ON DISTANCE PERCEPTION

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

A crucial, but little studied, visual function involves estimating distance from the self to an object in the environment (absolute distance perception). This is a fundamental component in the creation of our perception of the 3D world and is likely to be affected by alcohol, and be a factor in drunk driving accidents. To better understand which visual cues observers use to determine distance, participants completed a series of psychophysical judgments under different viewing conditions. By controlling and isolating specific distance cues through a novel viewing apparatus, we were able to investigate which cues are used to accurately judge distance. Alcohol intoxication allows us to selectively investigate the specific visual systems that are and are not involved in contributing to the accuracy of this type of task. Finally, an investigation of the effects of training and feedback on distance estimation tasks in a real 3D environment was also conducted. In summary, this research attempted to uncover not only how the visual system processes spatial information, but also how visual processing changes with alcohol intoxication with implications for understanding alcohol-related visual-spatial dysfunction that may arise in drunk driving. These findings will then be applied to a real world, 3D outdoor environment while investigating the impact of training and feedback on a distance estimation task.

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thought I knew a great deal about teaching and learning, but it took being challenged in his classes to more fully understand both concepts. As a researcher, he taught me how to write and how to do good research. He taught me to be open-minded, and to follow the data and let it tell the story. I would like to thank him for teaching me to design experiments to test theories, and to always be skeptical and objective. I am continually amazed at the research I have been able to accomplish under his careful and deliberate tutelage. Finally, I would especially like to thank him for taking a gamble on me as a biology student, when I only wanted the chance to make students as excited to learn about the brain as I was then- and continue to be. Because of him, this entire experience has been tremendously beneficial and improved my life beyond measure.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Visuomotor processing is essential to successful navigation, especially through a cluttered environment. Everyday tasks such as walking on the sidewalk to driving a car require not only visuomotor but also visuospatial processing. These types of processing combine incoming visual information with corresponding eye movements and lead to the creation of accurate cognitive maps that depict relationships between objects in space. These maps are made up of two key spatial relationship components. The first relationship component is relative depth, or the spatial relations of objects in the environment. The second relationship component is the distance perception from the observer to objects in their path, known as absolute distance. While these processes are automatic and do not require conscious effort from the observer, they occur multiple times every second. Generally, this process follows three steps. First, an observer makes saccadic eye movements, orienting the area of high-resolution vision, known as the fovea, on different objects of interest within the environment. This visual information is then combined with other distance cues to create the spatial interval between the self and the thing being observed with this foveal vision (red circle in Figure 1.; *f* in Figure 2., 3.). Next, based on this spatial interval, the visual system computes and scales relative depth, or the spatial relationship between objects throughout the environment (green squares in Figure 1.) creating a cognitive map in 3 dimensions. That is, the perception of "3D" is separate from, and depends on, distance perception. There are three interesting lines of evidence that suggest that humans rely on absolute distance to compute relative depth, yet, it is not known how individuals judge absolute distance accurately and the actual visual mechanisms for distance perception remain unclear.

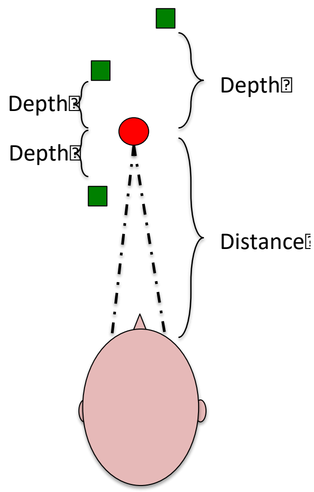


Figure 1. "Distance Perception" vs. "Depth Perception". Distance perception is the distance between an observer and their fixation target (red dot). Depth perception is the distance between objects (green squares) relative to the point of fixation (red dot). These different objects (green squares) are located at individual distances from the fixation point (red dot) and the objects' relationship among one another is know as relative depth.

Evidence of Absolute Distance

The first two lines of evidence for determining that our brains are capable of computing absolute distance come from two models and equations that exist for determining relative depth, which will be discussed next. The third line of evidence for determining that our brains compute absolute distance comes from the study of unconscious visual reflexes, and will be discussed later.

Binocular Disparity

Much more is known about how the brain computes relative depth than how the brain computes absolute distance. The two main models of relative depth are binocular stereopsis and motion parallax. Both of these fundamental aspects of vision have been researched extensively. One relative depth model is based on binocular inputs and the other relative depth model is based on monocular inputs, yet they both rely on absolute distance information (Figures 2 and 3, below), which is often arbitrarily decided. This relationship between distance and depth perception is even given in mathematical equations for depth perception, which is significant, given that the computation of absolute distance is rather poorly understood.

During binocular viewing, observers use both eyes to view the environment and the brain computes relative depth by binocular stereopsis. Figure 3 depicts how the two eyes take in differing information and the brain computes relative depth through differences in visual angles. Due the fact that the right eye and the left eye view the world from a different location within the skull, the retina of each eye receives a different pattern of stimulation for objects in the environment that occur nearer and further than fixation; this difference is known as retinal disparity. Essentially, if an object is on the same plane in space as the fixation point, the images will fall on corresponding points of the retina in both eyes. If this occurs, there will be no retinal disparity between the object and the fixation point and depth will not be perceived. However, if the object is closer to or further away from the point of fixation, a disparity will exist on the location of the retina, and depth will be perceived. The geometry of binocular stereopsis can be represented by an equation originally rendered by Cormack & Fox (1985) and simplified by Nawrot (2003) for the purposes of comparing depth from binocular disparity to depth from motion parallax:

$$d_s = \frac{(D_s^2 * \delta)}{i} \tag{1}$$

where *ds* is the specified depth, *Ds* is the absolute distance to the stimulus, δ is the amount of disparity, and *i* is the inter-ocular distance. Close investigation of equation 1 highlights the necessity for absolute distance (*Ds*) information to be known by the brain in order to produce a depth percept from stereopsis.

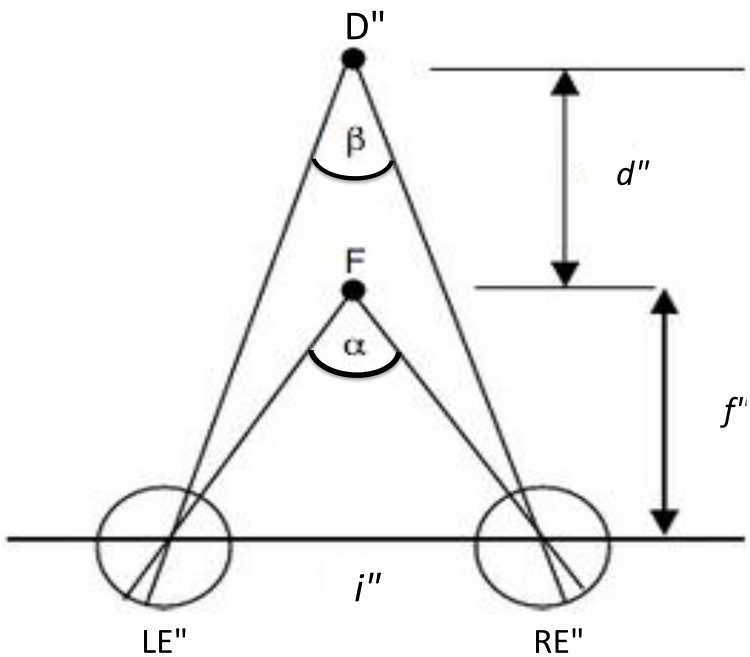


Figure 2. Relative depth from binocular disparity. The diagram is adapted from Cormack and Fox (1985), and depicts an overhead view of left eye (LE) and right eye (RE) and the space between them (*i*). The two eyes are fixating at a fixation point (F), given by $\angle\alpha$, that is at a distance (*f*). When point F is fixated upon, the image of F falls on corresponding points on the retinas of each eye, and F is fused, and seen as one object, not two. The distance between the fixation point and an object further than fixation (D) is given by distance *d.* This far object, (D) is given by $\angle\beta$. Objects nearer than fixation will be displaced on the retina more medially (nasally) and objects further than fixation (D) will be displaced on the retina more laterally (temporally) (Cormack & Fox, 1985). Note that a value of *f* is indicated and utilized by this depth model and equation 1, however, how the brain computes *f* remains somewhat unknown.

Motion Parallax

During monocular viewing, depth from motion parallax is created as the brain integrates retinal image motion with smooth pursuit eye movement signals. Figure 3 describes how the dynamic movement of the eye (laterally) updates retinal image motion information as well as produces the required eye movement signal. As an observer translates through space, the eye maintains fixation at a given object of interest (F) that is at a distance from the observer (*f*). Because the observer has not moved his or her eyes from the point of fixation, yet has translated leftward, a change has occurred in the eye's orientation to compensate for the movement (rotated rightward) (Miles & Busettini, 1992). The quantification of this eye movement is represented as dα. The value of dα can increase or decrease depending on the direction of observer translation relative to the starting point of the eye. Additionally, as the observer translates, other points (D) in the visual environment tend to move relative to F. The retinal image motion of D created with observer translation is represented here as dθ. The relative depth between points F and D in space is represented by *d* (Rogers & Graham, 1979). The dynamic geometry of motion parallax can also be represented in the following equation, known as the Motion/Pursuit Ratio (M/PR) (Nawrot & Stroyan, 2009, Stroyan & Nawrot, 2012):

$$\frac{d}{f} \approx \frac{\mathrm{d}\theta}{\mathrm{d}\alpha} \quad \text{or} \quad d \approx \frac{\mathrm{d}\theta}{\mathrm{d}\alpha} f \qquad (2)$$

where *d* is relative depth from motion parallax, *f* is viewing distance, dα is the pursuit eye movement, and dθ is the retinal image motion. The geometric relationship that exists among retinal image motion and visual pursuit eye movements is explained in the M/PR equation simply as the retinal image motion velocity divided by pursuit eye movement velocity, $\frac{\mathrm{d}\theta}{\mathrm{d}\alpha}$. This ratio value is then multiplied by *f* to provide a measure of relative depth present within a stimulus (*d*). The depth percept one experiences from motion parallax relies directly upon distance information (Ono, Rivest, & Ono, 1986), reiterating the assertion that motion parallax is a cue to depth, not absolute distance. The two lines of evidence previously discussed combine to indicate that absolute distance information is needed in order for relative depth to be perceived.

