia). If amblyopia is treated in childhood, stereopsis can sometimes be recovered. However, there is no agreed upon treatment for adults.

Prehension can be divided into phases: A ballistic preprogrammed movement called the reach and an adjustive more sophisticated sequence of movements called that grasp. The two phases are thought to use different visuospatial information. The reach is analogous to a saccade with the goal getting as close to the target as possible. In this phase, target location is encoded in egocentric coordinates and depends on determining the distance of the target with respect to the body[8]. The grasp, on the other hand, is a bit more sophisticated since the goals are to travel the remaining distance, make the necessary adjustments to the hand, and apply the grip. At this stage, visual feedback is very important since the observer is tasked with calculating the intrinsic 3-dimensional properties of the target and the remaining distance of the moving hand and fingers to the target[8]. Thus, at this phase, the target's location, the remaining distance to travel and the distance of the hand and fingers to the target are encoded in allocentric coordinates.

From previous studies, we know that binocular vision and in particular stereovision plays an important role in reaching and grasping[3] and that people with impaired stereopsis also show impaired deficits[4,9–12]. Not surprisingly, these deficits are most pronounced in movement aspects that rely on binocular vision and visual feedback[13]. However, some researchers have claimed possible motor movement adaptations from a lifetime of having impaired or nil stereovision[3,11,14,15]. However, many have made the claim that reduced binocular vision and in particular stereopsis is the reason for impaired visuomotor performance[12,14].

In three experiments, we attempt to (1) quantify the motor deficits in people with impaired or nil stereopsis (Chapter 3), (2) model the relationship between stereopsis and prehension (Chapter 3), (3) quantify the possible motor adaptations that result from a lifetime of experience with impaired or nil stereopsis (Chapter 4) and make the case for recovery of stereopsis via direct stereo training and perceptual learning (Chapter 2).

Chapter 2

Scaffolding Depth Cues and Perceptual Learning in VR to Train Stereovision: A Proof of Concept Pilot Study

2.1 Introduction

Our rich perception of depth provides important information for navigation[2] and action[3,4]. Depth perception is a complex process which requires the brain to integrate different visual cues[16]. Of those cues, many require only one eye (non-binocular cues) and include overlapping (interposition), perspective (conical projection), lighting-shading, chromatic attenuation, focus and motion parallax (created by the relative motion between an observer's head and the perceived scene).

Stereopsis plays a key role in extracting depth information from natural scenes[1], breaking camouflage[17], and planning and executing everyday visuomotor tasks[2–4]. However, abnormal visual experience during the "sensitive period" of development[18,19] may result in amblyopia and, as a result, in reduced or absent stereopsis[20]. Amblyopia, the leading cause of visual loss in children, is a neuro-developmental disorder arising from an imbalance between the ocular inputs to the visual pathway[21–23]. It is characterized as reduced visual acuity in an otherwise normal eye despite best optical correction[24] and is typically secondary to misalignment of the visual axis (strabismus) and/or unequal refractive error (anisometropia).

Under everyday conditions, the loss of stereopsis is the most significant issue for individuals with amblyopia and strabismus, affecting their ability to reach and grasp[4,9], navigate safely and rapidly[2] and play certain sports[25]. Indeed, a recent analysis suggests that ≈ 7% of the population may be stereoblind[7]. Thus, for the overall wellbeing of people with amblyopia, stereopsis may be an important function to recover and/or strengthen. Perceptual Learning (PL), defined as "any relatively permanent and consistent change in the perception of a stimulus array following practice or experience with this array…"[26], has demonstrated great potential in amblyopia treatment[27]. Although functionally suppressed when viewing binocularly[28,29], binocular mechanisms seem to be intact in some people with amblyopia[30–32], making stereo training a viable option. A number of different approaches have been evaluated for the recovery of stereopsis when compromised by amblyopia[33]. However, it is important to point out that stereopsis is more impacted in strabismic than in anisometropic amblyopia[33,34] and recovery may require more active treatment[33]. Interestingly, patients with strabismic amblyopia benefit more from dichoptic training compared to monocular training and fare even better with direct training[33]. Furthermore, people with normal binocular vision can also benefit from training, improving their stereoacuity thresholds[35–37]. However, laboratory-based paradigms require participants to sit through many hours of monotonous psychophysical training[38,39].

Considering that the main drawbacks of laboratory-based training paradigms are participant compliance, attention and motivation, several authors have proposed the use of specifically designed video games to treat amblyopia. Gamification, i.e. the use of game principles in non-game contexts, include the use of levels of increasing difficulty adapted to participant performance, rewards, a story line, and social context, among other aspects[40–42]. Several laboratory studies have reported benefits of using video games to treat amblyopia[43–48], including direct stimulation of stereopsis[49].

Recent commercialization of VR-HMDs has encouraged the design of therapies that incorporate gamification principles and builds upon successful laboratory-based techniques such as PL and dichoptic training. VR-HMDs provide the ability to present separate images to each eye, correct through software misalignment due to strabismus and adjust contrast or luminance independently for each eye until balanced binocular vision is achieved. VR-HMDs provide a wide visual field, facilitating vergence in users with strabismus, and large disparities that may help improve stereopsis[50,51]. Furthermore, VR-HMDs provide the ability to control depth cue content, with the exception of accommodation, which is the only cue without a commercial solution[52]. Depth cue content control facilitates design treatments based on a cue scaffolding strategy, assuring engagement in PL activities. This may be especially important for patients with poor to null stereopsis, who would become very frustrated by failing on a game with only binocular (disparity) cues. Indeed, Ding and Levi (2011) paired an informative monocular position cue with their disparity cue based on the hypothesis that patients with poor stereopsis have relied primarily on non-stereo depth cues, and with practice and feedback, patients could learn to increase reliance on the stereo information. Similarly, Vedamurthy et al. (2016), paired disparity cues with perspective cues while providing rich feedback and demonstrated that participants with poor or no stereopsis learned to upweight reliance on the stereo information.

Our aim was to develop and pilot two VR games that combine demanding stereovision tasks, dichoptic PL and depth cue scaffolding. The games were designed to incorporate nine principles: (1) alignment of images on corresponding areas in the two eyes, and (2) balancing the perceptual input to facilitate fusion; (3) combining non-binocular and binocular cues to depth as a 'scaffold' for depth judgements and systematically reducing the non-binocular cues; (4) exposure to large binocular disparities. Recent work has shown that viewing engaging and immersive 3D action videogames with large disparities improved stereoscopic vision in both amblyopic and neurotypical observers[50,51]. (5) A dichoptic anti-suppression task (6) requiring depth perception for action; (7) rich feedback, (8) ability to track in-game performance, including (9) trial-by-trial tracking. The latter requirement enabled us to compare the evolution of depth perception under different cue conditions.

2.2 Methods

2.2.1 Participants

Twenty adults (mean age: 28 ± 2.5, range: 18–62 years, 14 female), 10 with normal or corrected-to-normal vision and without ocular pathologies (stereo-normal group) and 10 with binocular impairment (stereo-anomalous group), participated in the study. Participants were recruited by telephone from the Meredith W. Morgan University Eye Center's internal list of patients who gave written consent to be contacted for research studies and through internal UC Berkeley student list serves. The Institutional Review Board of the University of California, Berkeley approved the study protocol. The study was conducted according to the tenants of the Declaration of Helsinki and informed consent was obtained from each participant. Exclusion criteria for the study included: (1) ocular pathologies (e.g., macular abnormalities) or nystagmus, (2) non-concomitant or large angle constant strabismus (> 30 prism diopter), (3) inability to fuse, (4) constant esotropia (> 20 prism diopters), (5) VA ≥ 20/200, and (6) previous dichoptic visual training of more than 10 h.

2.2.2 Study design and training

All participants underwent a complete clinical assessment before and after the study (Figure 2.1). The complete clinical assessment included evaluation of: (1) retinal health (ophthalmoscopy), (2) current prescription, (3) refraction at distance, (4) VA (Bailey Lovey visual acuity chart), (5) ocular deviation (monocular cover-uncover test and alternate cover test, using accommodative stimuli, and 4BO test), (6) binocular fusion (Worth Dot at 33 cm and 3 m) and (7) clinical stereoacuity (Randot Circles Stereotest and Random Dot 3 Stereo Acuity Test with Lea Symbols).

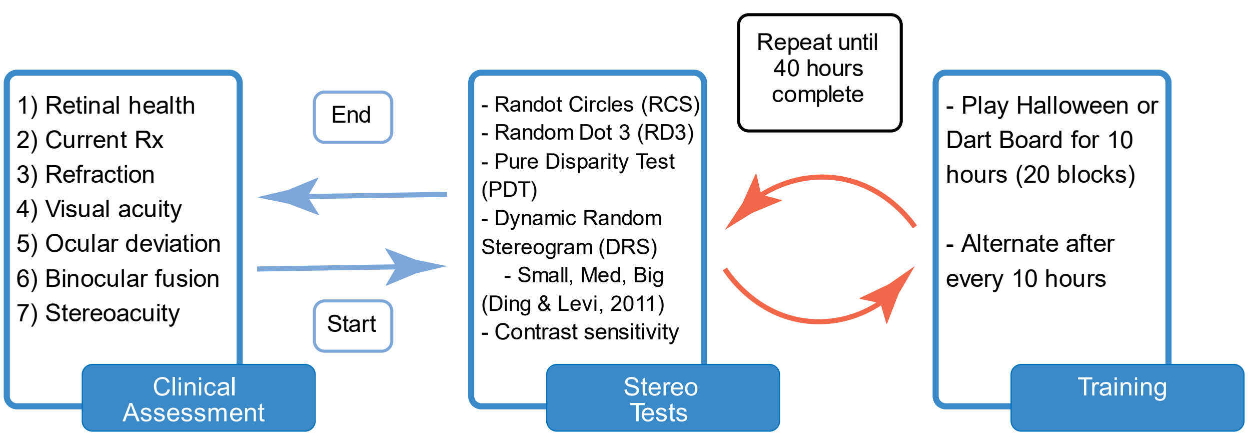

Figure 2.1. Study and training schematic. Each participant began with a clinical assessment. Followed by clinical and psychophysical stereoacuity tests. Participants then alternated between playing one of two games (Halloween or DartBoard) for 10 hours. After every 10 hours (20 blocks), clinical and psychophysical stereoacuity tests where administered until 40 hours were completed. Lastly, the clinical assessment was administered.

Participants were categorized as having anisometropia if there was a difference ≥ 0.50 D in spherical equivalent refraction or ≥ 1.5 D difference in astigmatism in any meridian, between the two eyes[53]. Participants were classified as having strabismus in the presence of a tropia with the cover test and/or showing micro-strabismus by the 4_{Δ}BO test.

Following the clinical assessment, eligible participants were placed in either the stereo-normal or stereo-anomalous group based on their initial Randot Circles Stereotest stereoacuity measurement. Inclusion criteria for the stereo-anomalous group was baseline stereoacuity of 50 arc secs or worse. According to this criterion, ten participants were assigned to the stereo-anomalous group and ten to the stereo-normal group. Four participants in the stereo-anomalous group had anisometropia and five strabismus (one of them micro-strabismus). The remaining participant in the stereo-anomalous group did not exhibit anisometropia or strabismus and was labeled stereo-weak.

Training was organized in four 10-h intervals, where participants played one of the two games designed specifically for this study: Halloween or DartBoard. On each day of training, participants played two 30-min blocks for a total of one hour. Most participants completed 80 blocks of training with the exception of N2 and N4 who completed 40 blocks, and AS1, AA1, N5, N7, N9, N10 who completed 100 blocks total (in these cases, DartBoard was played for 60 blocks).

After every 10 h of game play, participants completed the clinical and psychophysical stereoacuity tests. For clinical stereoacuity, we used the random-dot stereograms RCS and RD3. For psychophysical tests, we used the PDT and DRS described in detail in Ding & Levi, 2011. Briefly, stimuli were viewed through a stereoscope and presented on a Sony CRT monitor (CPD-G500) at a viewing distance of 68 cm from the participant. To correct for misalignment, participants were shown a nonius cross with a fusion-lock frame and were able to move the position of the mirrors to align the cross. For participants with strabismus, added prisms were used if necessary. DRS stimuli consisted of circular bright dots (126 cd/m_2) on a dark background (1.37 cd/m_2) and were presented in three different sizes (small: 22.64, medium: 90.55, big: 362 arc secs). PDT stimuli consisted of two 3° × 3°sine-wave gratings (0.67 cpd) at 48% contrast with sharp edges. DRS and PDT stimuli were visible to the participant for 2 s.

In addition to stereoacuity, we monitored contrast sensitivity using the qCSF with a Bayesian staircase[54]. The qCSF test was displayed on a 46″ NEC LCD monitor (model p463) with a resolution of 1920 × 1080 and a contrast ratio of 4,000:1. Participants were seated in a chair 6 m from the screen. CSF was measured on the dominant (DE), non-dominant (NDE), and both eyes (OU). For the stereo-anomalous group, NDE was determined by amblyopic eye in participants with amblyopia, deviated eye in participants with strabismus, and eye with worse VA in participants with anisometropia. For the stereo-normal group, eye dominance was assigned at random. The qCSF test consisted of 25 trials for each eye condition. On each trial, participants were presented with a set of three letters of the same size in decreasing spatial frequency and luminance from right to left. Participants were instructed to identify the letters on the screen.

Once the training was considered complete, the clinical assessment was administered again.

2.2.3 Games and apparatus

The games were played using the Oculus Rift DK-2, which is equipped with a gyroscope, accelerometer, and a magnetometer with an update rate of 1000 Hz. The Oculus Rift DK-2 has a resolution of 960 × 1080 for each eye, a 100-degree field of view, a refresh rate of 60–75 Hz, and a position tracking refresh rate of 60 Hz. To run the software, we used the Alienware AREA51R2 computer with Intel Core i7-5820 K CPU and an NVIDIA GeForce GTX 980 graphics card.

Importantly, for participants who were unable to fuse the images due to strabismus and/or suppression, games started with a high contrast fusion-lock frame presented to each eye, and a dichoptic nonius calibration. To correct for misalignment, the researcher manually adjusted the images presented to each eye (horizontal, vertical, and cyclo deviations, plus aniseikonia) until the participant reported complete alignment of the dichoptic cross (Figure 2.2- Top left), allowing correction for any deviation in the subjective angle of squint. To minimize or eliminate suppression, image luminance (ranging from equal luminance of both images to complete occlusion of one eye) was adjusted for the dominant eye until participants reported equal luminance of the dichoptic lines crossing at the reference frame.

Figure 2.2. DartBoard and Halloween game screenshots. Top left: Fusion-lock frame calibration for DartBoard (similar in Halloween) to eliminate subjective misalignment angles. Top right: DartBoard 3-AFC suppression task. Bottom left: DartBoard trial example. Bottom right: Halloween trial example.

Briefly, the Dartboard game required participants to judge the movement of a dartboard in depth (z-direction) and launch a dart (presented in front, perpendicular to the participants' eyesight) to hit the center of the board. After each attempt, they were given an auditory tone to indicate when they hit the board and visual feedback indicating the number of points they received. If the dart hit the center of the board, participants received a trophy which was displayed on the screen. Additionally, a scoreboard to the left of the participant kept track of a number of performance variables (e.g., condition, points, accuracy (stereoacuity in the video), average accuracy).

The main variables in the Dartboard game are the dart and the back wall, which are at a distance of 1.5 and 2.5 m respectively, from the participant. The board movement begins linearly and perpendicular to the wall, leaving a gap from the dart (0.7 m), which is the third variable. Movement of the board is paused at certain time intervals (pause of 0.5 ± 0.1 secs each 1.0 ± 0.2 secs of movement) to facilitate estimation of depth. However, to avoid any time-learning effects, both the dart and the board-to-dart gap distance change randomly from trial to trial (dart distance 1.5 ± 0.5 m, board-to-dart gap 0.7 ± 0.2 m). Furthermore, the speed of the board also changes between trials (0.25 ± 0.02 m/sec) and a perpendicular movement in the direction of the dart is also introduced (± 0.05 m/sec). Finally, as we will explain shortly, to avoid perspective cues in Condition 2 and 3, the size of the dart (length 0.20 ± 0.04 m) and the board (diameter 0.40 ± 0.08 m) vary from trial to trial.

The Halloween game required participants to judge which target in a series of 3–7 was closest and eliminate them sequentially (see video for reference). Again, participants were presented with both auditory (gunshot sound) and visual (points and written feedback such as "Great!") to indicate that they hit the target.

In the Halloween game, targets (phantoms, vampires, pumpkins) are presented at 2 m from the participant (first scene variable) and move closer to the participant at time constant intervals (5–8 steps, each 4 secs long), until they reach a close distance point (1.5 m from the participant). The player's task is to destroy the targets before they reach the close distance point. All targets (e.g., phantoms) are at different distances and before they reach the close point, the player must destroy them in order from closest to farthest. One of the targets presented can be an anti-suppression target named cyclops (has only one eye and is presented to only one eye of the participant), which should be avoided (i.e., not destroyed). The game is organized in levels, where the number of targets and steps varies (e.g., in level 1 there are five steps and three phantoms; in level 4 there are four phantoms plus one cyclops and eight steps). Linked to the concept of level is the stereoacuity demand (range: 800–400), i.e., the depth difference between each two consecutive targets: as an example, the depth between targets in level 1 is 800 arc secs while in level 4 the depth is 400 arc secs.