The amount of depth that a participant sees scales with distance in cases of both motion parallax as well as binocular stereopsis. The interesting thing about the two equations previously presented is that if one changes the value of the viewing distance (*Ds* in the case of the binocular disparity equation (1), and *f* in the case of the motion parallax equation (2)), the amount of depth perceived also changes, even if all of the other variables in the scene remain the same (Nawrot, Ratzlaff, Leonard, Stroyan, 2014). This is an important point to make, because it underscores the fact that the brain does take in absolute distance estimation as an input to inform relative depth judgments.

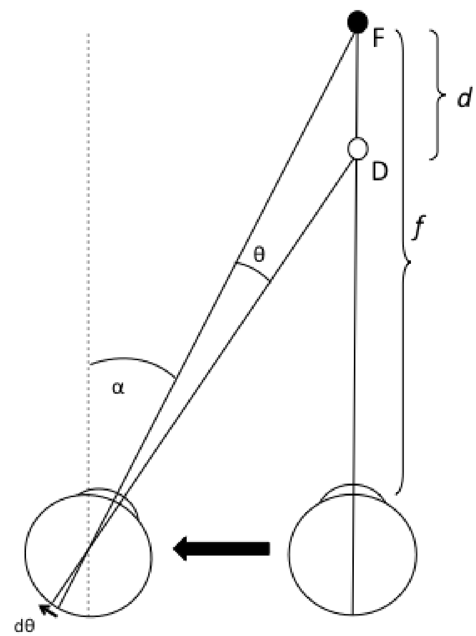


Figure 3. Depth from motion parallax. The diagram, adapted from Nawrot & Stroyan (2012), depicts the overhead view of one eye as it fixates a point (F) at *f* distance in space and then translates leftward (arrow), causing the eye to turn rightward to maintain fixation. This rightward turn of the eye is known as pursuit, and is given by dα. As the eye maintains fixation but translates, the image of the closer object (D) is moving on the retina relative to the fixation point. This movement is known as retinal image motion and is given by dθ. The relative distance between the fixation point (F) and the additional object in the environment (D) is given by *d*. Note that a value of *f* is given, but is never rendered by the model or the corresponding equation (equation 1) for depth from motion parallax.

Translational Vestibulo-Ocular Response

Finally, the third line of evidence that the brain is capable of computing absolute distance comes from an unconscious motor reflex, known as the translational vestibulo-ocular response (TVOR). This reflex occurs automatically during especially high frequency lateral head translations. During this fast head movement, TVOR allows the eyes to maintain fixation on an object (Bronstein & Gresty, 1988). The eyes are rotated in the direction opposite of the head translation and at an equal magnitude and speed (Paige & Tomko, 1991). This reflex is mediated by the vestibular system, particularly the otoliths within the vestibular labyrinth, and can occur just ~100ms post stimulus presentation (Bronstein & Gresty, 1988).

Interesting work conducted by Bronstein and Gresty (1988), as well as Schwartz, Busettini, and Miles (1989) uncovered that the gain of the TVOR system scales with absolute distance. Gain is the ratio of angular eye velocity to gravitational acceleration units; high gain values of near 1 indicate that the observer is closely maintaining fixation, and very small gains indicate the observer is not accurately maintaining fixation (Bronstein & Gresty, 1988). Specifically, TVOR evokes eye movements to compensate for the lateral translation of the body/head that are linearly related to the inverse of the target distance (Schwartz et al., 1989). If the eye movement gain elicited by TVOR scales with distance, it follows that the brain somehow is receiving cues about the absolute distance of the stimulus to inform the reflex. However, it is unknown which cues the brain uses to compute this distance, and how that distance informs the motor signals to each of the eyes.

Research conducted in darkness has quantified the TVOR response as having a typical gain of 17°/second/unit of gravitational acceleration (Barnes, 1980; Buizza, Leger, Droulez, Berthoz, & Schmid, 1980). In situations of very distant stimuli, the eye movement in this reflex is very small, requiring little movement to maintain foveal stabilization and the gain remains ~1, easily under the baseline gain. In situations of very close stimuli, the eye movement in this reflex is substantial, requiring a large amount of movement to maintain foveal stabilization, (Paige, 1989) and a TVOR baseline response of 17° is too slow. Targets that are located at a distance closer to the eyes than that of ~5 meters are not stabilized on the retina if the head is translating at frequencies of 0.5-1.0 Hz (Barnes, 1980; Buzzia et al., 1980; Tokita, Miyata, Masaki, & Ikeda, 1981). In these cases, the eye lags behind the stimuli, and the retinal slip is too great to maintain fixation. At this time, the brain seamlessly employs a pursuit eye movement signal to stabilize the image of the stimuli on the fovea (Miles & Busettini, 1992). The findings of Bronstein et al., (1988) and Schwarz et al., (1989), mentioned above, do indicate that one would be incorrect in attributing distance estimation abilities to TVOR, and that TVOR is likely less a contributor to distance perception as it is a product. TVOR is a muscular output of a reflex. It would therefore not make sense that TVOR computes absolute distance, but perhaps that TVOR has distance information "built in" to the efferent eye movement signal of this reflex.

Summary of Evidence

To summarize, both the monocular and the binocular models of depth acknowledge absolute distance (*f* and *Ds*, respectively), and the brain is capable of computing this distance. However, it is unknown what signals or information the brain is using to accomplish this task. In addition, TVOR is unlikely to give the absolute distance "signal" but is also utilizing distance information cues to inform efferent eye movements. Most researchers consider *f* to always be known and provided by the experimenter conducting the experiment, a constant, or some other arbitrarily given value, which does not explain how the brain actually computes absolute distance. In fact, which cues the brain uses to acquire or compute the value of *f* is uncertain. Fundamentally and theoretically, this is an immense problem for the field of visual perception. It is nearly impossible to believe that since the time motion parallax and binocular disparity were first thoughtfully described by Wheatstone (1838) and Helmholtz (1910/1925), respectively, the neural mechanisms underlying computation of absolute distance have remained a mystery, yet that is precisely the situation.

Remaining Problems

While *f* has been included in models of depth perception and shown to be computed by the brain to direct eye movements, research specifically looking at how the brain computes *f* has incurred semantic as well as methodological issues. There are three collective problems previous research has created and each will be discussed in the following pages in greater detail. First, studies conflate relative depth and absolute distance in their experimental designs. Adding to the confusion are many hypothesis tests of distance estimation using model organisms, such as preying mantids or gerbils, with visual anatomy and theoretical geometry of the visual system fundamentally dissimilar to that of humans. Finally, nearly all distance estimation research has focused primarily on stationary cues to distance, such as its given retinal image size, that is, how large or small the image appears, or the clarity of texture or brightness given from images to determine absolute distance. These experiments are problematic because humans are mobile, and it is rare that individuals remain stationary to estimate distance. Next, relevant literature will be included to illustrate and detail the three problems created by previous research.

Relative Depth vs. Absolute Distance

The terminology of absolute distance, relative depth, "relative distance" and "absolute depth" are often confused for one another in previously published literature. Relative depth and absolute distance have already been disseminated above (Fig. 1), however, the terms "relative distance" and "absolute depth" are often used interchangeably to refer to the correct terminology-relative depth or absolute distance. For example, "relative distance" is a term often used to describe the distance between two separate objects in space (ex. green squares, Fig. 1) or, incorrectly, as the distance of an object relative to the observer, which is actually absolute distance (see Epstein & Baratz, 1964 and Gogel, 1954 for examples). The problem with the terminology of “relative distance” can be illustrated by thinking through the physical steps of the process of determining the distance between two objects in space. First the observer is required to make an eye movement to each of the targets. In doing so, the foveated target automatically becomes a fixation point. From this point, a judgment about the space between each target is a relative depth judgment, and no longer a distance judgment. The term “relative distance” is essentially used in place of the term relative depth by some authors (see Chapanis & McCleary, 1953, and Gogel, 1956, for examples) though relative depth, or depth between two objects in space is actually what is being measured in a scenario like that which has been outlined above.

Similarly, the confusion of absolute distance and “absolute depth” has been propagated within the literature as well. This problem has been traced back to a footnote in Landy, Maloney, Johnston, & Young, (1995) in a paper written to about the combination of depth cues in a scene that are utilized by the brain. In their paper, Landy et al., (1995, p.391), use the term “absolute depth” to denote the distance from the observer to an object, not the correct term, “absolute distance”. This may seem like petty semantics, but this author finds numerous issues with their choice of wording. First, there is no explicit justification given by these authors to stray from the correct terminology of absolute distance and suddenly implement their own, though they acknowledge that is precisely what they are doing. Second, the reader becomes aware of this change in terminology only by reading the footnotes of the paper. Simply put, if the footnote is missed, the terminology error is perpetuated. Finally, this paper has been cited nearly 900 times since it was published in 1995 and has spawned havoc in the overall language of the field.

Fundamental misunderstandings also not only occur with semantics and with methods used in experimental designs, but also occur within explanations of relative depth. Recall from earlier, the brain has two mechanisms for determining relative depth, binocular disparity and motion parallax. Binocular disparity is a cue for determining relative depth, though, like motion parallax, it does rely on absolute distance information to make this judgment (see Figure 2 and Equation 1). Binocular disparity is sometimes erroneously thought to provide absolute distance information (Künnapas, 1968), rather than simply utilize distance information, as the model and equation would suggest. Unfortunately, the same fundamental mistake in understanding which perceptual depth cue is elicited by disparity also occurs within the study of motion parallax. Researchers have attempted to investigate the absolute distance cue capabilities of motion parallax, which by definition, is also singularly a relative depth cue. Not only does the following research have the semantics incorrect, there are methodological issues within each of the studies as well. Dees (1966) tested motion parallax accuracy for individual *absolute* distance perception at 20 different distances with a stationary background of random dots. Mistakenly, these researchers used the same fixation stimuli at each distance, giving participants non-controlled visual cues such as relative size and brightness to help with their relative depth judgments, which they mistook for absolute distance judgments. Another methodological problem is that a trial period in which feedback from the experimenter was given immediately for each distance estimation prior to the start of the experimental test. The main task of this experiment was to rank the 20 stimuli in order from closest to furthest. Participant knowledge of the minimum and maximum distance the stimuli could be from him/her is a large methodological confound. Due to the many flaws that existed within this experimental design, it is rather unsurprising that Dees found that training and motion parallax significantly increased the accuracy of *absolute* distance estimation. Ferris (1972, 1974) has also claimed that *absolute* distance estimation is possible through the utilization of motion parallax. These experimental designs utilized a large square aperture behind which, participants were seated and made absolute distance judgments to monocularly viewed stimuli either in an experimental lab (1972) or in an underwater pool (1974). The large square aperture is actually a confound in this experiment, giving participants a near target reference as well as a far reference (the background) with the fixation point (target) in between, insuring the relative depth judgments made would be accurate. The movement of the foreground and background as participants move their heads side to side while fixating on the target creates relative image motion as well as pursuit eye movements, the two components necessary for depth percepts from motion parallax. The *absolute* distance estimations of the fixation point are instead relative depth estimations. In addition to the near target confound, this research also utilized training feedback to each participant after seeing all of the stimuli twice prior to experimental test, creating another methodological confound. Underwater, Ferris (1974) found that it was not possible for participants to significantly judge *absolute* distance using motion parallax more accurately than participants instructed to remain as stationary as possible underwater. The authors attribute the null results to water turbidity, however, any movement of the head could have increased the abilities of these underwater "stationary" participants, giving them similar clues to relative distance as those created by the head motion in the parallax condition, which makes the similar results presented in this paper unsurprising. In addition, it is unclear how much movement the stimuli, which were black strips inserted from above the pool, were moving in the water in each of these conditions. The slight changes in the location of the stimuli in motion could also have given participants clues to the absolute distance. Little information given about the light source for these experiments and shadow or texture cues may also have been playing significant factors in the results obtained by these researchers. Finally, Johansson (1973) utilized an experimental design in which participants were shown a stimulus pattern projected in front of the participant. After viewing the pattern, participants were then instructed to operate a cart along a path extending in front of the observer to match the absolute distance the stimuli pattern appeared to be projected. The two conditions in this experiment were lateral head translation during monocular viewing or binocular visual information during lateral head translations. The experiment is a matching task and is not one of true absolute distance estimation. Additionally, powerful visual cues were available to the participants, including accommodation and perspective cues, and motion parallax was not isolated. The size of the cart and the track were constant and could have been utilized by participants as reference between each trial for spatial cues within the environment. The final problem with this experimental design is that only 4 different distances were used as stimuli, which ranged from 30 to 240 cm from the participant, making this task possible to memorize, especially if given feedback.

All of the above studies utilized the experimental methodology of providing feedback to the participants to help improve their estimations of absolute distance. In doing so, they were allowing participants to memorize stimuli appearance and attach correct distances to those appearances via feedback. It is also important to note that, utilizing motion parallax cues to depth is something the brain does unconsciously every second of each day. Therefore, there is certainly no need for someone to be "trained" on how to use motion parallax relative depth cues and there is also no need for feedback. This further illustrates the point that individuals cannot use motion parallax to judge absolute distance, and they must have been utilizing other distance cues not experimentally controlled to be able to successfully complete these distance tasks.

Model Organisms

The second major issue with the line of literature investigating absolute distance estimation is the confusion created when individuals use model organisms and attempt to extrapolate human distance estimation capabilities from their experimental findings. Model organisms are certainly helpful in the field of science and much can be learned from their use. However, the selection of appropriate model organisms, those organisms that have similar visual anatomy, should be carefully considered. Certain insects and animals have been observed slowly bobbing their head laterally within the frontal plane, forward and backward within the sagittal plane, or upwards or downwards in the coronal plane, prior to initiating a jump, movement, or peck, prompting some researchers to hypothesize the function of this motion is to increase available visual cues and an animal's attempt to use *motion parallax* to extrapolate absolute distance information. Preying mantids (Kral 2003), locusts (Sobel, 1990), pigeons (Davies & Green, 1988; Dunlap & Mowrer, 1930), and gerbils (Ellard, Goodale, & Timeny, 1984) have all been documented evoking these types of head movements, possibly to increase awareness of their spatial surroundings, or increase distance estimation accuracy. Some of these studies, particularly those involving mantids, claim that motion parallax is being utilized by these animals, though the geometry of these claims is somewhat difficult to evaluate. In addition, in most studies, confounding visual factors known to affect human distance perception, such as accommodation, shadows, shape and brightness, were loosely controlled. It is entirely unknown if these model organisms also use these cues in the same way human beings would. Certain visual cues utilized by humans with a small fovea may not be utilized by organisms with no fovea, in the case of insects, or a fovea of a different shape in the case of birds. Lastly, these model organisms do not have a slow eye movement system, which we know is responsible for sending signals to the brain about the relative depth of objects during monocular viewing (Nawrot, 2003). However tempting it may be to believe these model organisms do "human-like" behaviors and therefore must have "human-like" visual and neural processing occurring, these claims have not been substantiated. It could be that these observed behaviors in model organisms do not provide any potential useful information to apply to human depth or distance estimation capabilities. Therefore, prior to making comparisons between model organisms and humans regarding the behavioral significance of head bobbing, actual studies involving humans need to be conducted. To date, there have been no real attempts at studying humans to determine the functional significance of head bobbing, and whether or not head-bobbing influences distance estimation accuracy.

Stationary Visual Cues

The final major problem with current knowledge of distance estimation is that, in an attempt to better understand distance estimation, many of the visual cues researched thus far have been only stationary visual cues. Humans are creatures constantly on the move, even while sitting, and are unlikely to be motionless for every instance they are required to estimate distance. Rather, this situation would seem the rarity, rather than the norm. Studies utilizing observer translation and motion parallax provide evidence that the visual system is capable of incorporating observer movement with visual scene information to create relative depth percepts. Potential stationary cues to distance estimation such as accommodation, vergence, relative size, and brightness have been studied independently and rarely in combination. Seldom have studies been conducted that have thoughtfully attempted to isolate and later systematically combine individual visual cues to distance. By understanding which cues are important contributing factors to the perception of absolute distance, one may be able to better understand which input cues are utilized by the brain to compute f.

Goals

The primary goal of the first experiment in this dissertation is to lay the groundwork to fully understand which visual cues are utilized during distance estimation. Specifically, distance estimation will be thoroughly investigated in the laboratory under artificial viewing conditions designed to investigate each visual cue involved in accurate distance estimation. Participant accuracy on distance estimation tasks will be the main dependent variable, with each viewing condition as the main independent variables. This experimental design will show which visual cues participants use to accurately estimate distance. Secondary goals of the first experiment will be to determine whether absolute distance is able to be determined in motion parallax conditions during head movement.

Once it is known which visual cues the brain uses to compute absolute distance, a second experiment of this dissertation will to learn more about the underlying mechanisms controlling the distance estimation system by using alcohol as a deactivating agent. It is known that ingested alcohol has the capacity to selectively disrupt certain aspects of visual functioning while leaving other visual functions relatively intact. For example, color perception, visual acuity, and general tests of motion perception and peripheral vision are resilient to the effects of alcohol at Blood Alcohol Contents (BACs) within the legal driving limit (>0.08). However, research has shown that some visual cues are negatively affected by alcohol at or below the legal drinking limit in the United States. Accommodation, or the eye's image focus for close and distant stimuli- and a potential cue to distance, has been shown to take more time (Levett & Karras, 1977) and be less accurate under the influence of alcohol intoxication (Hill & Toffolon, 1990). Another potential cue to distance, vergence, is affected negatively by alcohol. Vergence is the ability of the two eyes to move together but in opposite directions, to focus a stimuli at a near or far distance. Under the influence of alcohol, the ability of the eyes to work in tandem to land the fovea of each eye in the same location is impaired. Specifically, one's eyes tend to excessively converge, or to land the fovea closer than an intended distant object, and excessively diverge, or to land the fovea further than an intended near object (Hogan & Linfield, 1983). Binocular disparity, a relative depth cue, has been investigated with small amounts of alcohol. Specifically, fixation disparity has been shown to increase with alcohol intoxication, due to the eyes becoming slightly misaligned (Wist, Hughes, & Forney, 1967). This misalignment is not enough to effectively eliminate binocular vision, but may affect the accuracy of relative depth estimation from binocular stereopsis. Another visual function affected by alcohol is pursuit eye movements. The gain of pursuit eye movements is decreased by alcohol actively depressing eye movement initiation, and decreasing eye movement velocity. One may recall from earlier that relative depth from motion parallax is created in part by pursuit eye movements. This decrement in pursuit functioning due to alcohol, leads to decrements in depth percepts from motion parallax (Nawrot, Nordenstrom, & Olson, 2004) and may also lead to decrements in absolute distance estimation during translational head movement.