Cue scaffolding was implemented in both games, creating three consecutive cue scaffolding conditions (Condition 1, 2, and 3), which progressively minimized or eliminated non-stereoscopic depth cues, from an up-to-date VR scene (where accommodation was the only depth cue not simulated) to a scene where only retinal disparity was available. Each block began with Condition 1, which consisted of non-binocular and binocular cues to depth including shadows, perspective, motion parallax, and binocular disparity. In Condition 2, shadows were eliminated and perspective reduced by removing relative size as a reliable cue (i.e., object size was not relative to object distance). Lastly, in Condition 3, motion parallax was limited (only rotational movements of the head were allowed by the software), making binocular disparity the most helpful (almost unique) cue to calculate distance.

A suppression task (by means of dichoptic images) was also inserted in each games' mechanics to help participants become aware of suppression episodes. For example, in the DartBoard game, participants were instructed to identify the smiley face (in a set of three) with both eyes open (3-AFC), which could only be seen if binocular fusion was maintained (Figure 2.2- Top right). In the Halloween game, participants were instructed to destroy all targets with both eyes open and avoid targets with only one eye, which again could only be achieved if binocular fusion was maintained. Importantly, the purpose of the suppression task was to bring awareness of suppression episodes to participants who actively suppressed. Suppression failures were registered in both games.

Game mechanics and respective in-game measurements were different in the two games. In DartBoard, participants were instructed to launch a dart, which was presented at the center of the screen, towards a dartboard that traveled from the back of the participant and moved towards the background of the scene (Figure 2.2- Bottom left). Each dart launch ended a trial. Movement of the dart once launched, was always linear and traveled from left to right, while movement of the board was linear, but not necessarily at a 90° angle or at the same speed of the dart. Both linear movements occurred in the same plane where the observers' eyes were. Thus, there was no way of guessing the intersection of both trajectories using purely monocular cues. The motion of the dart board was designed to stop at intervals in order to facilitate the exercise. The perceptual learning task for the participant was to estimate, using the background wall as reference, when the dart (the stationary object) and the dart board (the object moving in depth) were at the same distance (i.e. depth error could theoretically be as low as zero arc secs).

In Halloween, participants were instructed to shoot the closest target in a variable set of targets (from three to seven phantoms, pumpkins or vampires) as they approached the participant (Figure 2.2- Bottom right). Each shot ended a trial. Similar to the movement of the dartboard, the approaching targets stopped at intervals to facilitate the exercise. Importantly, relative parallax between the targets were constant, and decreased across trials from 1000" to 400" over time, depending on the participants' performance. Therefore, the perceptual learning task in Halloween was to determine the relative depth distance between several objects (an n-alternative forced choice task). It is important to note that DartBoard in-game measurements result in depth error values for each trial and for each cue scaffolding condition, while Halloween in-game measurements result in the proportion of correct responses for each stereo demand at each condition.

2.2.4 Data analysis

Differences between stereo-anomalous and stereo-normal groups and/or cue scaffolding conditions were calculated through mean comparisons. Analysis of variance was used to establish differences between variables with more than two levels of comparisons. ANOVA was used for variables with a normal distribution and Kruskal–Wallis when distributions were not normal. We performed a two-sample comparison using the Student's t-test when data followed a normal distribution and Wilcoxon-Mann–Whitney otherwise. The Kolmogoro-Simirnov test was used to confirm normal distribution of data. The relationship between variables was made through Pearson's correlation. The significance level was set to 0.05 for all comparisons. The R-Statistics (v3.6.3) and Python (3.6.8) were used to run the analysis.

2.3. Results

2.3.1 Changes in stereoacuity

The most important result of this study is the improvement of stereoacuity after training, particularly in the stereo-anomalous group (Figure 2.3). Note that several participants were “stereoblind” (i.e., unable to identify the largest disparity presented) initially, but showed measurable stereoacuity after training.

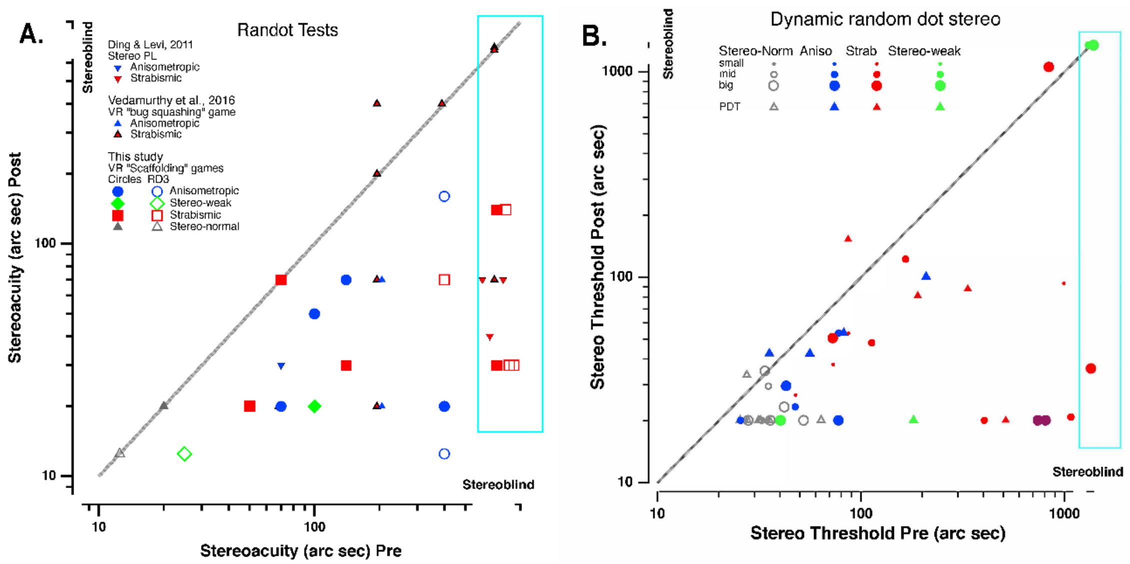

Figure 2.3. Stereoacuity transfer after training for clinical and psychophysical tests. (A) Improvement in clinical stereoacuity as a function of initial RCS (filled symbols) and RD3 (open symbols) threshold and comparison with Ding & Levi, 2011 (upside-down triangles) and Vedamurthy et al., 2016 (right-side up triangles). (B) Psychophysical stereoacuity improvement as a function of initial stereo threshold for PDT (triangle), DRS small (small circle), DRS medium (medium circle) and DRS big (big circle). In both figures, colors indicate binocular condition: anisometropia (blue), strabismus (red), stereo-weak (green), and normal stereo (grey). Data under the unity line indicate an improvement in stereoacuity.

We first analyzed the mean difference (before and after treatment) for each test between the stereo-normal and stereo-anomalous groups (Table 2.1). We found statistically significant differences between the stereo-normal and stereo-anomalous groups in both pre- and post-analysis for all tests, except for the Dynamic Random-dot Stereogram test (DRS) small pre- treatment (P = 0.052) and DRS big post- treatment (P = 0.100). When comparing pre- and post- results, although median results differ in the stereo-anomalous group clearly, significant differences occurred only in the Pure Disparity Test (PDT) for stereo-normal participants and in the Randot Circles Stereotest (RCS) test for stereo-anomalous participants.

Table 2.1

Pre and post median stereoacuity thresholds for each group and stereoacuity test and statistical mean comparison (p-value)

	Pre (median)		Post (median)		p-value Normal vs Anomalous		p-value Pre vs Post	
	Normal	Anomalous	Normal	Anomalous	Pre	Post	Normal	Anomalous
RCS	20.0"	100.0"	20.0"	30.0"	<0.001*	0.006*	-	0.004*
RD3	12.5"	400.0"	12.5"	89.4"	<0.001*	0.002*	-	0.164
PDT	29.5"	185.6"	20.1"	66.0"	<0.001*	0.002*	0.017*	0.054
DRS small	20.1"	59.1"	20.1"	23.6"	0.052	0.006*	0.078	0.507
DRS medium	20.1"	93.6"	20.1"	22.1"	0.004*	0.045*	0.871	0.168
DRS big	23.7"	239.6"	20.1"	24.4"	0.003*	0.100	0.121	0.055

The clinical tests show a clear improvement in stereoacuity for stereo-anomalous participants (Figure 2.3A), but not for stereo-normal since stereo-normal participants were at ceiling. The psychophysical tests, with neither monocular nor non-stereoscopic binocular cues, reveal significant improvements for both groups (Figure 2.3B and Table 2.1), even though the differences between pre- and post-treatment show no statistical significance.

Adopting the criteria for stereoacuity improvement as an improvement of at least two levels on the clinical tests and a final stereoacuity threshold of 140 arc secs or better[33], all participants in the stereo-anomalous group except for ASM1 improved in the RCS test, and all but ASM1, AS1, AS2 and AS4 improved in the Random Dot 3 Stereo Acuity Test with Lea Symbols (RD3).

Participant AMS1 failed to improve according to both clinical tests, although PDT and DRS small show an improvement. Participant AS1 failed to improve according to the RD3, but improved on all the other tests. Participant AS2 did not exhibit improvement with either the RD3 or the PDT (small regression) but showed improvements with all the other tests. Finally, participant AA3 appeared to regress in the PDT, but improved according to all other tests.

Seven of the ten participants in the stereo-normal group showed improvements in the PDT: N9 and N10 exhibited a regression and N1 was at ceiling. Similarly, seven of the ten participants showed improvements in DRS: N3 and N5 were at ceiling and N2 exhibited a slight regression in DRS big. Those improvements were not evident in the clinical tests because all stereo-normal participants were at ceiling before treatment.

Lastly, we analyzed whether the initial stereoacuity predicted the magnitude of improvement in stereoacuity following training (Table 2.2). Our analysis reveals strong and significant correlations between the initial psychophysical stereoacuity threshold and the amount of improvement (i.e., the Pre:Post stereoacuity ratio [PPR]) for the stereo-normal group, but failed with the clinical stereoacuity tests, as the participants were at ceiling. For the stereo-anomalous group the correlations are moderate and not statistically significant.

Table 2.2

Correlation coefficients and p-values using Pearson's test between PPR and initial stereoacuity values for stereo-normal and stereo-anomalous groups

	Stereo-normal		Stereo-anomalous	
Test	Correlation	p-value	Correlation	p-value
RCS	-	-	0.49	0.155
RD3	-	-	-0.18	0.625
PDT	0.92	< 0.001*	0.63	0.050
DRS small	1.00	<0.001*	0.57	0.084
DRS medium	0.82	0.003*	0.47	0.169
DRS big	0.88	< 0.001*	0.49	0.153

2.3.2 Changes in visual acuity and contrast sensitivity

No significant changes in visual acuity (VA) were observed after training across participants or between groups. This is not surprising since only two of the stereo-anomalous participants are amblyopic. Similarly, no significant changes in contrast sensitivity were observed between groups or eye tested for the quick Contrast Sensitivity Function (qCSF) area under the curve or acuity.

2.3.3 Preliminary control study

Prior to the study, to ensure that Condition 3 of our games required stereopsis for optimal performance, a neurotypical participant played the game under binocular and monocular conditions (via patching). For both games, performance was substantially worse and dichoptic errors increased under the monocular condition. This strongly suggests that the tasks in Condition 3 require stereopsis for optimal performance and cannot be solved otherwise.

2.3.4 DartBoard in-game performance

The DartBoard game provided 102,252 data points from 20 participants. This resulted in approximately 40 trials per condition and block. On each trial we calculated depth error in arc seconds, which is the difference between the dart landing position and the center of the board.

We define within-block learning as a decrease in depth error from the beginning to the end of a particular condition in a specific block. In Figure 2.4, we performed a linear fit on depth error per condition and block and extracted three within-block results: initial, final, and mean depth error. Most stereo-anomalous participants exhibit within-block learning per condition.

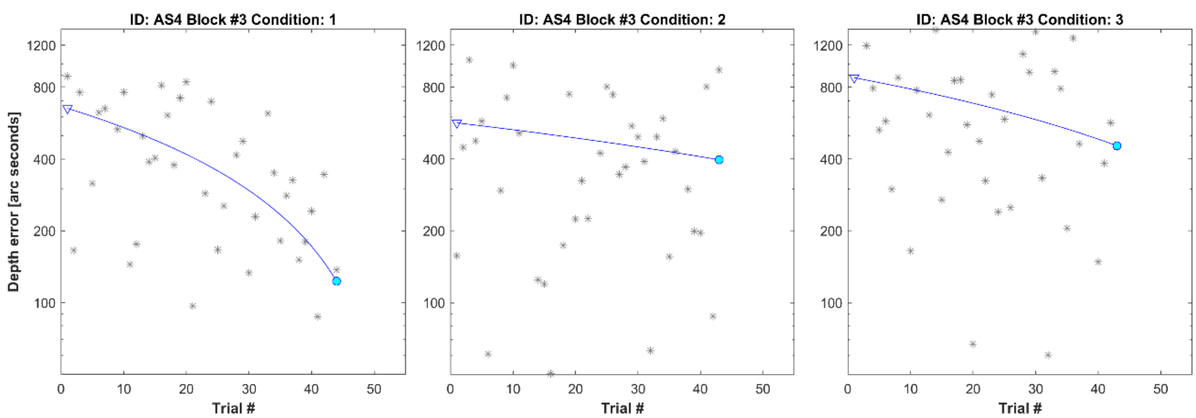

Figure 2.4. Within-block learning example (AS4, strabismic stereo-anomalous participant). From left to right, raw data in block number 3 under Condition 1, 2 and 3. Each asterisk represents depth error (arc seconds) from one trial. The continuous blue line represents a linear fit of the depth error at each trial. The triangle represents the start point and the circle the end point.

After training, an improvement is expected, and we call this across-block learning. Figure 2.5 shows 40 blocks of DartBoard data obtained from participant AS4. For clarity, each condition is represented in a different graph. Each within-block result is represented as a vertical line. The triangle represents the initial depth error while the circle represents the final depth error. Blocks with a triangle above the circle indicate a reduction in depth error (i.e., within-block positive learning). To quantify across-block learning, we fit an exponential function to the initial, final and mean within-block depth error for each participant and condition. The difference between the exponential fit of the initial and final depth error for each condition represents the within-block learning trend. AS4 exhibits a positive within-block learning trend in Condition 1, whereas within-block learning in Condition 3 tends to plateau after 30 blocks. The exponential fit also allows us to understand each participants' learning pattern across blocks. AS4 exhibits a clear across-block positive learning pattern in Condition 1, regardless of depth error considered (initial, mean or final), but not for Condition 2. In Condition 3 only initial depth error exhibits a clear positive learning pattern.

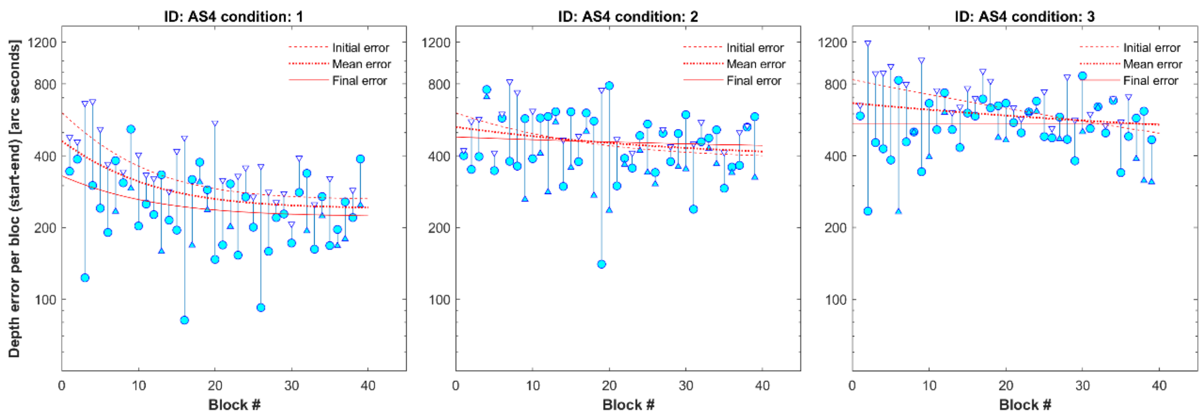

Figure 2.5. Across-block learning example (AS4, strabismic stereo-anomalous participant). From left to right, results under Condition 1, 2 and 3. Results from each block are represented as a vertical line, with a triangle on one end indicating the depth error at the beginning of the block and a circle indicating the depth error at the end of the block. A triangle at the top indicates depth error reduction within a block. Three exponential plots have been superimposed and represent across-block learning. The fits represent an exponential function to the initial error at each block (dotted line), mean error (hashed line), and final error (continuous line).

To visualize the across-block learning patterns in greater detail, Figure 2.6 shows only the exponential fit using the final within-block depth error for the three conditions in the same graph. This figure compares different learning patterns of four participants: AA4 (anisometropic), AS4 (strabismic participant shown in Figure 2.5), N7 (stereo-normal) and AMS1 (micro strabismic).

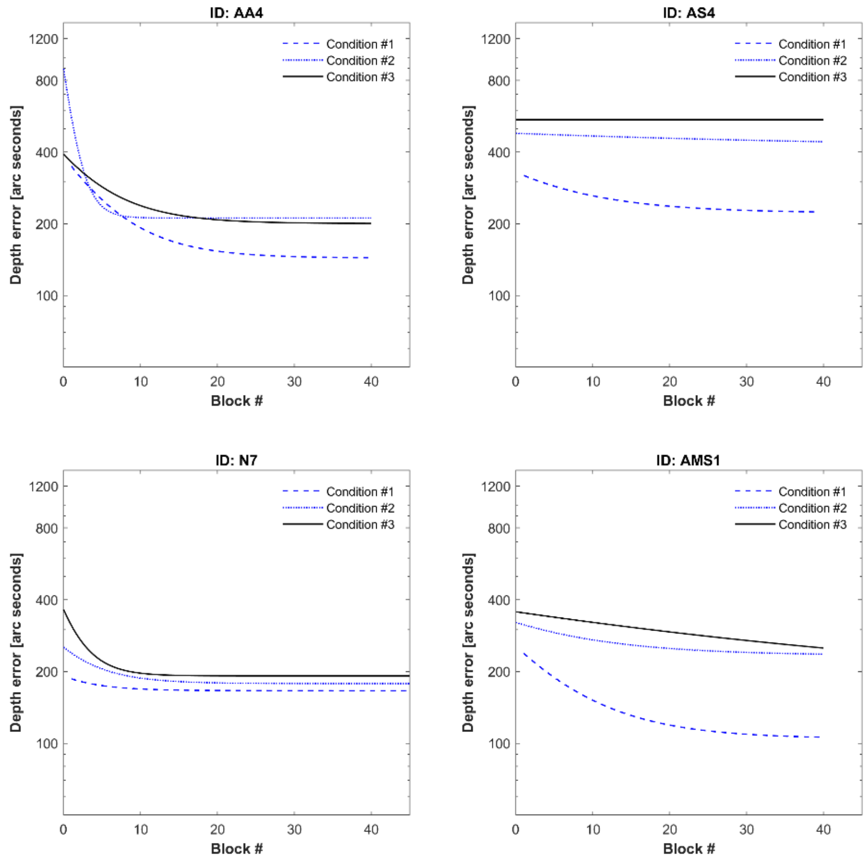

Figure 2.6. Across-block learning in four participants. From upper left to bottom right: AA4, stereo-anomalous anisometric; AS4, stereo-anomalous strabismic; N7, stereo-normal; AMS1, stereo-anomalous with micro strabismus. Each graph shows the exponential fit of the end-block depth error in the three conditions: Condition 1, blue dashed line; Condition 2, blue dotted line; Condition 3, dark continuous line. Although N7 performed 60 blocks of training, only first 45 blocks are represented to facilitate comparison.

As expected, the final depth error is lower in Condition 1 compared to Condition 3, meaning that it is easier to judge depth when all cues are available. Differences in learning pace and final depth error are more evident in Condition 3 compared to Condition 1. For example, AS4 exhibits no learning in Condition 3, whereas AMS1 has not reached the plateau after 40 blocks. Surprisingly, AMS1 achieved a final depth error in Condition 1 lower than any of these four participants.

2.3.5 Statistical analyses

To quantify these results, we first analyzed the DartBoard game raw data. Since the raw data did not follow a normal distribution when analyzed as a whole, or considering the six subgroups obtained from pairing participant group and cue scaffolding condition ($P < 0.01$ in all cases), non-parametric tests were used for the following analysis.

Median and interquartile range of trial depth error are shown for each group and condition in Table 2.3. Stereo-normal participants performed better than stereo-anomalous on each condition. However, Condition 3 provides worse results than Condition 1 or 2 regardless of participant group.

Table 2.3

DartBoard trial depth error median and interquartile range per condition and group

Condition	Stereo-normal (arc secs)	Stereo-anomalous (arc secs)
1	154 [72 – 270]	170 [78 – 308]
2	160 [74 – 286]	206 [92 – 377]
3	161 [75 - 286]	212 [98 – 393]

Trial depth error differences across conditions are statistically significant for both groups ($p < 0.001$), except between Conditions 2 and 3 for the stereo-normal group ($p = 0.395$). Finally, differences between stereo-normal and stereo-anomalous groups are statistically significant no matter the condition considered ($P < 0.001$).

In a second analysis approach, each participant was characterized by the exponential fit using the final within-block depth error for each condition (Figure 2.6). The exponential fit was obtained using a standard exponential function (Eq. 1) with three coefficients (a, b and c) and allows to estimate the depth error (y) for each block (x).

Equation 1. $Y = a - b * e^{(-c\,X)}$

Once we obtained the three coefficients, we calculated three variables per participant and condition: the final depth error at the last block (final depth error); the pre:post ratio between the error at the first and the last block (PPR), with a higher PPR indicating greater learning; and the time constant (TC), representing the rate of learning. Mean values and confidence intervals for each parameter per condition and group are shown in Figure 2.7.

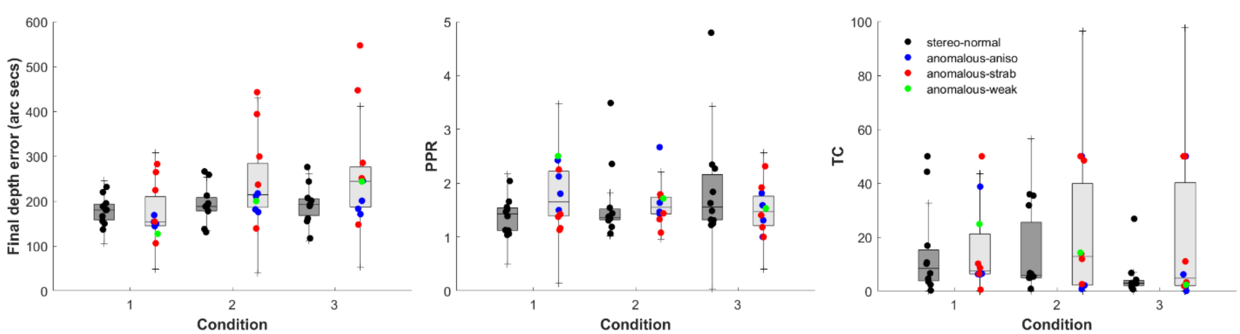

Figure 2.7. Box plots of DartBoard in-game performance accuracy, from the exponential fits: Final depth error, PPR, and time constant. Medians and interquartile ranges for each group and condition considered. Depth error values in seconds of arc.

First, the PPR results show that all participants (except AA2 in condition 3 [PPR = 1]) improved in all cue scaffolding conditions. We also found a statistically significant correlation between the PPR and the initial depth error (but not the final depth error) for the stereo-normal participants in all conditions (Table 2.4). That correlation is present, although lower, and not statistically significant, for stereo-anomalous participants.

Table 2.4

Pearson's correlation and p-values for PPR and initial stereoacuity threshold for each group and cue scaffolding condition

	Stereo-normal		Stereo-anomalous	
Condition	Correlation	p-value	Correlation	p-value
1	0.84	0.002*	0.25	0.494
2	0.81	0.004*	0.35	0.323
3	0.83	0.002*	0.56	0.094

For the stereo-anomalous group, the asymptotic performance appears to be higher (worse) in Condition 3 while the PPR seems to be more dependent on condition, decreasing as participants progressed in the game. Finally, the TC seems to be more dependent on condition, reaching longer values in Condition 3.

Nevertheless, these differences are not statistically significant for any of the three parameters, considering group, condition, or any of the possible combinations.

Shown in Table 2.5 are the number of blocks (median value) needed to achieve 110% of the asymptotic threshold. Although differences are not statistically significant, the number of blocks it takes for learning to stabilize in Condition 3 is lower compared to Condition 1. Furthermore, the number of blocks it takes for learning to stabilize in the stereo-anomalous group is about twice that of the stereo-normal group.

Table 2.5

Time to achieve learning in blocks (median value). The number of blocks needed to achieve 110% of the asymptotic threshold according to the exponential fit is calculated for each condition and for all participants, stereo-normal group and stereo-anomalous group

Condition	All participants	Stereo-normal	Stereo-anomalous
1	15.1	12.7	15.1
2	10.0	7.3	14.2
3	5.6	4.9	10.6
All	9.2	7.1	14.2

Finally, we were interested in comparing the improvements in Condition 1, where all depth cues are available and Condition 3, where only retinal disparity is available with the caveat that improvements may depend on the initial error. A participant who exhibits a lower error in Condition 1 but performs poorly in Condition 3, is perhaps likely to improve more in Condition 3 than in Condition 1 (i.e. the lower the initial error ratio between Condition 1 and 3, the lower the PPR ratio between Condition 1 and 3).

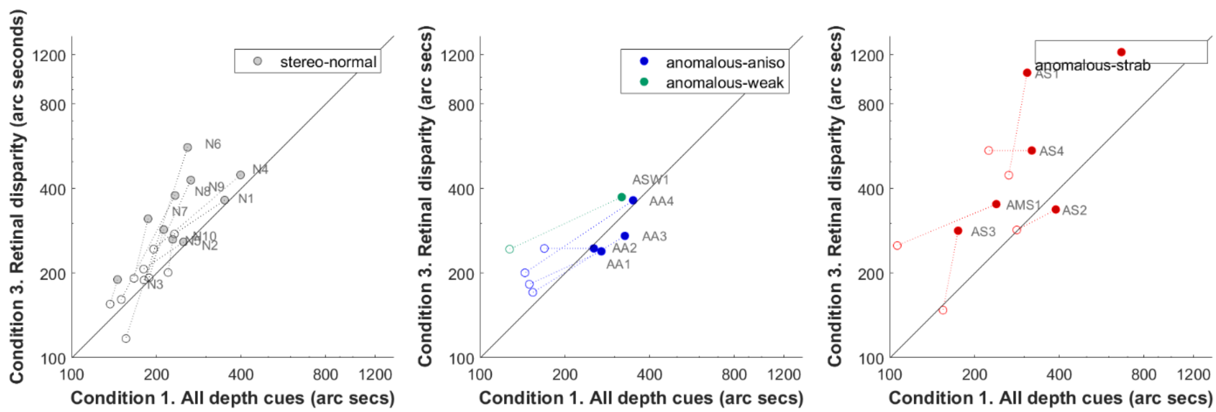

Figure 2.8. DartBoard in-game performance accuracy initial thresholds and PPR in two cue scaffolding Conditions (1 vs 3) for each group (stereo-anomalous; anomalous-anisometropic and weak; anomalous-strabismus). Each participant is represented as line, whose start point is a filled circle and end point is an open circle. The start point of the line represents the initial accuracy (arc secs); horizontal line length shows the improvement in game accuracy for Condition 1, and vertical length is the improvement in game accuracy for Condition 3. Points above the diagonal unity line show better performance when all depth cues are present compared to the performance when only retinal disparity is available (as naturally occurs). Lines with angles lower than 45 degrees show greater improvement with all cues than for stereoacuity alone. Stereo-normal participants are represented in gray, stereo-anomalous are represented in different colors depending on subclassification: anisometropic in blue, strabismic in red, stereo-weak in green.

In Figure 2.8, each participant is represented as a line, whose start point (filled circle) is the initial error, for Condition 1 on the abscissa and Condition 3 on the ordinate. The length of the horizontal is proportional to the improvement in PPR for Condition 1; the vertical line length is the improvement in PPR for Condition 3. All lines point towards a game accuracy limit that is in the lower left corner of the graph. If performance improves by the same amount in the two conditions, the arrows would be oriented at 45 degrees (parallel to the unity line). Arrows with less than 45 degrees of orientation indicate a greater improvement in Condition 1; arrows with an orientation greater than 45 degrees indicate greater improvement in Condition 3. Stereo-anomalous participants are mainly represented by lines at angles less than 45 degrees, i.e. the improvement attributable to the use of retinal disparity was less than the improvement attributable to the use of all depth cues combined (more similar to natural viewing).

Interestingly, the PPR ratio between Conditions 1 and 3 correlates (Pearson's test) strongly with initial performance ratio in the stereo-normal group (r = 0.94; $P < 0.001$) but not in the stereo-anomalous group (r = 0.53; $P = 0.117$). Worse initial performance in

Condition 1 compared to Condition 3 in stereo-normal participants predicts greater improvement in Condition 1 after treatment compared to Condition 3, but this is not necessarily true for stereo-anomalous participants. Similarly, this happens if performance in Condition 3 is worse than in Condition 1. We understand that the treatment benefits are more evident for the weaker initial condition in stereo-normal participants, but this trend is not clear for stereo-anomalous participants.

2.3.6 Halloween in-game performance

Our in-game performance measures for Halloween yield the proportion of correct responses (hits) for each stereoscopic demand (1000, 800, 600, and 400 arc secs) and each cue scaffolding condition for each session. To assess improvements, we performed an m-alternative signal detection (d') analysis[55], since the number of choices varied across trials (from 3 to 7). This analysis takes into account the number of available choices (targets) at each stereo demand[56,57]. Specifically, we computed d' for the first three hours of game play (pre) and the last three hours (post) to get a PPR assessment. Figure 2.9 shows that most participants improved their accuracy in the last three hours compared to the first three hours with the largest and smallest disparity levels across the three conditions.

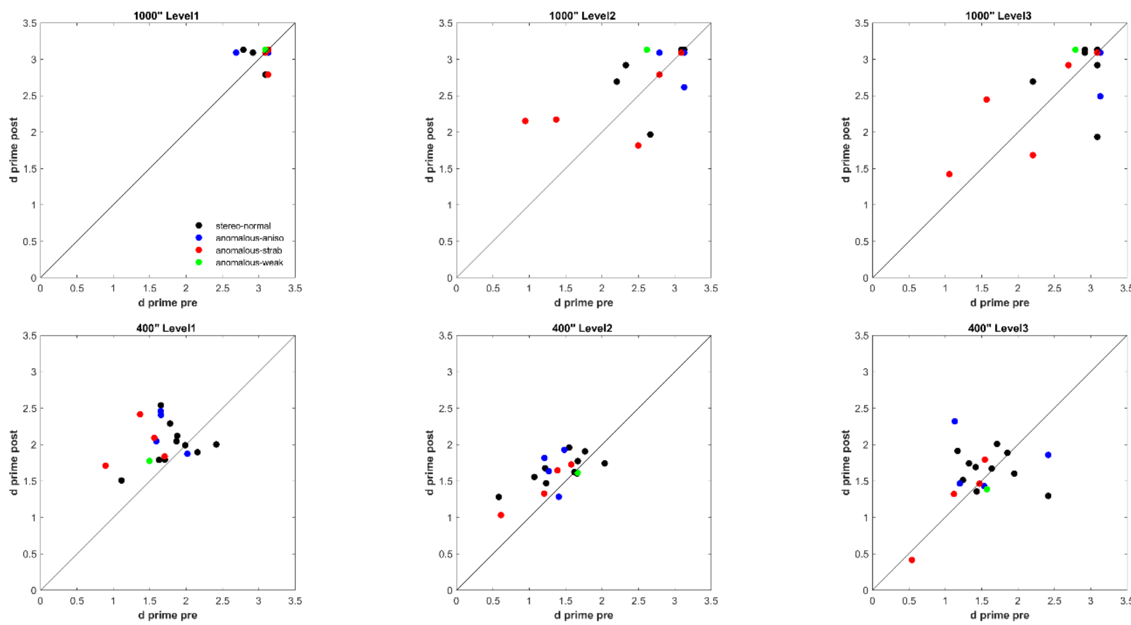

Figure 2.9. Halloween game pre post d' values for stereo demand of 1000" and 400" at each condition (level 1, 2 and 3). Symbols represent a different participant and group: anisometropia (blue), strabismus (red), stereo-weak (green), and normal binocular (grey). Points above the unity line indicate an improvement in accuracy in the first three hours compared to the last three hours of game play.

To assess the amount of improvement, we took the PPR of the d' value for each participant, cue scaffolding condition, and stereoacuity demand (Figure 2.10). Our analysis revealed a statistically significant difference between groups in d' PPR for

Condition 1 (P = 0.048) and Condition 2 (P = 0.035), but not for Condition 3 (P = 0.100) (Table 2.6). Indicating that the stereo-anomalous group increased their sensitivity to detect the stimulus more than the stereo-normal group. However, only d' PPR for 800" was statistically significant between the groups (stereo-normal M = 1.0; stereo-anomalous M = 1.51, P < 0.001). When comparing groups across cue scaffolding condition and stereoacuity demand, there was a significant difference in d' PPR for Condition 1 and 800" (P = 0.019), Condition 2 and 800" (P = 0.015), and Condition 3 and 800" (P = 0.012), but not between the remaining combinations (Table 2.7).

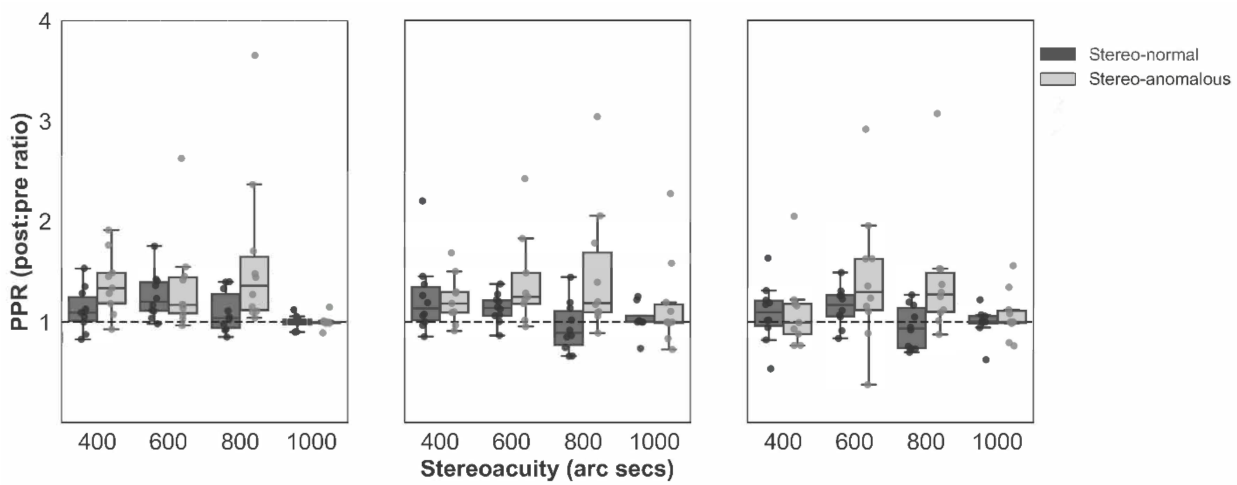

Figure 2.10. Box plot comparing d' PPR values between stereo-normal (dark grey) and stereo-anomalous (light grey) groups across stereoacuity demand (400", 600", 800", and 1000") and Conditions (1, 2, and 3). Condition 1 (left panel), Condition 2 (middle panel), and Condition 3 (right panel). Each symbol represents individual data.