To reiterate, due to the fact that relative depth from motion parallax and binocular disparity both rely on absolute distance information to produce their relative depth percepts, and both disparity and motion parallax have been shown to be impacted negatively by alcohol, it seems reasonable to hypothesize that alcohol will negatively affect absolute distance estimations. Aspects of other potential cues to distance estimation, such as accommodation, and vergence are both also affected by alcohol. Taken together, these clues also lend further evidence that absolute distance estimation may be negatively affected under alcohol intoxication. Even with hundreds of years of research on vision and visual processing, distance perception has so far been little explored, and there exists no literature about how absolute distance perception changes with alcohol intoxication. Thus, the goal of the second experiment is to better understand the visual mechanisms for distance perception, and how they are affected by alcohol intoxication.

The final purpose of this dissertation is to determine the role of feedback in distance estimation accuracy. This author took issue with the fact that previous studies investigated distance estimation accuracy while providing feedback to the participants (Dees, 1966; Ferris, 1972, 1974). This practice may have allowed the participants to use any and all uncontrolled visual cues to determine distance, as well as introduce practice effects to improve on distance estimation tasks. Evidence from these previous studies even indicates participants improved using cues only known to provide relative depth perception. How can this be? Likely, the participants were clued in to the narrow parameters of the experiment < 20 feet of distance to the farthest presented stimuli, and capitalized on this information to help inform their estimations after the feedback was provided. Additionally, the cues were uncontrolled, and by the time the test block of the experiment was completed, the participants had already been exposed twice to the same distances, one time even receiving feedback as to the actual exact distance of the stimulus. This author is interested in determining if the general concept of feedback influences the abilities of participants to determine distance accurately, no matter the viewing condition. In the third experiment, feedback will be provided to participants during a number of different types of viewing conditions, and accuracy will be investigated.

A supplemental goal of the third experiment is to expand and apply the findings of the first two experiments to real world environmental stimuli. In the first two experiments, visual cues were tightly restricted, creating an artificial environment. Almost no environmental or stimulus-based visual cues are available to the participants in either of these experiments, which limit the applicability of the findings, particularly to the real world. In order to add ecological validity to the findings of the first two experiments, the third experiment will be conducted utilizing naturally occurring real 3D stimuli in an outdoor environment. The outdoor environment is wrought with additional uncontrolled cues, similar to those presented by Dees (1966) and Ferris (1972) in the laboratory due to improper experimental designs. The third experiment will determine whether the cues discovered to be important for distance estimation within the laboratory may also be used and extrapolated to a real environment.

EXPERIMENT ONE: UNDERSTANDING CUES INVOLVED IN ABSOLUTE DISTANCE ESTIMATION

Understanding the spatial relationships of objects within any environment is dependent upon accurate distance perception. For example, in an office setting, it is imperative to accurately perceive the desk as 0.25 meters from oneself, and the file cabinet as 1 meter from oneself, and the door to the room is 5 meters from oneself, in order to plan motor processes to be able to act upon these objects. Misperception of the location of objects in the environment relative to the observer can be dangerous. Humans accurately and safely navigate cluttered environments, however, in some instances, do misperceive the distance from her/himself to an object and subsequently run into that object or reach out and grasp air instead of the object of intent. Why does this occur? To begin to be able to answer this question, we must be certain about which visual cues are involved in the brain's computation of absolute distance. Currently, it is not fully understood which cues are involved in this complex process.

Literature Review

Previous research has investigated a multitude of visual cues that have the potential to be involved in distance estimation. Some of these visual cues are physical properties of the stimuli or a product of the environment in which they reside. Examples of these types of cues include object size, height in the visual field, brightness, blur, and shadow or contrast. Other visual cues that may also aid distance estimation are internal cues and linked to eye function or movement. These types of cues are not pictorial, like those mentioned above, but are physiological cues. Examples of these types of cues include accommodation and vergence. Both types of visual cues have been previously investigated and found to be useful cues to determining distance, however, previous research efforts have been insufficient in systematically isolating each known visual cue. This problem makes it impossible to make concrete comparisons, quantify each individual cue's contribution to distance estimation accuracy, or know definitively which cues are informative and which cues are not.

Types of Visual Cues

The physical properties of the stimulus and the environment in which the stimulus is located have been extensively studied with regard to relative depth, but less so with regard to absolute distance. The visual cues individuals use to determine relative depth are important to hold constant in an absolute distance task. In relative depth tasks, participants determine which of two targets is nearer to/farther from them. In order to accomplish this task, participants must move their eyes back and forth, comparing the two stimuli on a number of dimensions. In absolute distance tasks, participants must indicate the absolute distance from themselves to a target in their environment. If one thinks about relative depth tasks as simply, two independent absolute distance estimations, whereby a participant first looks at an individual near target and gives a distance estimation, and then looks at an individual far target and gives a distance estimation, subtle, yet noticeable differences between the two stimuli in brightness, size, height, may be clues to distance, particularly so if they are being viewed in close succession to one another and in the absence of any other visual cues. If one can imagine a known or constant distance being assigned to one of the independent stimuli, the importance of minimizing any visual cues to the distance of the independently viewed second stimuli becomes evermore important. Participants may remember important features of the first stimuli that would help them increase their accuracy at the distance estimation task, particularly with regard to distance sign estimates. Therefore, attempting to hold all relative distance cues constant during a distance estimation task is extremely important.

Size

The size of an object can tell an observer about the distance it is located from her/him, as well as information about the relative depth between this fixated object and other objects visible in the environment. Relative size, also known as familiar size, is one cue that is important for both relative depth and absolute distance estimations. Relative size is a visual cue that allows one to make estimations of distance based on their knowledge of the object's known size. Famously, Ittelson (1951) conducted an experiment with playing cards as stimuli that were normal size, twice as large as a normal playing card, and half the size of a normal playing card that were all viewed under impoverished visual cue conditions. Participants in this experiment estimated the distance to the large card as closer than the distance to either the normal sized card or the card half the normal size. The opposite was found for the half sized card, which was estimated to be much further away than the normal sized card. These results demonstrate that in relative depth tasks, relative size can be used to indicate which of two targets, assumed to be identical in size, is located nearer or farther from the individual. Similarly, retinal size, or the amount of space an object encompasses on the retina is also an important cue to depth and distance. Retinal sizes for an object are larger when the object is near and the retinal size is smaller for that same object if it is located farther from the viewer. In an experiment conducted by Landauer & Epstein (1969), participants viewed different sized targets and were asked to estimate the absolute distance of each target. For participants in conditions where the target took up 1 or 2 degrees of visual angle, the participants guessed the target was farther form them. When the target took up 4 or 8 degrees of visual angle, the participants guessed the target was closer to them. This experiment demonstrates that size estimates vary directly with visual angle, and that distance estimates vary inversely with visual angle (Landauer & Epstein, 1969). Finally, the apparent size of an object-how large or small a particular participant determines an unfamiliar object to be, does not change with distance. Holway & Boring conducted a series of experiments in 1941 investigating how apparent size changes as function of physical distance. Using a size-matching task with white dots projected on a screen, participants were able to perceive the size of the dot as constant, even if the distance to the dots were manipulated. This is an important finding because it shows that participants may be able to be more objective about the size of an object and how that size appears to change when it is moved to different distances when the stimulus is not a familiar item.

Brightness

Brightness is another large cue contributing to distance judgments (Coules, 1955). The assumption that brighter objects are nearer to the participant, and more dim objects are farther away from the participant has been investigated under both binocular and monocular conditions, and is a relatively stable heuristic that participants use in both distance estimation tasks, as well as relative depth tasks (Coules, 1955; Egusa, 1982; Egusa, 1983). In an experiment conducted by Surdick et al., (1994), brightness was a vastly inferior relative depth cue compared to other "ground-based" (Gibson, 1979) perspective cues (texture, foreshortening, linear perspective) at absolute distances of both 1 and especially at 2 meters. Further, when participants are given dark targets against a white background or vice versa, the targets with the highest contrast to the background are perceived as nearer, indicating that "brighter does not always mean closer" and that stimulus contrast against the background is another cue utilized in distance estimations (Farnè, 1977, Rohaly & Wilson, 1999). O'Shea, Blackburn, and Ono (1994) experimentally found reliance on foreground/background contrast information even when size cues were manipulated to be discordant with their perceptions of near vs. far.

Blur

Blur is also an important cue to relative depth (Pentland 1987; Mather, 1996). This depth cue can be confounding in naturally occurring scenes to contrast depth cues. For example, stimuli that are objectively far from an observer tend to be blurred, but blurring also reduces the contrast of the stimuli (O'Shea, Govan, & Sekuler, 1997). Do blur and contrast work separately or together to depict relative depth? O'Shea, Govan and Sekuler, (1997) found that both blur and contrast depict relative depth. Blur continued to influence depth perception while contrast was held constant, indicating that blur alone is able to influence depth perception. Precisely, the amount of blur at edges between blurry and sharp objects contributes to the brain's spatial model of ordering of objects in depth (Mather, 1996). Held, Cooper, O'Brien, and Banks (2010) have used this information to engineer a model/algorithm to apply to photographs to enhance blur such that the absolute distance an observer perceives objects in the photograph is very near the model's predicted object distance. Shadows are also a naturally occurring relative depth cue, though often underutilized. Allen (1999) established that the shadow of a stimulus needs to be extremely large before the shadow cues would be given more emphasis than two other cues to distance- stimulus size, mentioned earlier, as well as stimulus height. The preceding examples show that many studies have been conducted with pictorial cues and relative depth, and only very few with regard to absolute distance.

Height

Stimulus height in the visual field is also a cue to distance. Whether the height of the stimulus appears to be above horizontal or below horizontal of the participant's gaze, an angle that forms between the eye of the participant and the stimulus tells participants something about the distance of the object. Angles that are above the horizontal of the eye are known as the angles of elevation. Angles that are below the horizontal of the eye are known as the angle of depression, or angular declination. Philbeck & Loomis (1997) tested binocular parallax and motion parallax, as well as angle of elevation as distance cues using a verbal report as well as a matching perceived distance by walking paradigm. In both brightly lit and dark conditions, they found angle of elevation to be the only cue that was useful in determining distance. In a separate set of set of studies, Ooi, Wu, & He (2001) found that angular declination, dependent on the physiological cue of eye level, is a possible mechanism for determining egocentric distance. Using the angular declination hypothesis, they posit that a simple, trigonometric relationship described by the following equation is able to provide absolute distance information to the observer:

$$d = \frac{h}{\tan(\alpha)} \tag{3}$$

where *d* is absolute distance, which is equal to h, the observer's eye height, divided by the tangent of α, the angular declination below the horizon. In a series of studies, participants wore prism glasses that deflected their eye height up or down and made distance estimations that varied according to their deflection direction. For participants who wore top down prism glasses, (5.75deg), which deflected their eyes downward, their estimations were underestimated, compared to their accurate performance on a baseline task. After removal of the prism glasses, participant eyes were deflected upward, causing their estimations to be overestimated, compared to their accurate performance in a baseline task. These experiments indicate that the physical property of height of an object in the visual field gives observers an important signal of object distance, but also the eye's height in the visual field is an important physiological cue to absolute distance (Mon-Williams, McIntosh, & Milner, 2001).

Other physiological visual cues include thought to be important to distance estimation tasks include accommodation and vergence. These cues are also linked to eye function or movement and have also been extensively studied with regard to relative depth. Both accommodation and vergence have been shown to be important visual cues to determining relative depth, but it is still rather unknown if these cues play a direct role in the determination of absolute distance.

Accommodation

The first internal cue to be discussed is accommodation. Accommodation is the process by which the shape of the lens of the eye is changed due to the contraction or relaxation of the ciliary muscle, which surrounds the lens. This muscular body allows the shape of the lens to change in order to maintain focus of the eye on objects at either near or far distances. By increasing the muscle tension, the eye’s lens curves to focus on near objects, and by relaxing the muscle tension, the eye’s lens flattens to focus on far objects. The ciliary muscle tension, whether relaxed or tight, provides an unconscious neural signal regarding the distance of the object being focused. The usefulness of this unconscious muscular signal is rather unknown with regard to distance estimation. Accommodation is usually studied in conjunction with vergence (to be discussed next), rather than as an individual cue to distance. However, unlike vergence, accommodation is a monocular visual cue, meaning that only one eye is needed to be able to accommodate.

Investigative work on accommodation and distance estimation has yielded mixed results due to confusing relative depth for absolute distance, differences in apparatus and previously unknown physical limitations of the accommodation process. Currently, it is known that the lens of the eye is fully flattened when viewing objects that are farther from the eye than 300cm and is fully curved when viewing objects that are ~20cm (Coren, Ward & Enns, 2004). Wundt (1862) controlled all other variables, and showed monocular participants two strings through a tunnel. Wundt found that accommodation was a poor cue to absolute distance, but was valuable for determining relative depth at distances of 100cm. These results can be explained by the fact that focusing on one of the objects (a string in this case) immediately makes any object at a different distance appear slightly blurry or less focused, telling the observer that the objects are not of equal distance from the observer. Results by Baird (1903) also indicated that accommodation alone cannot help participants determine absolute distance, but changes in accommodation can give information about relative changes in depth of stimuli located in 5 paired intervals between 28 and 66cm. More recent research has utilized matching tasks or pointing tasks rather than verbal numerical reports of absolute distance, and has shown that accommodation can contribute in some way to absolute distance estimations. For example, Swenson (1932) was interested in changing viewing conditions so that accommodation cues and vergence cues were in conflict with one another. While holding all other visual cues constant, they found that participants were able to move an unseen marker with their hand to very accurately match the distances of where the targets were previously presented in the dark when both accommodation and vergence were available and in agreement. Next each cue was isolated. Then, accommodation and vergence cues were in disagreement. In this final condition, the participants positioned the pointer in a location that was between the convergence-only distance and the accommodation-only distance, but was more closely located to the convergence distance, indicating that convergence was relied upon more than accommodation. In an experiment asking participants to report the absolute distances of points of light suspended in darkness, ranging from (25 to 395cm), Künnepas (1968), also showed that participants were not able to accurately estimate distance to a stimuli by using accommodation alone. However, Künnepas did not control for differing brightness levels at differing distances, thereby giving participants an important confounding cue to distance. Going back to attempting a manual method of distance estimation, Fisher and Ciuffreda (1988) asked participants to use their own hand and point to targets with different levels of blur (excellent, moderate, or poor) at different distances (31-93cm) after isolating all visual cues except accommodation. For the excellent and moderate quality targets, accommodation increased as target distance decreased and participants answered with very accurate and near linear estimates. However, when the poor targets (high blur) were used, participant accuracy decreased dramatically. Overall, participants showed large individual differences in this study. A similar experimental apparatus was also used by Mon-Williams and Tresilian (1999), in which they found that a small subset of participants (1/3) viewing stimuli through a narrow viewing box were able to accurately match their finger outside the box and out of view to the distance of the target within the box. Another 1/3 of the participants were moderately accurate at matching their finger to the visually accommodated perceived distance inside the box. A final 1/3 of the participants were not accurate at this task. Further work by Mon-Williams and Tresilian (2000) has reiterated the findings of the early 1900s, that accommodation is sufficient for determining relative depth, but not effective at absolute distance when in isolation. However, if the participants are shown two different objects at two different distances in rapid succession, there are some (1/3) participants tested that can sense the change in the object's distance using accommodation cues alone (Mon-Williams and Tresilian, 2000). The timing interval between stimulus onset and offset and new stimulus onset in these experiments is not known, rising question to whether or not this was a true absolute distance task or fast enough to be a relative depth task through the utilization of temporal visual cues. Participants were only told to blink between trials, though it is unclear whether or not this was enforced. In addition, the stimuli used were not all the exact same retinal size, though similar, which may have given participants an additional cue to distance. In general, previous results regarding accommodation's role in distance estimation are inconclusive and deserve more rigorous investigation before ruling out accommodation as a possible cue to absolute distance estimation.

Vergence

The final internal cue to be discussed is vergence. In contrast to accommodation, vergence is a process that occurs as a result of binocular vision, or having two eyes available for viewing. Vergence is the process by which the eyes move in opposite directions with equal magnitude to keep an object focused on the two foveae of the eyes. In order to focus on something that is far away, the two eyes must diverge, or move outward from their resting place. In order to focus on something that is near, the eyes must converge, or both move inward from their natural resting place. These eye movements, like those of the ciliary body during accommodation, provide a neural signal that may tell the brain distance information.

It is known that the convergence angle changes as a function of distance to the object of fixation, up to ~6m (Coren, Ward & Enns, 2004). Each distance increment between the nose and about 6 meters requires a unique combination of muscle contraction or relaxation and could potentially tell the brain how far way the object resides. The angle of convergence, or the angle that results from viewing a near object (larger angle of convergence) differs from the angle of convergence that results from viewing a far object (smaller angle of convergence). The distance between the eyes of an observer never changes, and objects farther than 6m tend to have this same small angle of convergence. Therefore, it has long been assumed that vergence cannot provide any additional distance information for objects residing farther than 6 meters from a participant.

Research regarding vergence as a cue to relative depth has been established (Mon-Williams, Tresilian, & Roberts, 2000), however research regarding absolute distance estimation from vergence is less certain. While this body of literature is in better agreement than the accommodation literature, particularly for older studies, methodological issues are a reality. Grant (1942) had participants view stimuli within a distance of 25-50cm in some conditions when convergence and accommodation were to the same distance, and in other cases when convergence was one diopter different from the accommodation distance. The participant was asked to judge the distance to each of the targets, and in the second condition to pay attention specifically to either the accommodation cue or to the convergence cue. The results of this study indicate that both accommodation and convergence are equally useful in determining distance. More recent studies have been more thorough with condition creation and restriction of visual cues, rather than simply instructing participants to pay attention to certain cues to make their estimations while disregarding other available cues. Künnepas (1968) found that in viewing conditions with vergence, accommodation and binocular disparity were much more accurate than in viewing conditions with accommodation alone, indicating that vergence and mistakenly, binocular disparity, play a major role in distance estimation. In experimental conditions allowing participants to see the movement of the stimuli moving closer to the participants between trials, distance estimates based on convergence information decreased less than when participants were not allowed to see the movement of the stimuli between trials (Komoda and Ono, 1979). These experimental findings are interesting in that in some experiments, participants are simply asked to look away or close their eyes during stimulus movement (e.g. Künnepas, 1968) without enforcement, which could change or artificially bias the accuracy of subsequent estimations. Experiments conducted under low illumination have shown that distance estimates are more accurate using vergence than accommodation (Owens, Liebowitz, & Herschel, 1980) and that base out prism glasses and negative lenses affected perceived distance for vergence but did not influence the resting state of accommodation, indicating that vergence cues are being utilized more than accommodation cues to make distance estimations in the dark. Morrison and Whiteside (1984), compared visual cues over 0.5-9.2 meters (1.64-30.18 feet) to a single point source of light in a dark room. Observers made accurate judgments when viewing stimuli at different distances and when a split mirror was used to create vergence cues, however, observer judgments were not accurate when only accommodation cues were present. Finally, using a matching paradigm, Viguier, Clement, and Trotter (2001) also found that participants with normal visual acuity and normal visual recognition were able to reproduce distances previously viewed in the personal space of between 20 and 120cm, by using vergence cues. Objective measurements of eye movements showed participants were using vergence information to accomplish this task, particularly within personal space.