Table 2.6.

Kruskal-Wallis mean comparisons between group and condition for PPR d' values

Condition	Stereo-normal	Stereo-anomalous	p-value
1	1.128	1.344	0.049*
2	1.094	1.322	0.035*
3	1.049	1.258	0.100

The suppression task, inserted in the Halloween mechanics, proved to be valuable as a means of tracking participant engagement and suppression episodes. Figure 2.11 shows each participants' failure to detect one of the dichoptic targets.

Table 2.7.

Mann-Whitney pairwise comparisons between group, condition, and disparity demand for PPR d' values

Condition	Disparity	Stereo-normal	Stereo-anomalous	p-value
1	1000	0.99	1.00	0.675
	800	1.10	1.63	0.019*
	600	1.26	1.36	0.912
	400	1.13	1.38	0.095
2	1000	1.03	1.17	0.856
	800	0.95	1.48	0.015*
	600	1.14	1.41	0.156
	400	1.25	1.23	0.720
3	1000	0.99	1.07	0.822
	800	0.95	1.42	0.012*
	600	1.16	1.43	0.280
	400	1.09	1.11	0.604

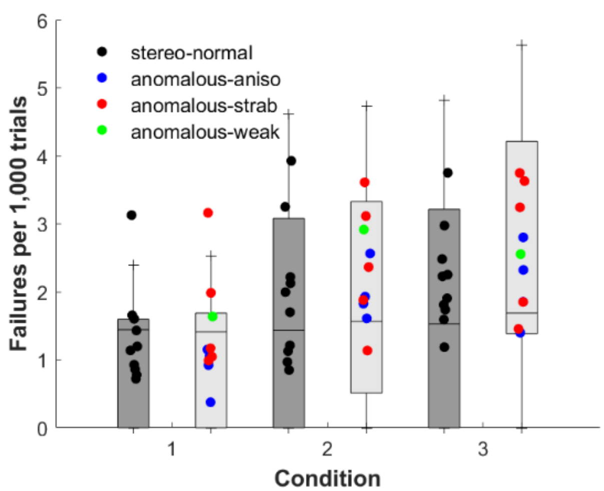

Figure 2.11. Box plots of Halloween game failures to detect dichoptic targets per 1,000 trials for stereo-normal (grey bars) and stereo-anomalous (white bars) groups for each Condition (1, 2 and 3). Symbols represents data from one participant: stereo-normal (black), anisometropic (blue), strabismic (red) and stereo-weak (green). The horizontal line represents the group median while the whiskers represent the interquartile ranges.

A Kolmogorov–Smirnov test showed that the dichoptic errors did not follow a normal distribution when analyzed as a whole or when considering the six subgroup pairings between participant group and cue scaffolding conditions ($P < 0.001$ in all cases), thus a Kruskal–Wallis test was applied. Our analysis revealed significant differences as a function of condition for the stereo-normal ($P = 0.006$) and stereo-anomalous group ($P < 0.001$), except between Condition 2 and 3 in the stereo-anomalous group ($P = 0.330$). Furthermore, Mann–Whitney pairwise comparisons showed significant differences between the stereo-normal and stereo-anomalous group in dichoptic errors for all conditions when considered as a whole ($P = 0.041$) and in Condition 2 ($P = 0.023$), but not in Condition 1 ($P = 0.578$) or Condition 3 ($P = 0.109$).

2.4 Discussion

Our aim was to evaluate whether cue scaffolding and dichoptic PL in VR could be used as a platform to train stereovision. For this proof of concept study, we designed two custom video games, which use a combination of demanding stereovision tasks. Our results show that most stereo-anomalous participants improved in the games and most importantly, the learning transferred to clinical and psychophysical stereoacuity tests (Figure 2.3). Despite the different design and nature of the video games, these results support the viability of training stereoacuity by means of videogames, as other studies have previously shown[33,39,47,58].

Our small sample size of participants with anisometropia or strabismus does not allow us to make statistical inferences beyond the stereo-normal and stereo-anomalous groups. Nevertheless, some participants did not show improvement across stereoacuity tests (AS1, AS2, AA3, and ASM1); all with strabismus except for AA3 who has anisometropia. It has been well documented in the literature that persons with anisometropia retain better stereoacuity at low spatial frequencies[59]. Although their stereoacuity is not as acute as normal, it is nevertheless functional. Therefore, individuals with anisometropia are more likely to recover stereoacuity after treatment.

On the other hand, stereoacuity in people with strabismus is more impaired[33]. A possible explanation for this difference may be that in order to avoid diplopia, suppression scotomas may be playing an active role in strabismus, whereas in anisometropia, suppression may be playing a more passive role, as a result of degraded visual acuity.

Furthermore, people with strabismus have been shown to be more resistant to stereoacuity training compared to people with anisometropia[33,58]. Indeed, participants AMS1, AS1 and AS2 (all strabismic) showed no improvement when measured with RD3, but showed improvement with the other stereoacuity tests. This may be due to poor performance on tests with random dot stimuli in people with subtle binocular angles of deviation. Participant AMS1, with micro-strabismus, is likely to have developed a harmonious anomalous correspondence[60], providing some binocularity. Training stereopsis cannot succeed in the absence of some neural substrate for binocular fusion.

Regarding the stereo-normal group, most showed small improvements in the psychophysical stereoacuity tests. The small improvements are likely due to a test ceiling of 20 arc seconds. Those improvements were not detected by the clinical tests since all stereo-normal participants were at ceiling at the beginning of the study. However, previous studies have shown improvements in stereoacuity for individuals with normal binocular vision after training[61] or playing 3D (but not 2D) videogames with large disparities[50]. Furthermore, in certain professions, where specific stereo demanding tasks are common such as those required from dressmakers, stereoacuity seems to be enhanced[53]. There is reasonable doubt about whether good stereoacuity is a requirement for becoming a dressmaker or whether stereoacuity is enhanced by continuous stereo demanding tasks. However, our results indicate that training can improve stereoacuity in individuals with normal binocular vision.

As for VA, we did not detect changes after training, which is not surprising, since only two of our participants were amblyopic. Previous studies aimed at improving stereoacuity have reported a lack of change in VA after training[39,58,61]. Furthermore, current state of the art of VR headsets lack fine resolution, which makes them a poor tool for VA training. Similarly, we did not find significant changes in contrast sensitivity.

For both clinical and psychophysical stereoacuity tests, stereo-normal participants with worse initial stereoacuity thresholds show a higher PPR, i.e., greater improvement (Table 2.2). DartBoard in-game results show the same trend (Table 2.3). Somewhat surprisingly, the same is not reflected in the stereo-anomalous group with non-significant correlations. A recent study using a PL stereo training paradigm with random dot stimuli in participants with a history of amblyopia found a strong inverse association between initial stereoacuity threshold and PPR[62]. Similar trends have also been reported for VA recovery, showing that baseline acuity loss does not predict PPR after dichoptic training[63].

For participants with strabismus, no change was detected in visual angle deviation. There is strong scientific evidence for the success of training convergence insufficiency[64]. Despite each game requiring participants to diverge (DartBoard) or converge (Halloween) to moving targets, the small sample in our proof of concept study is not sufficient to detect changes if they occurred.

Although participants did not adjust luminance balance once set, the Halloween game recorded failures to detect dichoptic targets, where participants were either suppressing or unaware of the task. Stereo-normal participants are not expected to have problems with suppression. However, they exhibit a statistically significant increasing rate of failures across conditions, which may be attributed to binocular rivalry in the headset, or more likely, boredom or fatigue. Stereo-anomalous participants however, behave differently, with a higher error rate, i.e. the dichoptic errors are not only a measurement of fatigue but of something else, likely suppression or rivalry. Nevertheless, embedding a binocular imbalance test in a VR device[65] seems worthwhile. This would allow researchers the ability to track binocular vision beyond stereoacuity function. Anti-suppression therapy by means of dichoptic games has little or no effect on stereoacuity according to previous studies[48,66–68]. However, direct stimulation of stereoacuity does appear to contribute to the re-balancing of binocular vision by reducing suppression[61]. Indeed, it has been suggested that improved stereoacuity after PL might reflect a decrease of interocular suppression[39], although it could also be the result of a signal enhancement in the amblyopic eye.

Although gamification can be a useful tool for increasing motivation, attention and compliance, it comes at a cost. Game results are not as sensitive in tracking the participants' evolution compared to results obtained through traditional PL tasks. Nevertheless, the DartBoard game results are coherent with clinical and psychophysical tests. First, trial depth error, regardless of the condition, differentiates stereo-normal and stereo-anomalous participants. Second, improvement in Condition 3 (only retinal disparity available), is evident in all participants with the exception of one stereo-normal participant (PPR > 1).

The nature of the Halloween game does not provide as rich a dataset as Dartboard. The disparities used in the game were large, with the lowest stereoacuity demand set to 400". Given these conditions, it is reasonable to suggest that perceptual training took place at or slightly above threshold for most stereo-anomalous participants, whereas clearly above threshold for stereo-normal participants. Nevertheless, stereo-normal participants also improved. When designing a PL task, above-threshold activities are not considered since there's a notion that the activity would become (even) less interesting and engaging[33]. Nevertheless, at least one study has reported improvements in stereoacuity in a control group whose activity was chosen to be above threshold[49]. In that case the improvement was attributed to the stimuli used (random dots), which potentially improved binocular fusion and signal to noise discrimination. Those aspects may be especially important for strabismic patients. We cannot definitively know whether the improvement in clinical and psychophysical measures of stereoacuity were due to DartBoard and/or Halloween, but it is important to point out that strabismic observers fare better with larger disparities[69]. Thus, the Halloween stimulus might have allowed them to strengthen their stereopsis by providing a stimulus they can latch on to.

Finally, the novelty of this study is the use of a cue scaffolding approach for improving stereovision. We demonstrated that cue scaffolding is present using DartBoard results: trial depth error differences across conditions are statistically significant regardless of group assignment (except Condition 2 and 3 for the stereo-normal group). Differences are more notable between Condition 1 (almost all depth cues available) and Condition 3 (only retinal disparity).

When we analyze DartBoard within-block learning, we observe that in most blocks there is a positive difference between initial and final depth error, meaning that the participant's skill improves during the block on any condition (Figures 2.4 and 2.5). This behavior is not present in all blocks (Figure 2.5), maybe due to fatigue, and because of the nature of the proof of concept study the trend does not reach statistical significance. In any case, within-block learning also seems to be more evident in the first blocks of training than in the last (Figure 2.6), meaning that after some training participant responses are more consistent during a new block practice. A key feature of cue scaffolding is that improvements made in the previous condition potentially influence the depth error of the condition that follows. We detect this behavior when surprisingly, the final depth error in Condition 3 is lower than in Condition 1 in one block. How is it possible that the performance is better when all depth cues have been removed except binocular parallax? The logical explanation is that performance on a condition is influenced by the previous condition. This approach can be especially important for patients with strabismus and/or poor baseline stereoacuity, who might benefit from a design where associations between monocular and binocular cues are strengthened over time. Beginning each training session with the easiest condition where all binocular cues to depth are available and progressing to the last condition where disparity is the most reliable cue to depth is analogous to starting each session with training wheels and removing them at the end.

Stereo-normal participants tend to improve more in conditions with worse performance (Figure 2.8). However, stereo-anomalous participants show an improved ability to integrate all depth cues. Previous studies[61] have demonstrated that in adults deprived of normal binocular vision, repetitive depth demanding tasks contribute to a reweighting of depth cue integration where the weight of the disparity cue is increased (learned behavior). However, they do not all achieve the same reweighting as normal control participants. In situations where disparity depth valuation is contradictory with other depth cues, e.g., texture, the weight of disparity in the final estimation increases after treatment. Sensory integration (Condition 1) is less resistant to improvements than just disparity depth perception (Condition 3). This might explain why patient reports of improved depth perception after visual therapy treatments are not correlated with measurable stereoacuity improvements[70].

Our interventional model of direct stereopsis stimulation using VR and incorporating depth cue scaffolding improved in-game performance in normal and stereo-deficient subjects. This improvement transferred to stereoacuity measured with both clinical and psychophysical stereoacuity tests. Importantly, this approach provides rich in-game performance measures which may provide useful insights into principles for effective treatment of stereo anomalies.

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Author contributions:

This paper was published in 2021. A.G. and D.L. contributed to the conceptualization of the study and funding acquisition. A.G. was involved in data collection, data curation, project administration, and wrote the original draft of the manuscript. A.G., D.L. and S.M. came up with the methodology, former analysis, visualization of the data, and contributed to writing/ editing. A.G. and S.M. were involved in data validation. S.M. wrote the software for the games. O.I. contributed

to the data analysis. D.L. provided resources and supervision. All authors reviewed the manuscript.

Competing interests:

One author of this manuscript has the following competing interests: SM promoted, with the support of the University of Oviedo, the creation of the startup VisionaryTool. He has assisted VisionaryTool, S.L. (www. Visionarytool. com) to create a commercial version of both the Halloween and DartBoard games described in this manuscript (University of Oviedo contract FUO-EM-19-099). VisionaryTool has not had any role (writing, analysis, or control over publication) in the production of the paper. This does not alter our adherence to the journal policies on sharing data and materials. AG, DL and OI declare no potential conflict of interest.

Chapter 3

Quantifying the Relationship Between Stereoacuity and Motor Movement in a Reach-to-grasp Task

3.1 Introduction

Executing motor movements is costly and requires constant processing and read-out of visual information. Within this context, the role of vision is to enhance task-relevant information by taking into account the goal, minimizing costs and optimizing potential rewards[71]. In the case of reaching and grasping an object, vision and in particular depth perception, provides important information for planning and executing motor movements.

Depth perception arises from a variety of cues: occlusion, perspective, lighting-shading, chromatic attenuation, focus, motion parallax and stereopsis. Of those cues, only stereopsis, which arises from the computation of binocular disparity, requires the functional coordination of both eyes. Stereopsis is important for extracting depth information from natural scenes, breaking camouflage and executing everyday visuomotor tasks such as reaching and grasping a cup. For reaching and grasping (i.e., prehension) in particular, stereopsis is important for extracting intrinsic 3D properties of the object of interest and planning and estimating relative disparity of the object with respect to other objects and with respect to the hand and fingers.

Prehension can coarsely be divided into two phases that rely on different visuospatial information. The reach can be thought of as a preprogrammed ballistic movement with the goal of getting the hand close to the object of interest. Programming of the reach relies on spatial information about the location of the body and the distance of the object with respect to the body[8]. The grasp on the other hand is a bit more sophisticated with the goal(s) of traveling the remaining distance, making the necessary hand adjustments and applying the grip. Programming and executing the grip relies on information about the intrinsic 3D properties of the object, visual feedback and online correction.

When binocular vision is artificially disrupted and limited to one eye via occlusion, performance overall is impacted by longer movement duration[9,13,72], greater online corrections[9,13] and greater errors[9,13]. In the reach, participants exhibit a lower peak velocity[13,72] and a longer low velocity phase (i.e., deceleration phase before object contact)[9,13,72] and a spatially altered approach to the target[9]. For the grip, participants typically formed a wider grip aperture[9,72] programmed farther away from the object and took a longer time to apply the grip[13].

Studies where stereovision is disrupted artificially, provide useful information, but raise a potential confounding variable, namely that a temporary disruption of stereopsis cannot fully capture the effect of having the long-term experience of weak or no stereopsis. For that reason, studies with people who experience degraded stereovision at an early age due to anisometropia and/or strabismus with or without amblyopia are particularly important. From these studies, we have learned that under binocular viewing, people with impaired stereopsis take a longer time to approach the target[9–11] with a lower peak velocity[11] and also take longer to apply the grip[9,12], which consequently factors into a longer overall time to complete the task[9]. In addition there is an increase in reaching and grasping errors[9,12] and the grasping errors are largely due to additional opening and closures of the hand before object contact[9].

But what is the relationship between stereoacuity and prehension? Observational results suggest that movement timing increases with the amount of disparity sensitivity loss[4], with some studies reporting a high correlation between stereo sensitivity and the binocular to monocular ratio on the timing of a specific movement parameter, namely the time it took to transport and place the peg once it had been picked up[73]. Studies that have examined the reach component only, also report stereo sensitivity to be the best predictor of motor control strategy, accounting for 23% (amblyopic group) and 12% (strabismus without amblyopia) of the variance in a ratio that considers peak acceleration and end-point precision.

Considering the role of stereovision in motor movement and the reported correlations between stereoacuity sensitivity and motor planning and execution, this study aims to quantify whether there is a model that best explains the relationship between motor movement and stereoacuity.

3.2 Methods

3.2.1 Participants

Twenty-one adults (mean age: 34 ± 17, range: 18 – 67 years, 9 female) without ocular pathologies participated in the study. Important for the study, our participants had a wide range of stereoacuity (mean = 441”, range = 31” – 1400”; a value for 1400” refers to nil stereo) as measured by the ASTEROID[74]. Eight of those participants had typical binocular vision and thirteen had binocular impairments: 6 with anisometropia, 5 with strabismus and 2 mixed. Participants were recruited by phone or email from the Meredith W. Morgan University Eye Center’s internal list and The Smith-Kettlewell Eye Research Institute’s participant database. The Institutional Review Board of The University of California, Berkeley and The Smith-Kettlewell Eye Research Institute approved the study protocol. The study was conducted according to the tenants of the Declaration of Helsinki and informed consent was obtained from each participant. Exclusion criteria for the study include ocular and/or neural pathologies.