The research team of Mon-Williams and Tresilian have done many studies which have indicated that vergence plays a pivotal role in distance estimation in healthy subjects, particularly at close distances (<60cm) (Mon-Williams & Tresilian, 1999). Using a matching task and a viewing box with a small aperture, subjects were presented with targets at different distances and asked to point on the outside of the box to the location of target distance. Keeping almost all other visual cues constant, vergence was utilized by the participants when making their estimations. This research team has even investigated the use of vergence with individuals affected by brain damage (Mon-Williams, Tresilian, McIntosh, & Milner, 2001). Visual form agnosia, also known as object blindness, is the inability to name or differentiate objects in an individual’s environment. Despite having normal visual acuity and visual sensory functioning, these people cannot visually decipher or recognize objects in their environment due to brain damage or a lesion in the occipital-temporal lobe (Atkinson & Braddick, 2008). Compelling work using a famous visual agnostic patient, DF, showed the usage of vergence cues in determining distance of an object within personal space (Mon-Williams, Tresilian, McIntosh, & Milner, 2001) which is qualified as a distance of less than 1.5 meters (Cutting, 1997). DF was able to use vergence cues to reach and point to the objects at a distance, indicating that DF was able to extract distance information from the scene, though was unable to recognize or name the object was she was pointing toward. However, other researchers have shown that DF is capable of making accurate reaches to objects at different distances, even under conditions of monocular viewing (Carey, Dijkerman, Milner, 1998; Marotta, Behrmann, & Goodale, 1997) whereas other visual agnosics are not, indicating that accommodation might also be utilized by patient DF. In all studies conducted by the Mon-Williams and Tresilian team, the viewing range they use is quite limited, >60cm, whereas as it is known that vergence can be elicited and utilized up to 6m from participants. The distances described in the above two experiments are also aptly suited for available accommodation cues to help inform distance, even if simply from a glimpse of the experimental setup between trails.

The previous literature review points to a few important conclusions. Information about the stimulus is often utilized as cues to the distance of that stimulus, and these cues are often given more weight over the physiological cues. With regard to the isolation of physiological cues, accommodation does not seem to be relied upon for distance estimation, though some participants have been able to use this cue, in some cases. Vergence seems to have strong support that it is involved in accurate distance estimation, particularly within personal space. It is not clear how participants determine distances located greater than 120cm from them. Additionally, the problem with attributing vergence as the singular most important cue to distance, is that in some experiments, accommodation is not isolated, and therefore could be contributing to the accuracy that has been demonstrated by vergence. Indeed, it is easier to test accommodation independent of vergence, than vice versa. However, it is difficult to discern whether or not vergence alone or in combination with accommodation is truly the signal the brain is using to determine distance. True isolation of accommodation, of vergence, and then a test of the combination of these two cues together at a large range of distances should be undertaken to definitively determine the cue(s) the brain is using to estimate distance.

Goal

The goal of the first experiment is to fully discern which visual cues are utilized by the brain to discriminate absolute distance. The dependent variable in this experiment is distance estimation accuracy. The independent variables in this experiment are the differing viewing conditions, and subsequent visual cues available in each estimation block. These cues are the physiological cues of accommodation, vergence, and vestibular cues, as well as combinations of each. In order to overcome the shortcomings of previous research on absolute distance estimation, a novel apparatus has been developed to isolate individual cues to distance. The cues that are inherent to the physical properties of the stimuli or a product of the environment in which they reside will be held constant using this apparatus. The internal cues that are linked to eye function or movement will be strategically manipulated via the proposed experimental design, which will also allow direct comparisons in accuracy of each visual cue condition.

Method

Observers

Twenty participants over the age of 21 with normal or corrected to normal vision participated in the following experiment. Ten women and 10 men (mean age= 26.2 years) participated. Each participant was recruited through an equitable recruitment posting and offered $10 as compensation. Prior to acceptance into this experiment, the visual functioning of each participant was assessed and met specific criteria. This criterion consisted of scores better than 20/60 (6/12) on the Snellen visual acuity chart (Graham-Field, Atlanta, GA), and better than 1/35 on the Pelli-Robson Contrast Acuity chart (Haag-Streit, Essex, UK). Participants not meeting these visual criteria were excluded from participation.

Stimuli/Apparatus

The selection and design of stimuli and an apparatus for this experiment required careful thought about all visual cues to distance, and how to remove each one from the experimental design. Table 1 lists the known environmental and stimulus-based visual cues to distance and the method of removal from observation in this experiment.

Removed cues

Arial perspective is a cue to very far distances, which involves stimuli appearing more faint and blue than similar stimuli that are near. This is a distance cue that occurs due to atmospheric interference, and is controlled in this experiment by keeping all stimuli nearer than 12 feet from the participant. Similarly, sharp focus, texture, definition and blur are also important cues to distance and rely on visual acuity. Visual acuity is the sharpness or clarity of one’s vision. These cues usually occur with stimuli far away from the participant becoming less defined with increasing distance and near stimuli appearing very focused and defined. Stimuli for this experiment are all points of light in a dark room. The use of three layers of diffusion filters helps each stimulus appear uniform in shape. Participants who have normal 20/20 vision, or corrected to normal vision have accurate acuity to the farthest stimuli at 450cm, which only requires ~20/25 vision to see perfectly.

Table 1

Environmental and Stimulus-based Visual Cues in Experiment 1

Visual Cue to Distance	Method of Removal in Experiment
Arial Perspective	Farthest stimulus is 11 feet from participant; stimuli at this distance do not appear more faint or bluer due to green LED bulbs being used and their brightness controlled.
Sharp Focus/ Blur	Participants are required to have normal/corrected to normal vision, which insures all stimuli will be in focus and without blur.
Definition & Textures	Participants are required to have normal/corrected to normal vision, which insures all stimuli will be uniform in definition and texture.
Retinal Projection	All stimuli will be stationary.
Shadows	The experimental environment is imperceptibly dark and contains no shadows.
Relative Size	Unfamiliar stimulus of unknown size.

These cues were not available to participants during experimental trials.

Other distance cues relating to the stimuli and the environment are retinal projection, shadows, and relative size. Retinal projection is a cue to distance that occurs when an object approaches the viewer. The change in size from the starting point as the object advances toward an observer is an important cue to distance. This cue has been removed from this experiment by keeping all stimuli stationary. Shadows can be an important cue to distance if the light source is known. Objects that have a light source between them and the participant have shadows that are behind the object, meaning the shadow is farther than the object. However, if the light source is behind the object and far from the observer, the shadow occurs between the object and the observer and in this instance, the shadow is nearer to the participant than the object casting said shadow. This depth cue has been removed from the experiment by conducting the experiment in an imperceptibly dark room. The LED light sources are dim and are not bright enough to illuminate the room or any feature of the testing apparatus. Without a main light source, shadows cannot be defined by the observer, and therefore cannot give participants cues to relative distance. Finally, the cue of relative size is important to distance estimation. Humans engage with, see, manipulate, feel, touch, and recognize hundreds of items in their environment every day. The known size of these items is a powerful cue to determining which item she/he is looking at and importantly, how far away the items are from the observer. The stimuli selected for this experiment consist of green points of light in an otherwise dark environment. It is unknown to the observers the actual size of the light stimuli, so familiarity with the stimulus does not yield clues to distance.

Cues held constant

Three other very important stimulus-based cues to distance that are available to the participants but do not vary with distance (held constant) are, size of the stimulus, brightness, and height in the visual plane. Table 2 summarizes these stimulus-based visual cues. Size cues are important, in that objects appearing larger on the retina tend to be closer and objects that appear smaller on the retina tend to be farther away. Brightness is a cue to distance in that objects that are nearer are usually brighter than objects that are farther away. Height in the visual plane is simply a visual cue whereby objects that are lower in the visual field appear nearer, and objects that appear higher in the visual field appear farther away. These cues are given to participants in this experiment, but are held constant for each viewing distance.

Table 2

Stimulus-based Visual Cues Kept Constant in Experiment 1

Important Visual Cues	Definition	Controlled in Experiment
Size	Larger objects appear nearer; Smaller objects appear farther.	Stimulus
Brightness	Brighter objects appear nearer; Darker objects appear farther.	Stimulus
Height in the visual field	Lower objects appear nearer; Higher objects appear farther.	Apparatus

Stimuli for each condition are generated using individual green LED bulbs housed within small black cylinders. Figure 4 depicts a single stimulus for this experiment. Each LED bulb face is 5mm with a maximum 200mcd brightness capacity and 15° viewing angle. Green bulbs were selected due the very dim testing environment, (~0 Lux). In the darkness, the rods of the participant’s eyes will be activated, not the cones that are usually active while exposed to a brightly lit environment. Rod-pigment absorbs wavelengths near 500nm the best; green LED bulbs have wavelengths falling within 495-570nm. Simply put, green LED bulbs should be the easiest for participants to see in the dark.

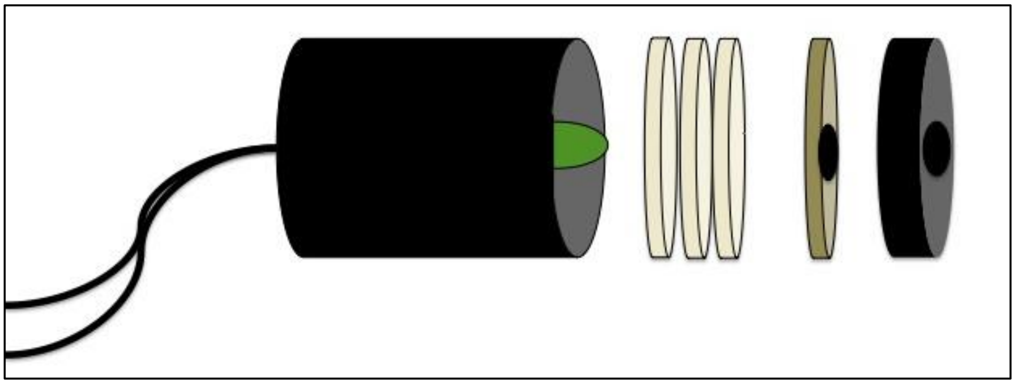


Figure 4. Depiction of stimulus used in experiment 1. A single green LED bulb is housed within a 2-inch x 1.25-inch diameter black canister. Anterior to the LED bulb are three layers of Lee 250 Half White Diffusion Lighting Gel Filter (thickness not drawn to scale). Anterior to the three layers of diffusion filter is a layer of 0.41mm (.016 in.) thick brass with an aperture of predetermined size (thickness not drawn to scale). Anterior to the brass layer is the plastic cover to the canister, further preventing light from escaping in an unwanted direction.

Each black canister (2-in x 1.25-in) will house the individual LED lights for experiment 1. The small canisters and LED bulbs will be displayed at a distance of 150, 200, 250, 300, 350, 400, or 450cm from the participant. Canisters allow the light to be securely housed, while being impenetrable to the light contained inside. Directly in front of each LED bulb are 3 layers of Lee 250 Half White Diffusion Lighting Gel Filter. This diffusion filter disperses the light produced by the bulb evenly and softens the glare so participants see a uniform light point in the distance, rather than outlines and contours of the LED bulbs.

Directly in front of the diffusion filters is a thin (.41mm / .016in) sheet of brass with an aperture of varying sizes, followed by a black plastic cover with a large aperture that keeps all layers in order. Brass is a durable metal found to be amenable to aperture creation, despite the incredibly thin width, allowing perfect aperture circles of varying sizes to be produced. Brass was also selected because it reflects light not escaping the aperture back toward the bulb, which helps to create a clear image with defined boarders for viewers. Each aperture size was calculated to give each stimulus the perception of equal retinal image size, despite being located at different distances from the participant.

Each aperture has been calculated to be 0.1 degree of visual angle on the participant's retina no matter the distance from the observer. For reference, 1 degree of visual angle on the retina is equivalent to the size of one's thumbnail extended in front of the body at an arm's length. Each aperture will appear to be 1/10 of one thumbnail, regardless of distance. The drilling of calculated aperture sizes through the brass insures that retinal image size remains constant, and eliminates a change in retinal image size as a cue to distance. Recall, one may assume that a stimulus is nearer to her/him if the size appears larger, and further from her/him if the size appears smaller (Table 2). By keeping all apertures 0.1 degree of visual angle, each stimulus appears to be the exact same size, thereby eliminating relative size as a cue to distance. The formula used to calculate aperture size is given below:

$$A = \sin D \left(\frac{\pi}{180}\right) * d \qquad (4)$$

Aperture size (A) is equivalent to the sine of the degree of visual angle (D) multiplied by π divided by 180°, all multiplied by the absolute distance (d) in cm of the stimuli from the participant. Table 3 shows the calculations for aperture size and the resulting aperture error. Though painstaking effort was taken to minimize the error in aperture size, admittedly, some small error still exists. However, one may note that the largest aperture error is equivalent to 0.028cm or roughly 3/10 of one millimeter. This aperture is on the canister located the farthest from the participants. Subjective and objective data from all pilot participants indicate these subtle errors in aperture creation are imperceptible to the human visual system during this experiment.

Table 3

Aperture Sizes of Each Stimulus

Distance (cm)	Aperture Size (cm)	Aperture Size (in)	Available Bit Size (in)	Bit contribution to Aperture Error (in)	Actual Aperture Size (cm)	Total Aperture Error (cm)
150	0.262	0.103	0.109375	-0.006	0.270333	-0.009
200	0.349	0.137	0.140625	-0.003	0.353666667	-0.005
250	0.436	0.172	0.171875	0.000	0.436	0.000
300	0.523	0.206	0.203125	0.003	0.512333333	0.011
350	0.611	0.240	0.234375	0.006	0.601	0.010
400	0.698	0.275	0.265625	0.009	0.680666667	0.017
450	0.785	0.309	0.296875	0.012	0.757333333	0.028

Aperture sizes for each stimulus were calculated as a function of absolute distance from the participant in the experiment. First calculated in cm, the values were then converted to inches, which could be readily compared to available drill bits. The difference in the aperture size (in inches) and available drill bit sizes are listed. Finally, the average of three independent measurements of each actual aperture used in the experiment is also shown. Actual aperture size, minus the calculated aperture size gives total aperture error for each stimulus used in this experiment.

Brightness is a cue to distance that is reliant on aperture size. The larger the size of the aperture, the more light that will escape toward the human eye, giving a perception of increased brightness. To combat brightness cues, in addition to careful aperture creation, a few other techniques were used. First, three layers of diffusion paper are placed in front of each bulb, which was found to be required to maintain minimum brightness. Without the diffusion paper, the individual LED lights were bright enough to illuminate areas of the testing apparatus. It is imperative to hold constant room darkness, and not reveal additional visual cues to participants or illuminate portions of the experimental apparatus. Similarly, the brightness of each bulb is a powerful cue to distance and is experimentally controlled so that each light will appear to have equal brightness despite their location at different distances from the participant. Brightness is the amount of light we detect from a source and is dependent on the distance from the source

(Zaha, 1972). The Inverse-Square Law equation was used for determining how bright each light should be, based on the LED bulb's distance from the participant:

$$B = \frac{L}{D^2} \tag{5}$$

This equation states that brightness (B) is equal to the luminosity (L) of a source divided by the distance (D) squared. Brightness is inversely proportional to the square of the distance. Each light's intended brightness based on the distance from the participant was computed, and this information was used to modulate each bulb's brightness as a ratio of the furthest stimuli.

Each LED will be lighted and extinguished using an Arduino Uno microcontroller board (Scarmagno, Italy). This board contains 14 digital input/output pins and 6 pins that can be used as Pulse Width Modulation (PWM) outputs. The PWM pins are utilized to vary the voltage sent to 6 of the 7 LED stimuli. The 7^{th} LED stimuli will be manually modulated via a potentiometer. A 13-inch Macintosh laptop computer with MATLAB will be used to control the Arduino Uno via USB cable. The voltage given to each of the LED stimuli will be titrated in accordance with distance. For example, if the farthest stimuli receives one volt of energy, the closest stimuli should receive 1/9 of 1 volt in order to appear equally bright to a participant compared to the farthest stimuli. Similarly, a stimulus that is halfway between the farthest stimulus and the participant should receive 4/9 of 1 volt in order to appear equally bright to a participant compared to the farthest stimuli. Table 4 depicts the ratios of each light's brightness with respect to distance.

Table 4

Ratio of Each LED's Brightness with Respect to Distance

Distance	Ratio/ Voltage Applied	Fraction
150 cm	0.111111111	1/9
200 cm	0.197530864	1/5
250 cm	0.308641975	1/3
300 cm	0.444444444	4/9
350 cm	0.604938272	3/5
400 cm	0.790123457	4/5
450 cm	1	1

Much work has been undertaken to insure the perception of brightness is not an available visual cue able to be utilized by participants. In order to determine whether the voltage presented to each LED stimuli had a linear relationship with the luminance of the stimuli, two different types of measurements were taken.

The first type of measurement was taken using a Konica Minolta LS-110 Luminance Meter (Chiyoda-ku, Tokyo, Japan). A luminance meter works by measuring the strength or intensity of light emitted from an object's surface per unit of area traveling in a given direction (Zaha, 1972). This surface area must be kept constant in order for the LS-110 to be accurate. Due to the fact that apertures were used in this experimental setup (Table 5, below), the surface area was unable to be kept constant at the same distance. As such, accurate luminance readings were unable to be taken from the viewpoint of a participant during the experiment and instead, were required to be taken 12 inches from the surface of the LED bulb with the 3 diffusion filters and brass aperture in place. Table 5 lists the average of 3 luminance readings per stimuli. Figure 5, below, is a graph of three individual luminance readings per stimuli. The average luminance readings were closely related to a linear regression line, with an R^2 value of 0.9577.