3.2.2 Vision and handedness assessment

All participants completed a battery of tests to assess vision and handedness. Vision evaluation included: (1) visual acuity (Bailey Lovey-Visual Acuity Chart at 3 m), (2) ocular deviation (Monocular cover-uncover test and alternate cover test) at 40 cm and 3 m, (3) horizontal and vertical phoria (Modified Thorington Test) at 40 cm and 3 m, (4) clinical stereoacuity (Randot Circles Stereotest®), and psychophysical stereoacuity (Accurate STEReotest (ASTEROID)) and a two-alternative forced-choice (2-AFC) computer stereotest.

Some individuals with strabismus or related conditions have dynamic stereopsis, but no detectable static stereopsis[70,75]. Thus, we included static clinical and dynamic psychophysical measures of stereoacuity with a range of sensitivity.

For clinical stereoacuity, we used the three-alternative forced-choice random-dot stereogram Randot Circles Stereotest®.

We also used two psychophysical tests of dynamic stereoacuity. The first, ASTEROID, is a four-alternative forced-choice (4-AFC) dynamic random dot stereotest with a Bayesian staircase[74]. ASTEROID was presented on a 10.1-inch 3D tablet (Commander 3D, Toronto, Canada) at a 40 cm distance from the participant.

The second psychophysical test consisted of two vertically stacked patches (0.33° horizontal x 1° vertical with a separation of 0.5° at the fovea) and separated by a fixation point, reported in a previous study[76]. The patches were made up of bright, dynamic random dots on a gray background with a luminance of 145 and 35 cd/m^2, respectively. Participants were seated 1 m away from the computer and were instructed to report which of the two vertical nonius lines appeared closer by pressing the appropriate key. The stimulus duration was 100 ms. The 2-AFC test was presented on the 3D-Vision Ready Asus LCD stereo display (1920 x 1080 at 120 Hz) with Intel® Xeon® processor power by the NVIDIA® Quadro M4000 graphics card. The stimulus was viewed through NVIDIA® 3D Vision™ wireless shutter glasses 2 with each eye stimulated at 60 Hz. The stimulus was generated with MATLAB R2012b and the Psychtoolbox library: 3.0.12-Flavor: beta-corresponds to SVN Revision 7550.

To assess hand dominance and determine the hand to be used in the prehension task, participants completed the Edinburgh Handedness Inventory[77]. All participants were right-handed with a laterality quotient > 50 and performed the prehension task with their right hand.

Participants were categorized as having anisometropia if there was a difference ≥ 0.50 D in spherical equivalent refraction or ≥ 1.50 D difference in astigmatism in any meridian, between the two eyes[78]. Participants were classified as having strabismus in the presence of a tropia with the cover test.

3.2.3 Prehension task and equipment

To quantify prehension, we used a peg-placement task[73] with a commercial pegboard (Geometric Peg Board 5125; Plan Toys, Plan Creations Co. Ltd., Bangkok, Thailand) (Figure 3.1A) presented just below eye height to better isolate stereopsis (Figure 3.1B). The pegboard was positioned 30 cm above the table, at a distance of 40 cm from the participant. The pegboard had four rows, each containing four unique shapes (circle, triangle, square, and rectangle).

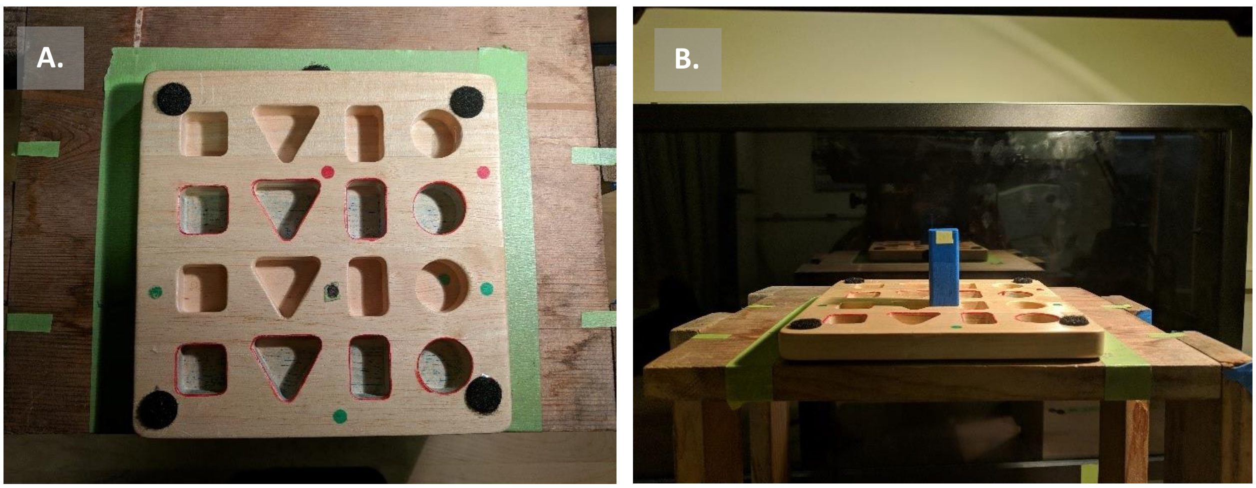

Figure 3.1. Pegboard and participant view. (A) The pegboard viewed from the top. The small black dot at the center indicates the position of the peg at the start of each trial. Participants were instructed to place the peg on the appropriate slot on the first row from the participant for ‘near’ and third row for ‘far’ (B) The pegboard from the participants’ view- 10 cm below eyesight.

To minimize head movements, participants were seated with their chin and forehead resting on a head mount (Figure 3.2A). Participants began each trial with their dominant hand in a closed-grip starting position and were instructed to wait for an auditory signal before initiating the reach-to-grasp movement. Before the auditory signal, the experimenter placed a randomly selected shape at the center of the board, in line with the second row, indicated with a black circle on the pegboard. Participants were instructed to reach for the predetermined shape and place it in one of two locations (near or far), first or third row respectively, with relative disparities of 15 and 17 arc minutes with respect to the peg starting position.

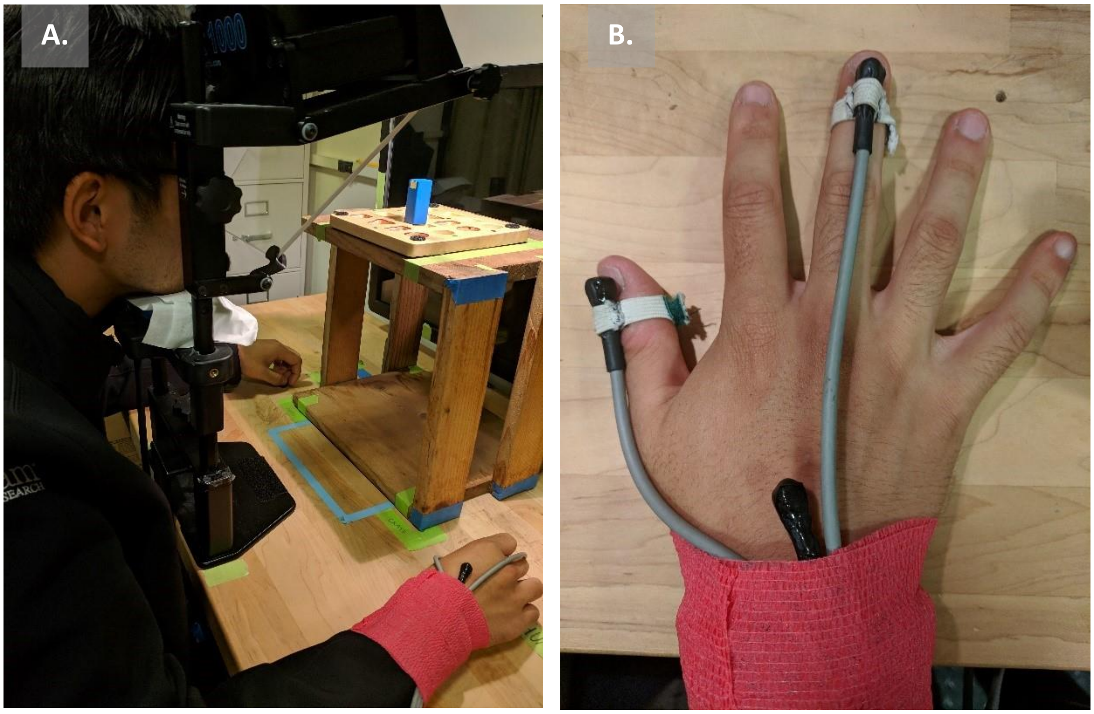

Figure 3.2. Participant setup and sensor placement. (A) Participant setup and ready for the ‘go signal’. Participants’ head was stabilized using the chin rest from the EyeLink 1000 Eye Tracker (SR Research, Ottowa, ON, Canada). Participants were instructed to touch their grasping finger and thumb and rest it on two small Velcro circles and wait for the tone signal to begin the movement. (B) Sensor placement. Three sensors were placed on the reaching hand and secured on the wrist with kinesiology tape (pink)- One on the wrist and the other two on the distal portion of the thumb and grasping finger (here middle).

Participants completed a total of eight trials under binocular viewing for practice. After the practice trials, each participant completed 16 trials per viewing condition: binocular (B), dominant-eye (DE) and non-dominant-eye (NDE) for a total of 48 trials per participant (except AA2 who is missing three binocular condition trials due to a recording error).

We used the Polhemus (Colchester, VT, USA) Liberty 240/16 motion tracker at a sampling rate of 240 Hz to capture the 3D position of three sensors, which were placed on the grasping finger (index or middle), thumb and wrist (Figure 3.2B). Sensors were secured on the phalanges and wrist via kinesiology tape and the position was captured by a magnet under the table. Hand movements were recorded from the initial auditory signal until after the peg was placed and the experimenter manually pressed a key to stop recording.

3.3.4 Prehension dependent variables

To assess performance on the task, we analyzed five kinematic variables: peak velocity (PV), maximum grip aperture (MGA), time to maximum grip aperture (tMGA), deceleration phase (D-phase), and peg-placement time (PPT). We were particularly interested in these variables since they give us insight on reach planning and execution (PV), grip planning

(MGA and tMGA), grip execution (D-phase) and object transport and drop-off efficiency (PPT). Furthermore, previous studies have demonstrated the importance of binocular vision on these variables[3,4,13,79].

Velocity was calculated as the absolute summed difference between the 3D position of two sensors (thumb and finger). From velocity, we calculated PV— the maximum velocity before object-pick-up (Figure 3.3A).

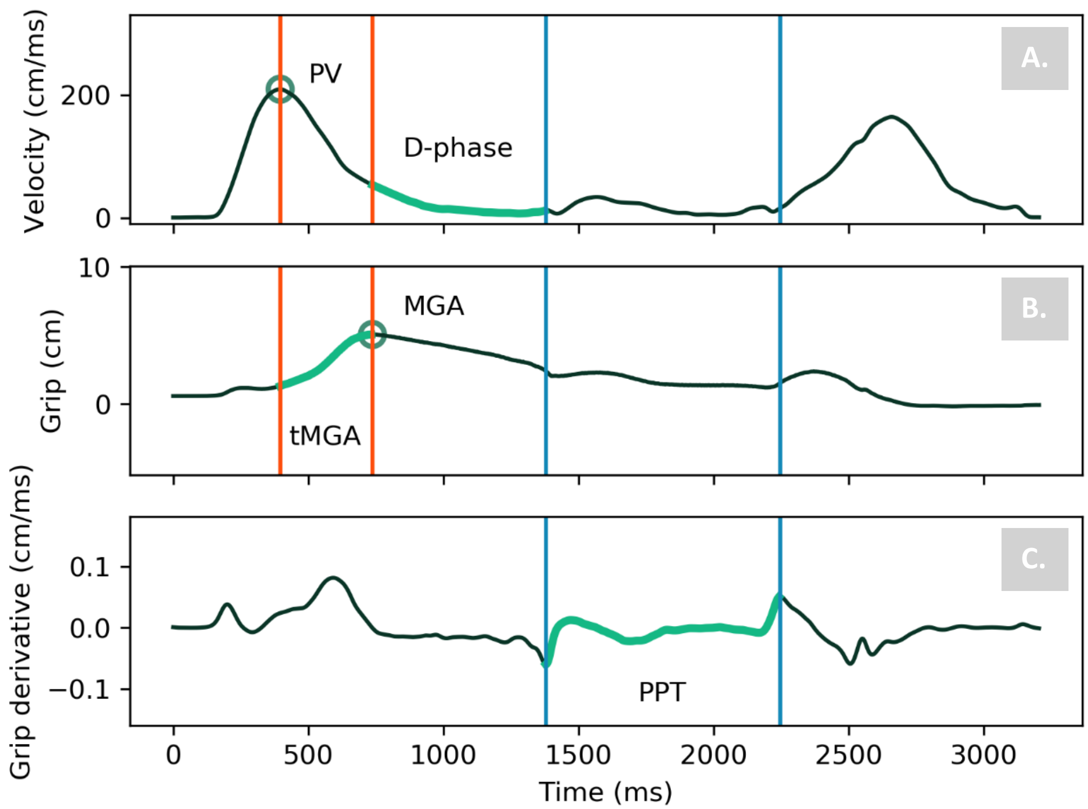

Figure 3.3. Prehension dependent variables as indicated by one participants' trial. The blue vertical lines indicate object-pick-up (first) and object-drop-off (second). (A) Velocity trace showing PV (dark teal circle) and D-Phase (green segment between the orange and blue lines). PV was defined as velocity global maximum before object-pick-up (first blue line). D-phase was defined as the time segment between MGA and object-pick-up. (B) Grip trace showing MGA (dark teal circle) and tMGA (green segment between the orange lines). MGA was defined as the global maximum grip aperture before object-pick-up. The start of tMGA (first orange line) was defined as the global maximum in acceleration (not imaged here) before object-pick-up, while the end of tMGA (second orange line) was defined as the global maximum grip aperture before object-pick-up. (C) Change in grip trace showing PPT (green segment between the two blue lines) was defined as the time between object-pick-up and object-drop-off.

Grip aperture was calculated as the 3D distance between two sensors (thumb and finger). Maximum grip aperture (MGA) (Figure 3.3B), defined as the maximum grip aperture before object-pick-up, represents the largest scaling of the hand before object-pick-up. Time to maximum grip aperture (tMGA) (Figure 3.3B), defined as the segment between PV and MGA was calculated as the time segment between global maximum velocity before object-pick-up to global maximum grip aperture before object-pick-up. D-phase, defined as the time segment between MGA and object-pick-up, represents the low-velocity phase as the participant is getting closer to the object and closing the grip.

Object-pick-up and -drop-off were calculated using the derivative of grip, which reflects when the grip aperture changes direction from open to closed or vice-versa. First, we split the trace into two segments (first and second). Object-pick-up was calculated as the global minimum (indicates changing grip from open to close) in the first segment, while object-drop-off was calculated as the global maximum (indicates changing grip from close to open) in the second segment. PPT was defined as the time segment between object-pick-up and -drop-off (Figure 3.3C).

3.3.5 Data analysis

Hand movement data were initially processed using custom-written programs in Matlab software (The MathWorks Ltd., Cambridge, UK). However, kinematic and statistical analyses were completed in Python (v3.6.8).

To account for variations in finger size and placement of the sensor on the index versus middle finger, grip aperture values for each participant were calibrated by subtracting the geometric mean of the grip size while participants gripped the square peg (i.e., a value of 0 in the grip aperture traces indicated that the participant was gripping the peg). We calculated a geometric mean since we had three measures, pertaining to a single calibration at the start of each viewing condition.

To remedy high-frequency noise in the velocity traces, we replaced values outside the inner and outer fences with 'nan' and filled the 'nans' by interpolating between the points. We then smoothed velocity using a second-order low-pass Butterworth filter with a sliding window of 50 frames. The derivative of grip was also smoothed using the same second-order low-pass Butterworth filter.

We calculated the median across sixteen monocular and binocular trials for each participant, unless trials were missing (AA2 missing 3 binocular trials) or were excluded (AS2: 1 binocular; N5: 1 monocular and N7: 1 monocular). Trials were excluded from analysis if they were incomplete or too noisy that kinematic landmarks could not be extracted.

Data analysis consisted of two parts. In the first part, we split participants into stereo-typical (no binocular impairments, n = 8) and stereo-anomalous (people with anisometropia, strabismus or mixed, n = 13) and computed mean differences on average aggregate data.

Differences between group (stereo-typical vs stereo-anomalous) and conditions (binocular and monocular) were calculated through mean comparisons. Shapiro-Wilk test was used to test whether within group or between group data were normally distributed. Since our data were often not normally distributed, we used the Wilcoxon signed rank test for within group comparison (binocular vs monocular) and an independent samples Mann-Whitney U test for between group comparisons (stere-typical vs stereo-anomalous).

In the second part, we used stereoacuity as a continuous variable and ran a multiple linear regression analysis to determine the kinematic variable that best predicts stereoacuity.

3.3 Results

We measured performance on a peg-placement task using five kinematic variables under two viewing conditions (monocular and binocular) for participants with a range of stereoacuity. Importantly, for the first part of the analysis, we split participants into two groups: stereo-typical (n = 8) and stereo-anomalous (n = 13) to better understand the difference in performance. PV, MGA, tMGA, D-phase and PPT are depicted as box plots in Figures 3.4A, 3.4B, 3.4C, 3.4D, and 3.4E, respectively. Each panel shows four box plots displaying data for each group (Stereo-typical: left; Stereo-anomalous: right) and viewing condition (Binocular: orange; Monocular: teal). The central horizontal line indicates the median while the edges of the box indicate the 25th and 75th quartiles of the data. The whiskers indicate the rest of the distribution, except for outliers, which are displayed outside of the whiskers. Each circle represents the median of 16 trials (unless trials were missing or excluded- see Methods) for one participant.

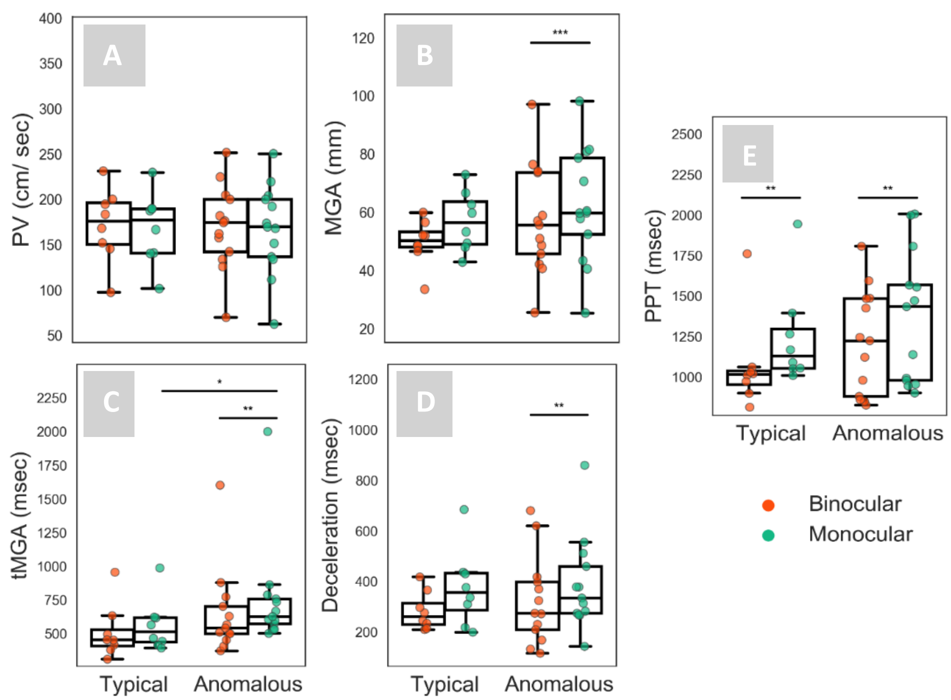

Figure 3.4. Average performance on the five kinematic variables: (A) PV, (B) MGA, (C) tMGA, (D) Deceleration, and (E) PPT. Each panel shows aggregate data for the stereo-typical (left) and stereo-anomalous (right). Individual mean data are depicted as circles for the binocular (orange circles) and monocular (teal circles) viewing conditions.

To compare monocular vs binocular performance within-subjects, we used the nonparametric Wilcoxon rank test. See Table 3.1 (columns 1 and 2) for mean comparison significance levels and Table 3.2 for mean and standard deviations.

For the stereo-typical group, disruption of binocular vision via patching had little effect on performance. Performance under binocular viewing was significantly better in PPT (p = 0.008) consistent with previous work[73] and MGA showed a non-significant trend (p = 0.055), indicating that under monocular viewing, stereo-typical observers were 176 msec slower in placing the peg in the appropriate slot and adopted a more cautious and wider grip (see Table 3.2). All other comparisons were non-significant ($p > 0.05$).

Contrary to the stereo-typical group, the stereo-anomalous group seems to be more impacted by the disruption of binocular viewing. There was a significant difference of viewing condition for all kinematic variables (all $p \leq 0.010$) except for PV (p = 0.340). Under monocular viewing, MGA was significantly wider (5 mm) and the timing variables (tMGA, D-phase and PPT) were all longer. On average, stereo-anomalous participants were 103, 62 and 151 msec slower in tMGA, D-phase and PPT, respectively. These results are surprising and indicate that people with impaired stereopsis are more impacted when vision is restricted to one eye. Furthermore, although the stereo-anomalous group was 118 msec slower than the stereo-typical group on PPT, the difference was not significant (p = 0.428). However, it is interesting to note that the binocular PPT of the stereo-anomalous group (1213 msec) was quite similar to the monocular PPT of the stereo-typical group (1246 msec).

Table 3.1

Mean group comparisons and significance levels (p values)

	Binocular vs Monocular		Stereo-typical vs -anomalous	
	Stereo-typical	Stereo-anomalous	Binocular	Monocular
PV	0.195	0.340	0.428	0.457
MGA	*0.055*	0.001***	0.246	0.269
tMGA	0.148	0.010**	0.079	0.038*
Deceleration	0.195	0.010**	0.486	0.486
PPT	0.008**	0.003**	0.202	0.428

Within-subjects (columns 1 and 2) mean comparison using the Wilcoxon rank test and between-subjects (columns 3 and 4) mean comparison using the Mann-Whitney *U* test. Significant values (* for $p \leq 0.5$, ** for $p \leq 0.01$, and *** for $p \leq 0.001$) are indicated with an asterisk while non-significant trends are in italics.

To compare performance differences between the stereo-typical and stereo-anomalous groups, we used the nonparametric Mann-Whitney *U* test.

The only significant difference between the stereo-typical and stereo-anomalous groups was in tMGA, with the stereo-typical group forming the maximum grip 188 msec faster than the stereo-anomalous group (see Table 3.2). All other comparisons between groups for monocular and binocular viewing were non-significant ($p > 0.05$).

Table 3.2

Mean and standard deviations for each group and viewing condition

	Stereo-typical		Stereo-anomalous	
	Binocular	Monocular	Binocular	Monocular
PV	171 ± 41 cm/sec	168 ± 40 cm/sec	169 ± 47 cm/sec	167 ± 49 cm/sec
MGA	50 ± 8 mm	57 ± 10 mm	57 ± 19 mm	62 ± 20 mm
tMGA	510 ± 202 msec	562 ± 193 msec	647 ± 321 msec	750 ± 391 msec
D-phase	281 ± 75 msec	373 ± 153 msec	323 ± 174 msec	385 ± 181 msec
PPT	1,070 ± 290 msec	1,246 ± 310 msec	1,213 ± 326 msec	1,365 ± 408 msec

Values represent the mean and standard deviation of participant median values per group and viewing condition.

In the second part of the analysis, we treated stereoacuity as a continuous variable and analyzed data for the binocular viewing condition only. First, we computed the median value for each kinematic variable and participant across the sixteen trials for the binocular condition. To avoid inflation and scaling errors, all variables were centered (i.e., mean of all variables was equal to 0) and standardized (z-score).

Our approach to finding the best model began with a kitchen-sink model, which included all variables.

Multiple linear regression (Equation 1) analysis was used to develop a model for predicting stereoacuity from the five kinematic variables (PV, MGA, tMGA, deceleration, and PPT). The model is a sum of the intercept (β_0) and the best fit for each kinematic variable via least squares sum.

Equation 1. $Stereoacuity = \beta_0 + \beta_1 PV_1 + \beta_2 MGA_2 + \beta_3 tMGA_3 + \beta_4 Dphase_4 + \beta_5 PPT_5$

Basic descriptive statistics and regression coefficients are shown in Table 3.3. Although our kitchen-sink, five-predictor model was able to account for 43% of the variance in stereoacuity, the model overall was non-significant, which indicates that most of the correlation coefficients are close to zero. $F(5, 15) = 2.29$, $p = .098$, $R^2 = .43$, 95% CI [0.025 0.975]. However, even with this non-significant model, tMGA had a significant ($p = 0.036$) correlation with stereoacuity and thus a good candidate for predicting stereoacuity.

Table 3.3

Multiple linear regression table for stereoacuity and all kinematic variables.

	Coeff	SE	t	p-value	95% CI
					[*LL* *UL*]
PV	0.454	0.418	1.086	0.294	[-0.437 1.345]
MGA	0.324	0.303	1.071	0.301	[-0.321 0.970]
tMGA	0.830	0.361	2.298	0.036*	[0.060 1.599]
D-phase	-0.252	0.268	-0.941	0.361	[-0.823 0.319]
PPT	0.380	0.384	0.991	0.337	[-0.437 1.197]

Notes. R^2 = .43 (*p* = 0.098). CI = confidence interval; *LL* = lower limit; *UL* = upper limit.

To determine whether collinearity within our predictor variables may be influencing our results, we ran a simple linear regression on all of our variables. Figure 3.5 shows a heat map with our six variables (stereoacuity, PV, MGA, tMGA, D-phase and PPT) where dark squares indicate a high correlation (red: positive; blue: negative) and light squares indicate a weak correlation.

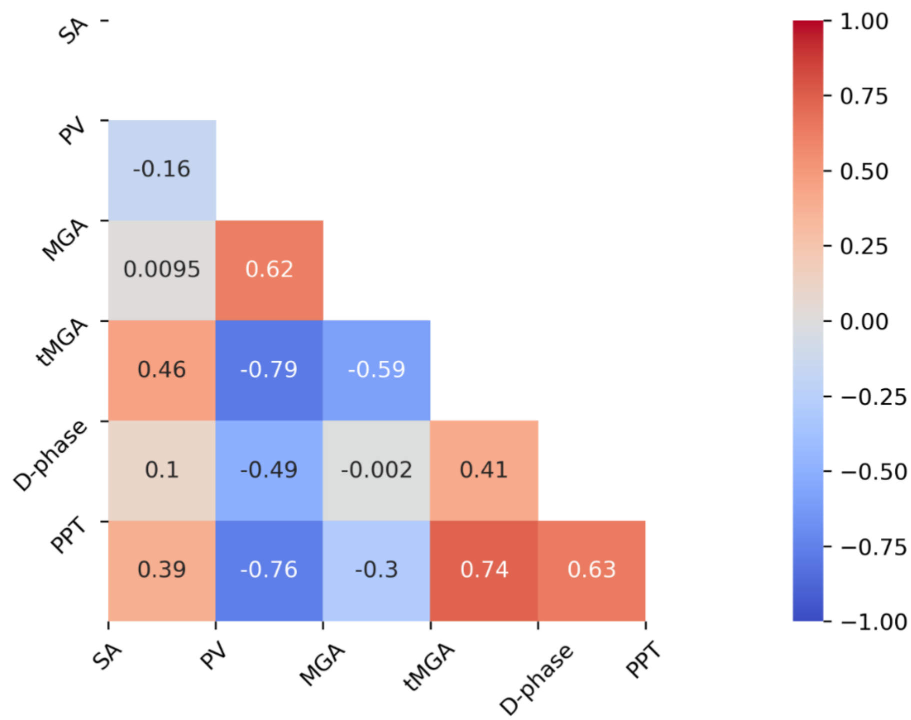

Figure 3.5. Correlation matrix for all variables (stereacuity, PV, MGA, tMGA, D-phase, and PPT) derived from simple linear regression analysis. Boxes with a warm colors represent a positive correlation (red = 1) while cool colors represent a negative correlation (blue = -1). Pearson's correlation is shown at the center of each box.

It is important to note that although there are relatively high correlations in the data, a variance inflation factor (VIF) analysis confirms that all variables have a VIF of less than five, which indicates low to moderate collinearity.

Surprisingly, the correlation matrix reveals high collinearity between tMGA and nearly all other variables. Participants who took a longer time forming the maximum grip aperture, tended to have higher stereoacuity thresholds, lower peak velocity, narrower grip apertures and took longer in the deceleration phase and the time it took to place the peg.

Furthermore, PV shows a high negative correlation with tMGA and PPT, indicating that participants who show a lower peak velocity also tend to be slower to form the maximum grip aperture and complete the task. Additionally, PV shows a high positive correlation with MGA, meaning that participants with a higher PV (faster) form a narrower grip aperture.

A key question that arises from these results is whether a single kinematic variable or a combination of variables best predicts stereoacuity. Given the moderate collinearity results, it is fair to assume that there might be one or more interaction effects within our data. To test for interactions, we built a model that treated each two-pair combination as a variable. Table 3.4 shows p-values for our five kinematic variables and the ten two-pair combinations.

Table 3.4

P-values for all-inclusive model to test interactions between variables.

Variable	p-value	Variable	p-values
PV	0.044*	PV: PPT	0.905
MGA	0.996	MGA: tMGA	0.052
tMGA	0.050*	MGA: D-phase	0.039
D-phase	0.285	MGA: PPT	0.998
PPT	0.484	tMGA: D-phase	0.168
PV: MGA	0.413	tMGA: PPT	0.069
PV: tMGA	0.031*	D-phase: PPT	0.358
PV: D-phase	0.904		

P-values for multiple linear regression model that treats each interaction as a variable. Significant values (* for $p \leq 0.5$, ** for $p \leq 0.01$, and *** for $p \leq$) are indicated with an asterisk while non-significant trends are in italics.

After confirming that our data did indeed show a significant interaction effect, we built the final model using our significant terms (PV, tMGA and the interaction between PV and tMGA). Overall, our simplified model turned out to be significant $F(5, 15) = 4.95$, $p = 0.012$,

R^2 = 0.47, 95% CI [0.025 0.925] and predicts 47% of the variance in stereoacuity (Equation 2). Descriptive statistics for the final model can be found in Table 3.5.

Equation 2. $Stereoacuity = 0.26 + 0.005\ tMGA + 0.016\ PV + 2.84e - 05\ PV{:}tMGA$

Table 3.4

Descriptive statistics for simplified model.

	Coeff	SE	t	p-value	95% CI [*LL* *UL*]
PV	0.016	0.006	2.672	0.016*	[0.003 0.028]
tMGA	0.005	0.001	3.481	0.003**	[0.002 0.008]
PV: tMGA	2.843e-05	1.3e-05	2.188	0.043*	[1.02e-06 5.58e-05]

Notes. R^2 = .47 (p = 0.012). CI = confidence interval; *LL* = lower limit; *UL* = upper limit.

3.4 Discussion

Our aim for this study was to quantify the relationship between stereoacuity and motor movement in prehension using a reach-to-grasp task. We analyzed five kinematic variables (PV, MGA, tMGA, D-phase, and PPT). We then used those five kinematic variables to (1) compare performance between two groups: stereo-anomalous and stereo-normal and (2) build a model that best captured the relationship between stereoacuity and our data.

For the first analysis, we derived three major results: (1) Binocular disruption via patching had a large impact on performance in the stereo-anomalous group. This was quantified by a wider grip aperture (5 mm difference) and longer movement times: 103, 62, and 151 msec for tMGA, D-phase and PPT, respectively.

These results support evidence from previous studies[9,10,12] and indicate that when binocular vision is disrupted, participants with stereo-impairments adopt a more cautious approach. However, the fact that patching one eye had a deleterious effect on their performance supports evidence that the use of both eyes is still important for prehension, despite reduced or absent stereopsis[11], perhaps through vergence or other non-stereoscopic binocular cues.

(2) Binocular disruption did not have the same impact on performance in the stereo-typical group. Consistent with Verghese et al., 2016, the only kinematic variable that showed an impact on performance was PPT with stereo-typical participants performing the task 176 msec faster in the binocular condition.

These results indicate that the stereo-typical group might be benefiting from the experience of stereovision or making use of other cues. However, further claims will need more evidence.

The last major result from the first analysis is that (3) the only significant difference in performance between the stereo-typical and stereo-anomalous groups was in the time it took to form the maximum grip aperture when viewing was restricted to the dominant eye. On average, the stereo-typical group was 188 msec faster in forming the grip compared to the stereo-anomalous group – indicating less uncertainty in the objects' intrinsic 3D properties.

In the second part of the analysis, our aim was to build a model that best describes the relationship between stereoacuity and our five kinematic variables. The model that best describes the relationship between stereoacuity and prehension accounts for 47% of the variance and is a linear combination of the tMGA, PV and the interaction of tMGA and PV with PV contributing three times more to the prediction of stereoacuity than tMGA.

Overall, the model that best predicts the relationship between stereoacuity and prehension in our data is simple and indicates that stereoacuity can be predicted by factors that indicate movement planning (PV) and the certainty of object intrinsic 3D properties (tMGA).

Chapter 4

Quantifying the difference in a reach-to-grasp tasks between long-term and recent stereo-loss

Data for Experiment 3 is comprised of data from Experiment 2 (stereo-anomalous only) and data from a previously published paper from our collaborator[73]. Both datasets were collected on the same apparatus, using the same task but on different populations of people. Both populations degraded stereovision. However, participants from Experiment 2 experienced stereo-impairments from an early age due to anisometropia and/or strabismus with or without amblyopia. Participants from the previously published paper[73] have only recently experienced stereo-impairments due to the onset of age-related macular degeneration (AMD).

4.1 Introduction

We know from previous studies and from Experiment 2 that people with binocular-impairments perform worse on motor tasks compared to individuals with typical stereovision[9–12]. Furthermore, we know that these impairments are most apparent in the movement phases where visual feedback and stereovision are most beneficial (i.e., low-phase velocity of reach and application of the grip). However, humans are highly adaptive creatures and when one modality is unreliable, a process of learning and reweighting can, within reasonable limits, potentially lead to lasting changes and movement optimization.

In the case of prehension and stereovision, recent evidence suggests that there might be potential adaptations in adults with long-standing stereovision loss – namely, researchers infer a “greater reliance on tactile/ kinesthetic feedback”[14], evidenced by the observation that adults with impaired stereovision take a longer time to lift the object once contact has been made[11,14] – contributing the additional time to proprioceptive feedback.

Additionally, the argument can surely be made that a more cautious approach and longer time spent on movement duration (hallmarks of movement kinematics in people with impaired stereovision), specifically the low velocity phase[9–11] and the application of the grip[9,12] could indeed also be adaptations to mitigate issues that arise from impaired stereovision.

Thus, a key question arises: are these adaptive behaviors a result of a long-term reweighting of cues and optimized movement patterns? Or are they quick, reflexive responses to increased uncertainty?

When comparing long-standing stereo-loss to a temporary disruption via patching, we neglect the influence of a lifetime of experience using stereovision and the knowledge that after this task, their stereovision will be restored. But what happens when people experience a more permanent form of stereo-loss in adulthood via natural causes such as AMD? Do they behave like people with a long history of stereo-impairments?

People with AMD experience central vision loss, which impacts everyday activities such as reading[80,81], facial recognition[82] and motor action[83,84], to name a few. These deficits are in part due to the multifaceted visual impairments (e.g., low vision, impaired color vision and contrast sensitivity) people with AMD experience. However, the impact to reaching and grasping might be attributed to reduced stereovision[73].

When compared to age-matched controls, participants with AMD take longer to complete the task[15,83] and display a longer acceleration phase[15]. However, while some studies report what seems to be better performance: a higher peak velocity[15] and shorter time to maximum grip aperture[15], others report what is more in line with a general visuomotor processing deficit and includes: a shorter peak velocity and longer time to maximum reach aperture[83]. Furthermore, researchers attribute the impairments to a reduced time for visual inspection since those differences were eliminated when participants were allowed 500 to 2000 msecs of visual inspection (without movement) before the trial began[15].

To tease out whether the “deficits” observed in prehensile movements of people with long-term stereo-loss are actually adaptive behaviors, we decided to compare reaching and grasping kinematic data between a group with long-term stereo-loss and a group of AMD patients who have experienced recent stereo-loss due to AMD.

4.2 Methods

4.2.1 Participants

Twenty-three adults (mean age: 57 ± 24, range: 18 – 90 years, 9 female) participated in the study. Participants were divided in two groups (early and recent stereo-loss) based on the nature of their stereo deficit. The early stereo-loss group was comprised of thirteen participants with impaired stereopsis (stereoacuity = 539” ± 5”) due to developmental manifestations of: anisometropia (6), strabismus (5) or both (2). The remaining ten participants formed the recent stereo-loss group with impaired stereopsis (stereoacuity = 945” ± 10”) due to maculopathy (Table 4.1). Participants with early stereo-loss were recruited by phone or email from the Meredith W. Morgan University Eye Center’s internal list and The Smith-Kettlewell Eye Research Institute’s participant database. Participants with recent stereo-loss were referred from the low vision rehabilitation practice of D.C.E. at California Pacific Medical Center and recruited by phone. The Institutional Review Board of The University of California, Berkeley and The Smith-Kettlewell Eye Research Institute approved the study protocol. The study was conducted according to the tenants of the Declaration of Helsinki and informed consent was obtained from each participant. Exclusion criteria for the study included neural pathologies.

Table 4.1

Participant stereo and visual acuity

	Stereoacuity (arc secs)	Visual acuity (Snellen)	
		Binocular	Monocular
A1	50	20/20 +2	20/20 +2
A2	100	20/20 -1	20/20 -2
A3	70	20/20 +3	20/20 +2
A4	1800	20/20 +2	20/20 -1
A5	1800	20/20 +1	20/20
A6	1800	20/20 +2	20/20 +1
A7	1800	20/32 -1	20/32 -1
A8	70	20/20 +1	20/20 -2
A9	70	20/20	20/25
A10	40	20/20 +1	20/32 +3
A11	400	20/32 +1	20/32 -1
A12	1800	20/25 -2	20/32 +1
A13	1800	20/16 -2	20/16 -2
M1	220	20/40	20/40
M2	1800	20/25	20/25
M3	1800	20/25	20/32
M4	1800	20/80 -1	20/80
M5	800	20/63	20/80
M6	600	20/400	20/20
M7	1800	20/25	20/25
M8	1800	20/320 +2	20/16
M9	-	20/80	20/160 +3
M10	300	20/25	20/25

4.2.2 Vision and Handedness Assessment

All participants completed a battery of tests to assess vision and handedness. Vision evaluation for both groups included: (1) visual acuity, (2) clinical and psychophysical stereoacuity. Since the groups were part of different studies, the tests used to measure their vision where slightly different.

For the group with early stereo-loss: visual acuity was measured using the Bailey Lovey visual acuity chart at a viewing distance of 3 m. Stereoacuity was measured clinically with the Randot Circles Stereotest® and psychophysically with the Accurate STEReotest (ASTEROID), which is a four-alternative forced-choice (4-AFC) dynamic random dot stereotest with a Bayesian staircase[74].

For the group with recent stereo-loss: visual acuity was measured with the MN Real visual chart at a viewing distance of 40 cm (or closer, if necessary). Similar to the group with early stereo-loss, clinical stereoacuity was measured with the Randot Circles Stereotest®. For participants with measurable stereopsis, psychophysical stereoacuity was measured in a custom-built pellicle system with a beam splitter that combined images from two separate monitors placed at right angles.

Additional visual evaluation for participants with early stereo-loss included: (1) ocular deviation (Monocular cover-uncover test and alternate cover test using accommodative stimuli) at 40 cm and 3 m and (2) horizontal and vertical phoria (Modified Thorington Test) at 40 cm and 3 m.

Participants were categorized as having anisometropia if there was a difference ≥ 0.50 D in spherical equivalent refraction or ≥ 1.50 D difference in astigmatism in any meridian, between the two eyes[78]. Participants were classified as having strabismus in the presence of a tropia with the cover test.

Additional visual evaluation for participants with recent stereo-loss included: (1) Cognitive status (Mini-Mental State Examination (MMSE)) and (2) Monocular and binocular scotomas via microperimetry using the Optos Optical Coherence Tomograph/ Scanning Laser Ophthalmoscope (OCT/SLO); Optos, Marlborough, MA, USA), with a field size of 29.7°. All participants passed the MMSE.

To assess hand dominance and determine the hand to be used in the prehension task, participants completed the Edinburgh Handedness Inventory[77]. All participants were right-handed with a laterality quotient > 50 and performed the prehension task with their right hand.

4.2.3 Prehension task and equipment

To quantify prehension, we used a peg-placement task[73] with a commercial pegboard (Geometric Peg Board 5125; Plan Toys, Plan Creations Co. Ltd., Bangkok, Thailand) (Figure 4.1A) presented just below eye height to better isolate stereopsis (Figure 4.1B). The pegboard was positioned 30 cm above the table, at a distance of 40 cm from the participant. The pegboard had four rows, each containing four unique shapes (circle, triangle, square, and rectangle).

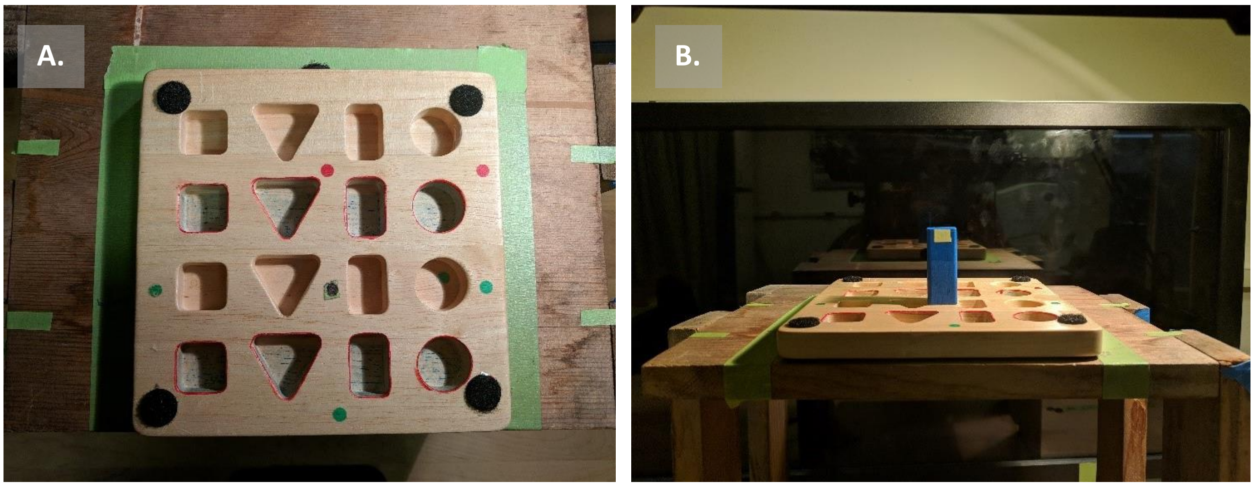

Figure 4.1. Pegboard and participant view. (A) The pegboard viewed from the top. The small black dot at the center indicates the position of the peg at the start of each trial. Participants were instructed to place the peg on the appropriate slot on the first row from the participant for ‘near’ and third row for ‘far’ (B) The pegboard from the participants’ view- 10 cm below eyesight.

To minimize head movements, participants were seated with their chin and forehead resting on a head mount (Figure 4.2A). Participants began each trial with their dominant hand in a closed-grip starting position and were instructed to wait for an auditory signal before initiating the reach-to-grasp movement. Before the auditory signal, the experimenter placed the randomly generated shape at the center of the board, in line with the second row, indicated with a black circle on the pegboard. Participants were instructed to reach for the predetermined shape and place it in one of two locations (near or far), fist or third row respectively, with relative disparities of 15 and 17 arc minutes with respect to the peg starting position.

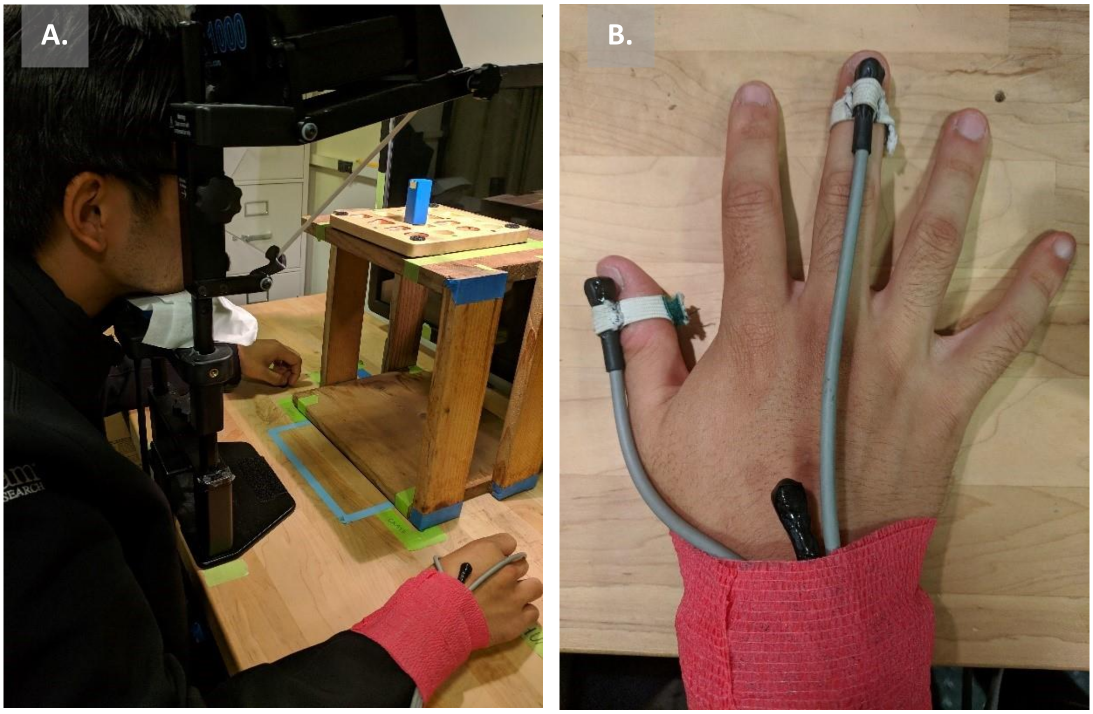

Figure 4.2. Participant setup and sensor placement. (A) Participant setup and ready for the ‘go signal’. Participants’ head was stabilized using the chin rest from the EyeLink 1000 Eye Tracker (SR Research, Ottowa, ON, Canada). Participants were instructed to touch their grasping finger and thumb and rest it on two small Velcro circles and wait for the tone signal to begin the movement. (B) Sensor placement. Three sensors were placed on the reaching hand and secured on the wrist with kinesiology tape (pink)- One on the wrist and the other two on the distal portion of the thumb and grasping finger (here middle).

Participants completed a total of eight trials under binocular viewing for practice. After the practice trials, each participant completed 16 trials per viewing condition: binocular and monocular for a total of 32 trials per participant. Trials were excluded if persistent artifacts did not allow for kinematic points to be extracted. From a total of 736 trials, a total of 104 trials were excluded from the analysis.

We used the Polhemus (Colchester, VT, USA) Liberty 240/16 motion tracker at a sampling rate of 240 Hz to capture the 3D position of three sensors, which were placed on the grasping finger (index or middle), thumb and wrist (Figure 4.2B). Sensors were secured on the phalanges and wrist via kinesiology tape and the position was captured by a magnet under the table. Hand movements were recorded from the initial auditory signal until after the peg was placed and the experimenter manually pressed a key to stop recording.

4.2.4 Prehension dependent variables

To assess performance on the task, we analyzed five kinematic variables: peak velocity (PV), maximum grip aperture (MGA), time to maximum grip aperture (tMGA), deceleration phase (D-phase), and peg-placement time (PPT). We were particularly interested in these variables since they give us insight on reach planning and execution (PV), grip planning (MGA and tMGA), grip execution (D-phase) and object transport and drop-off efficiency (PPT). Furthermore, previous studies have demonstrated the importance of binocular vision on these variables[3,4,13,79].

Velocity was calculated as the absolute summed difference between the 3D position of two sensors (thumb and finger). From velocity, we calculated PV— the maximum velocity before object-pick-up (Figure 4.3A).

Grip aperture was calculated as the 3D distance between two sensors (thumb and finger). Maximum grip aperture (MGA) (Figure 4.3B), defined as the maximum grip aperture before object-pick-up and represents the largest scaling of the hand before object-pick-up. Time to maximum grip aperture (tMGA) (Figure 4.3B), defined as the segment between PV and MGA was calculated as the time segment between global maximum velocity before object-pick-up to global maximum grip aperture before object-pick-up. D-phase, defined as the time segment between MGA and object-pick-up represents the low-velocity phase as the participant is getting closer to the object and closing the grip.

Object-pick-up and -drop-off were calculated using the derivative of grip, which reflects when the grip aperture changes direction from open to close or vice-versa. First, we split the trace into two segments (first and second). Object-pick-up was calculated as the global minimum (indicates changing grip from open to close) in the first segment, while object-drop-off was calculated as the global maximum (indicates changing grip from close to open) in the second segment. PPT was defined as the time segment between object-pick-up and -drop-off (Figure 4.3C).

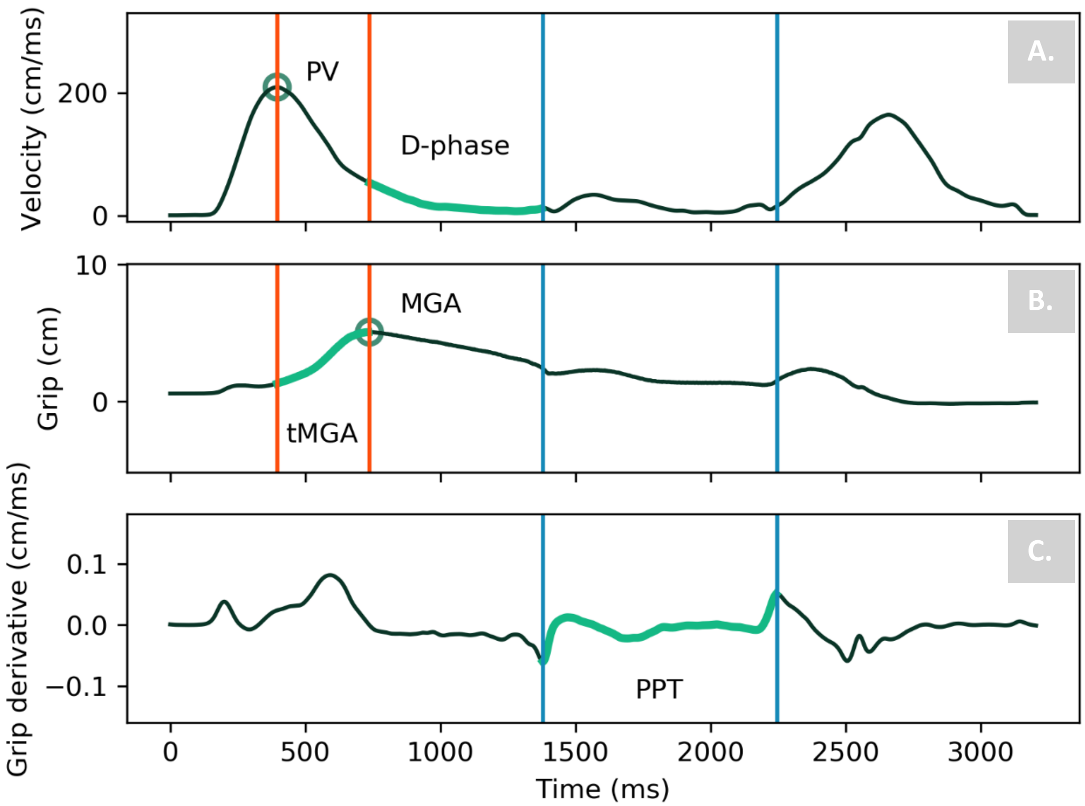

Figure 4.3. Prehension dependent variables as indicated by one participants' trial. The blue vertical lines indicate object-pick-up (first) and object-drop-off (second). (A) Velocity trace showing PV (dark teal circle) and D-Phase (green segment between the orange and blue lines). PV was defined as velocity global maximum before object-pick-up (first blue line). D-phase was defined as the time segment between MGA and object-pick-up. (B) Grip trace showing MGA (dark teal circle) and tMGA (green segment between the orange lines). MGA was defined as the global maximum grip aperture before object-pick-up. The start of tMGA (first orange line) was defined as the global maximum in acceleration (not imaged here) before object-pick-up, while the end of tMGA (second orange line) was defined as the global maximum grip aperture before object-pick-up. (C) Change in grip trace showing PPT (green segment between the two blue lines) was defined as the time between object-pick-up and object-drop-off.

4.2.5 Data analysis

Hand movement data were initially processed using custom-written programs in Matlab software (The MathWorks Ltd., Cambridge, UK). However, kinematic and statistical analyses were completed in Python (v3.6.8).

To account for variations in finger size and placement of the sensor on the index versus middle finger, grip aperture values for each participant were calibrated by subtracting the geometric mean of the grip size while participants gripped the square peg (i.e., a value of 0 in the grip aperture traces indicated that the participant was gripping the peg). We calculated a geometric mean since we had three measures, pertaining to a single calibration at the start of each viewing condition.

To remedy high-frequency noise in the velocity traces, we replaced values outside the inner and outer fences with ‘nan’ and filled the ‘nans’ by interpolating between the points. We then smoothed velocity using a second-order low-pass Butterworth filter with a sliding window of 50 frames. The derivative of grip was also smoothed using the same second-order low-pass Butterworth filter.

We calculated the median across sixteen monocular and binocular trials for each participant. Trials were excluded from analysis if they were incomplete or too noisy that kinematic landmarks could not be extracted.

Shapiro-Wilk test was used to test whether within group or between group data were normally distributed. Since our data were often not normally distributed, we used the Wilcoxon signed rank test for within group comparison (binocular vs monocular) and an independent samples Mann-Whitney U test for between group comparisons (stere-typical vs stereo-anomalous).

4.3 Results

We measured performance on a peg-placement task using five kinematic variables under two viewing conditions (monocular and binocular) for participants with different stereo-loss etiologies: long-term stereo-loss (n = 13) and recent stereo-loss (n=9). PV, MGA, tMGA, D-phase and PPT are depicted as box plots in Figures 4.4A, 4.4B, 4.4C, 4.4D, and 4.4E, respectively. Each panel shows four box plots displaying data for each group (Long-term: left; Recent: right) and viewing condition (Binocular: orange; Monocular: teal). The central horizontal line indicates the median while the edges of the box indicate the 25th and 75th quartiles of the data. The whiskers indicate the rest of the distribution, except for outliers, which are displayed outside of the whiskers. Each circle represents the median of 16 trials (unless trials were missing or excluded- see Methods).

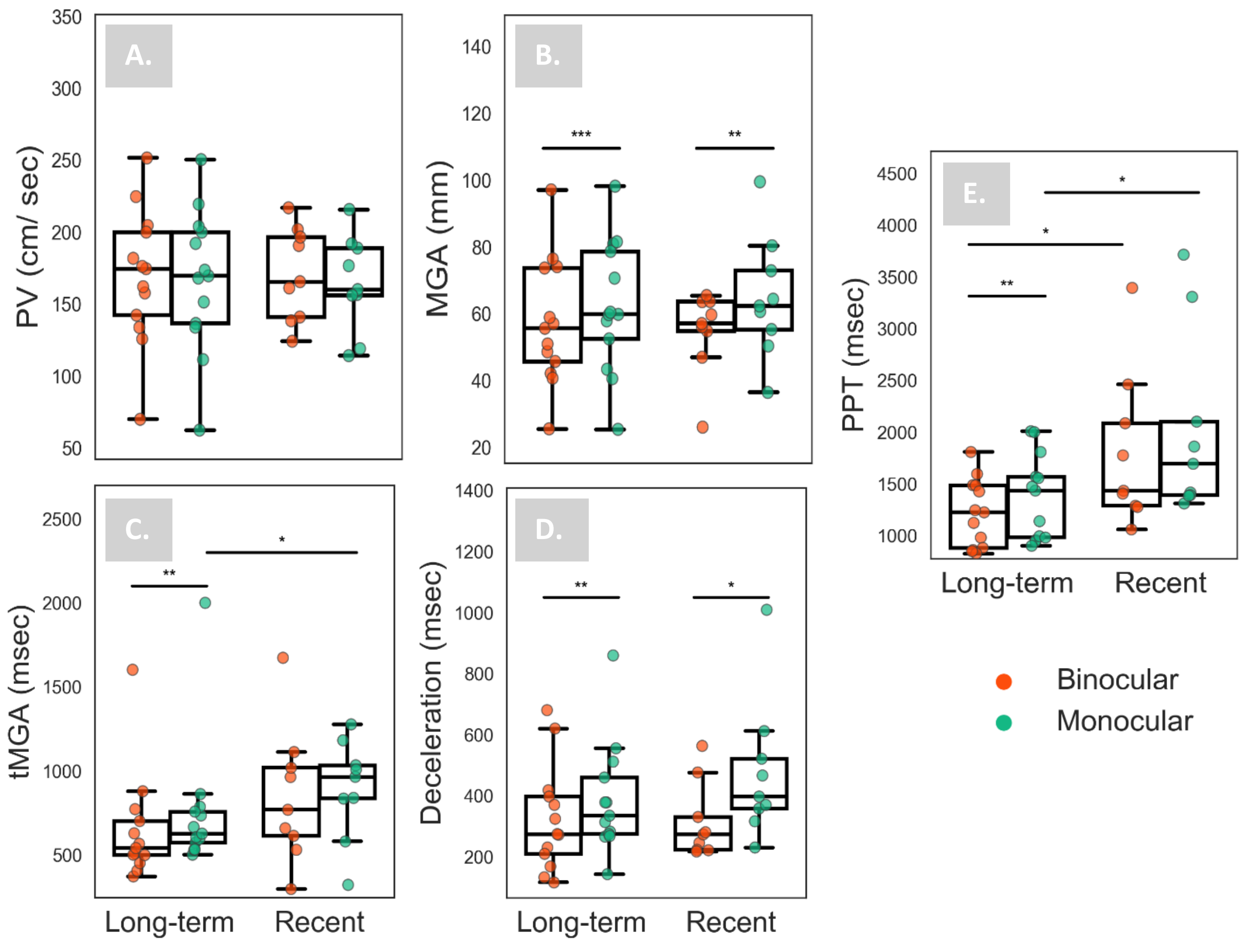

Figure 4.4. Average performance on the five kinematic variables: (A) PV, (B) MGA, (C), tMGA, (D) Deceleration and (E) PPT. Each panel shows aggregate data for the long-term (left) and recent (right) stereo-loss groups. Individual mean data are depicted as circles for the binocular (orange) and monocular (teal) viewing conditions.

To compare monocular vs binocular performance within-subjects, we used the nonparametric Wilcoxon rank test. See Table 4.2 (columns 1 and 2) for mean comparison significance levels and Table 4.3 for mean and standard deviations.

Binocular disruption via patching had a significant effect on performance for the group with long-term stereo-loss. There was a significant difference of viewing condition for all kinematic variables (all $p \leq 0.010$) except for PV ($p = 0.340$). Under monocular viewing, MGA was significantly wider (5 mm) and the timing variables (tMGA, D-phase and PPT) were all longer. On average, long-term stereo-loss participants were 103, 62 and 151 msec slower in tMGA, D-phase and PPT, respectively. These results are not surprising and indicate that people with long-term impaired stereopsis are highly impacted when vision is restricted to one eye.

Contrary to the long-term stereo-loss group, performance in the group with recent stereo-loss does not seem to be equally impacted by disruption of binocular vision. Only MGA (p = 0.008) and D-phase (p = 0.039) showed a significant difference in performance between the monocular and binocular viewing conditions. On average, the recent stereo-loss group formed a wider grip (10 mm) and took longer decelerating (161 msec) in the monocular condition.

Table 4.2

Mean group comparisons and significance levels (p values)

	Binocular vs Monocular		Long-term vs Recent	
	Long-term	Recent	Binocular	Monocular
PV	0.340	0.300	0.473	0.395
MGA	0.001***	0.008**	0.421	0.369
tMGA	0.010**	0.359	0.062	0.036*
Deceleration	0.010**	0.039*	0.473	0.128
PPT	0.003**	0.250	0.023*	0.048*

Within-subjects (columns 1 and 2) mean comparison using the Wilcoxon rank test and between-subjects (columns 3 and 4) mean comparison using the Mann-Whitney *U* test. Significant values (* for $p \leq 0.5$, ** for $p \leq 0.01$, and *** for $p \leq 0.001$) are indicated with an asterisk while non-significant trends are in italics.

To compare performance differences between the long-term and recent stereo-loss groups, we used the nonparametric Mann-Whitney *U* test.

In the monocular condition, the only significant differences between the long-term and recent stereo-loss groups were observed in tMGA ($p = 0.036$) and PPT ($p = 0.048$) with the recent stereo-loss group taking 142 msec longer to form the maximum grip aperture and 653 msec longer to place the peg.

Similar to the monocular condition, in the binocular condition, the group with recent stereo-loss was on average 583 msec slower in the PPT ($p = 0.023$) compared to the group with long-term stereo-loss. Although the recent stereo-loss group took 200 msec longer in the tMGA compared to the group with long-term stereo-loss, the difference was not significant ($p = 0.062$).

Table 4.3

Mean and standard deviations for each group and viewing condition

	Long-term		Recent	
	Binocular	Monocular	Binocular	Monocular
PV	169 ± 47 cm/sec	167 ± 49 cm/sec	170 ± 32 cm/sec	164 ± 33 cm/sec
MGA	57 ± 19 mm	62 ± 20 mm	55 ± 12 mm	65 ± 18 mm
tMGA	647 ± 321 msec	750 ± 391 msec	847 ± 402 msec	892 ± 295 msec
D-phase	323 ± 174 msec	385 ± 181 msec	313 ± 124 msec	474 ± 230 msec
PPT	1,213 ± 326 msec	1,365 ± 408 msec	1,796 ± 744 msec	2,018 ± 890 msec

Values represent the mean and standard deviation of participant median values per group and viewing condition.

To assess whether the significant group differences where due to the etiology of stereo-loss or the confounding variable that people in the recent stereo-loss group were indeed much older and thus potentially slower, we ran the Mann-Whitney *U* test on the ratio between binocular and monocular performance (Table 4.4).

Surprisingly, when neutralizing intra-subject differences by taking the ratio, there are no significant differences between groups in any of the kinematic variables. This indicates that the previously reported group differences, may be due to other factors such as age or possibly the difference in the visual acuities or stereoacuities of the two groups.

Table 4.4

Mean, standard deviation and p-values for binocular to monocular ratio group mean comparison

	Mean ± SD		p-value
	Long-term	Recent	
PV	1.02 ± 0.07	1.05 ± 0.17	0.473
MGA	0.92 ± 0.7	0.86 ± 0.12	0.066
tMGA	0.87 ± 0.16	0.96 ± 0.31	0.344
D-phase	0.82 ± 0.18	0.75 ± 0.36	0.096
PPT	0.90 ± 0.09	0.91 ± 0.17	0.263

Values represent group mean and standard deviation of participant binocular to monocular performance ratio and p-values for Mann-Whitney *U* test group comparisons.

To assess whether visual acuity or stereoacuity could explain performance on the task, we computed Pearson's correlation between stereoacuity, binocular visual acuity and the five kinematic variables under binocular viewing (Table 4.5 columns 2-3 and 6-7). There were no significant correlations between performance and stereoacuity or visual acuity. We also ran the correlations using the performance ratio between binocular and monocular viewing (Table 4.5 columns 4-5 and 8-9). The only significant correlation observed was between binocular visual acuity and the binocular to monocular PV (r = -0.44, $p = 0.05$), indicating that worse visual acuity is associated with a higher binocular to monocular ratio. In other words, participants with worse visual acuity have a higher peak velocity, and thus are faster, in the binocular condition compared to the monocular condition.

Table 4.5

Pearson's correlation and p-values for stereoacuity, visual acuity, binocular performance on the five kinematic variables and the binocular to monocular ratio

	Stereoacuity				Visual acuity			
	Binocular		B:M ratio		Binocular		B:M ratio	
	r	p-value	r	p-value	r	p-value	r	p-value
PV	-0.10	0.67	0.25	0.29	0.12	0.62	-0.44	0.05*
MGA	-0.07	0.76	0.23	0.33	0.20	0.39	0.19	0.42
tMGA	0.37	0.10	0.25	0.29	-0.32	0.15	0.16	0.51
D-phase	0.08	0.73	0.15	0.52	-0.06	0.80	-0.03	0.92
PPT	0.26	0.26	0.34	0.14	-0.36	0.10	-0.02	0.92

Significant values (* for $p \leq 0.5$, ** for $p \leq 0.01$, and *** for $p \leq 0.001$) are indicated with an asterisk while non-significant trends are in italics.

4.4 Discussion

Our aim for this study was to quantify the difference in reaching and grasping strategy between people with long-term stereo-loss and those who have experienced stereo-loss in adulthood. We analyzed five kinematic variables (PV, MGA, tMGA, D-phase, and PPT). We then used those five kinematic variables to (1) compare performance between viewing condition within each group and (2) compare performance between groups.

From the within-group comparisons we conclude that binocular disruption via patching had a large impact on performance in the stereo-anomalous group as evidenced by a wider grip aperture (5 mm difference) and longer movement times: 103, 62, 151 msec for tMGA, D-phase and PPT, respectively. Although the recent stereo-loss group formed a wider grip aperture (10 mm difference) and took 161 msec longer to decelerate, the impact of artificially disrupting stereovision did not have the same impact as it did in participants with long-term stereo-loss.

These results suggest that a lifetime of stereovision experience provides additional benefit to people who experience stereo-impairments later in life that are not present in people with a lifetime of stereo-deficiency. However, it is also reasonable to suggest that the difference could be attributed to a difference in the nature of stereo-loss between the two groups.

From between group comparisons, we conclude that the difference between the two groups can be attributed to a slower movement time in the group with recent stereo-loss. In the monocular condition, the recent stereo-loss group took 142 msec more to form the grip aperture and 653 msec more to place the peg compared to the long-term stereo-loss group, while in the binocular condition, the recent stereo-loss group took 583 msec more to place the peg.

However, when neutralizing intra-subject differences by taking the binocular to monocular ratio and minimizing confounding variables such as age and reaction-time, the differences between groups were eliminated.

Furthermore, there were no significant correlations between visual acuity or stereoacuity with any of the performance variables. The only significant correlation we observed was between visual acuity and binocular to monocular, indicating that worse visual acuity is associated with a higher peak velocity in the binocular compared to the monocular condition.

Returning to our bigger question, it was quite surprising to find no results that indicate an adaptation in prehension to motor movement. The population with long-term stereo-loss performed nearly the same as the population with recent stereo-loss. Furthermore, the group with recent stereo-loss seems to have preserved something from a lifetime of stereovision experience not present or available to the group with long-term stereo-loss.

Chapter 5

Conclusion

From the experiments in this dissertation we provide evidence that stereopsis is an important function for everyday visuomotor tasks. People with impaired stereopsis perform worse when binocular vision is disrupted and perform worse in movement aspects that rely on binocular vision and visual feedback (Chapter 3). In addition, the model that best describes the relationship between stereoacuity and reaching and grasping is one that includes the time it takes to form the grip aperture (a common metric used for the influence of binocular vision) and peak velocity (reach movement aspect that relies on visual processing before movement initiation) (Chapter 3).

We also provide evidence that the experience of stereovision seems to provide stability or an additional benefit when binocular vision is disrupted. This was confirmed not only in the difference in performance between the 'stereo-anomalous' and 'stereo-typical' groups in Chapter 3, but also in the difference in performance between the 'long-term' and 'recent' stereo-loss groups in Chapter 4.

Lastly, we provide evidence that the recovery and strengthening of stereopsis can be achieved through direct stereovision training using perceptual learning scaffolding of cues in a gamified and entertaining manner (Chapter 2). Our assertion of the importance of stereovision recovery/ training in adulthood is in direct conflict with claims that have been made about possible adaptations in motor movement as a result of the experience of a lifetime with impaired or nil stereovision.

The argument can be made that people who have impaired or nil stereopsis have developed a strategy that could indeed be termed an "adaptation", namely a slower a more cautious approach. However, these strategies are not better compared to movement kinematics when compared to a group with recent stereo-loss, which leads us to conclude that these strategies might stem from a reflexive response to the uncertainty that arises when cues like stereopsis are missing[11] as opposed to an adaptive strategy that has been learned through time.

However, the key finding that we can draw from this dissertation is that the experience of stereovision is highly important for everyday visuomotor tasks.

This is why in concluding, we argue that (1) stereopsis is an important function to recover/ strengthen and the best method of recovery might actually be through direct stereo training since (2) the biggest motor movement deficits are in movement aspects that rely on binocular vision and visual feedback and (3) although a lifetime of stereo-impairment does lead to visuomotor adaptations, (4) those adaptations are not superior to ones present in people with recent stereo-loss. On the contrary, people who have had the experience of stereopsis and lost it later in life, seem to benefit or have additional information at their disposal when binocular vision is artificially disrupted.

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