Table 5

Average Luminance and Average Illuminance Reading of Each Stimulus

Stimulus (Distance in Experiment)	Average Luminance Reading (cd/m^2) Measured 12 in from surface	Average Illuminance Reading (fc) Measured 6 in from surface
1 (150cm)	5.553333333	0.005
2 (200cm)	11.26333333	0.018
3 (250cm)	24.89	0.044
4 (300cm)	52.57	0.073
5 (350cm)	75.57666667	0.095333333
6 (400cm)	101.7666667	0.130333333
7 (450cm)	141.5333333	0.147

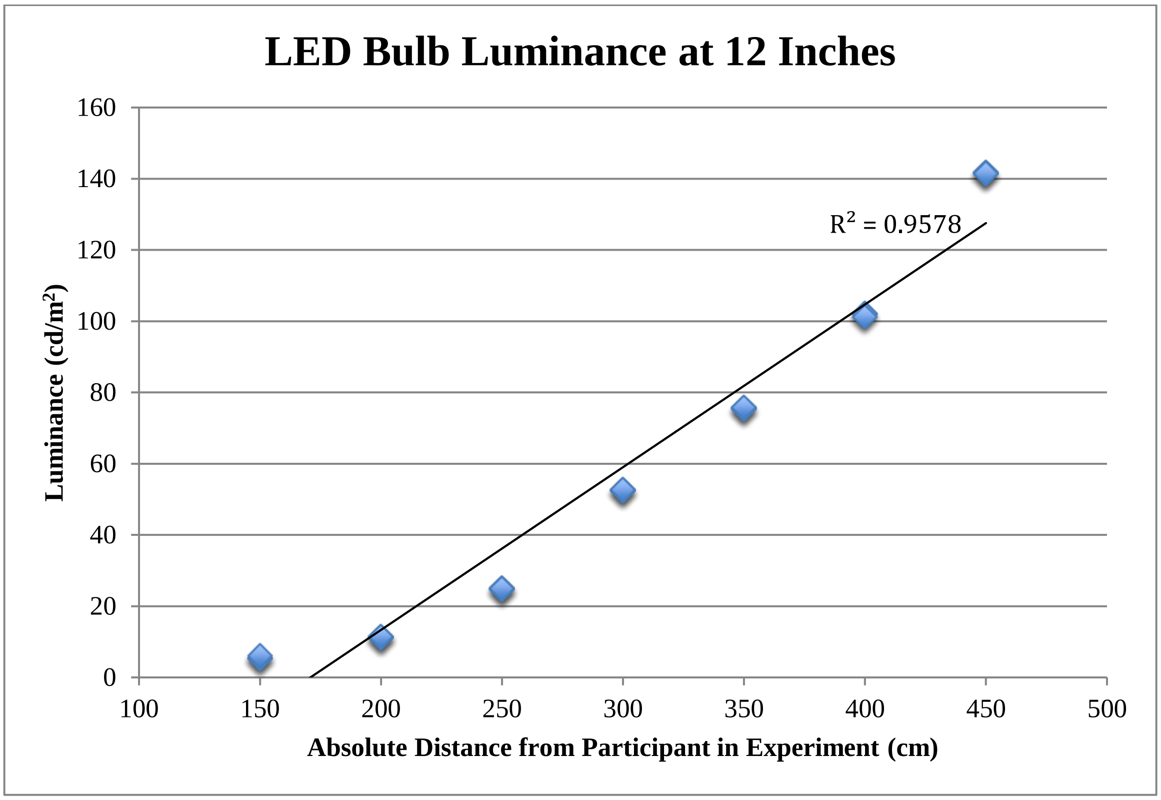


Figure 5. Graphical representation of the luminance of each LED bulb. Each bulb for the experiment was measured from a distance of 12 inches.

The second type of measurement that was taken was using a Tektronix J1811 LumaColor™ Photometer Illuminance Sensor Head (Tektronix, Inc., Wilsonville, OR). An iIlluminance meter works by measuring the amount of visible light falling on the detector head's surface. This is the preferred method for measuring a point-source type of stimuli, such as an LED bulb (Zaha, 1972). The most accurate measurements must be taken within close proximity to the LED bulb in order to be certain the illuminance head is completely illuminated by the light. All measurements were taken 6 inches from the surface of the LED bulb with the 3 diffusion filters and brass aperture in place. The average of 3 illuminance readings per stimuli is listed in the Table 5 (above) and the three individual luminance readings per stimuli are graphed below (Figure 6). The average illuminance readings were closely related to a linear regression line, with an R^2 value of 0.98929.

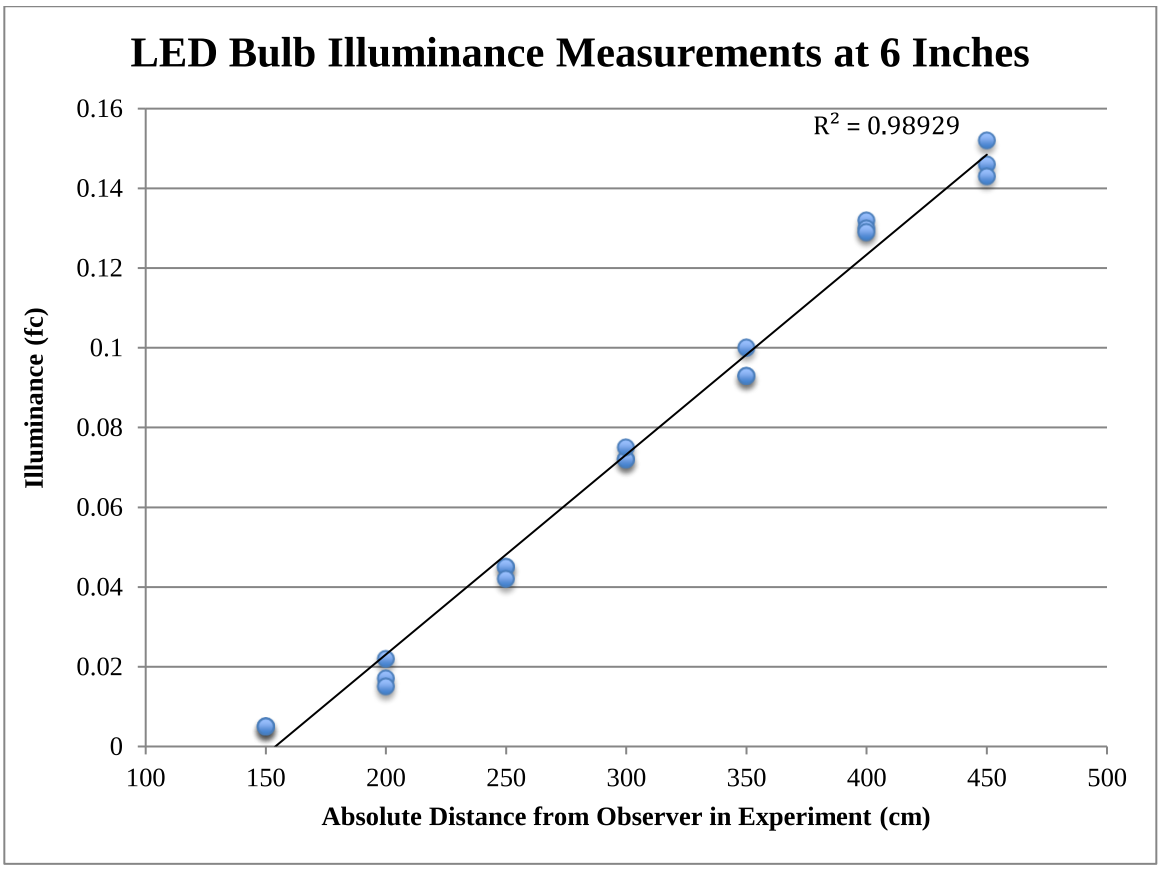
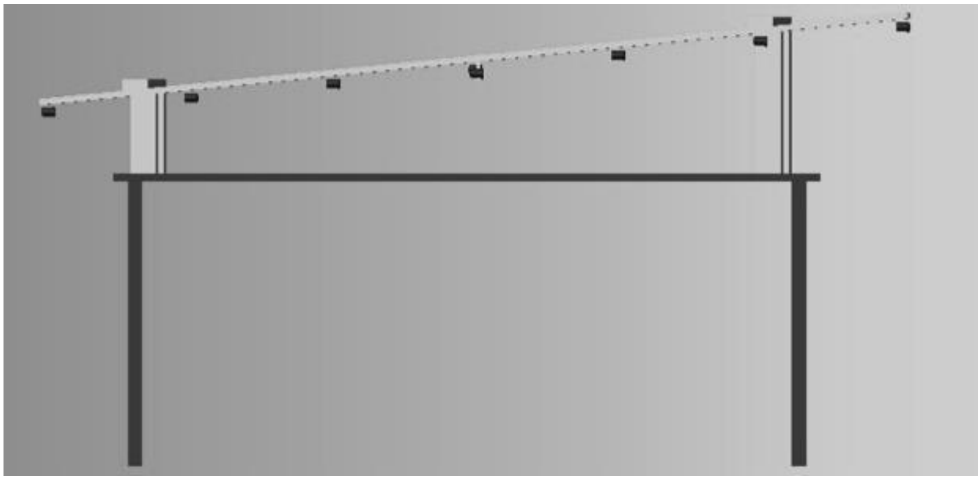


Figure 6. Graphical representation of the illuminance of each LED bulb. Each bulb for the experiment was measured from a distance of 6 inches.

The cue of height in the visual field was combatted with a unique viewing apparatus constructed by this author in the lab. The apparatus (shown in Figure 7, below) on which the canisters are mounted, is $2\frac{6.5}{16}$ inches wide and 12 feet long. The apparatus slopes downward 5° (6 inches) from the front (150cm from participant; closest) to the back (450cm from participant; furthest). The utility of this novel apparatus is multifold and was designed to eliminate participant use of cognitive strategies and allow the research team to fully examine low-level visual cues. First, the apparatus is novel to participants and positions the stimuli just close enough together to not overlap or impede the view of the next farthest stimuli. All stimuli are located on the apparatus within 6 vertical inches of one another. The apparatus eliminates the distance cue of relative height in the visual field, as each stimulus appears to be nearly the same height to the participant, and reverses the assumption that visual field height (higher = farther) as a cue to distance (see Table 2, above).

A.



B.

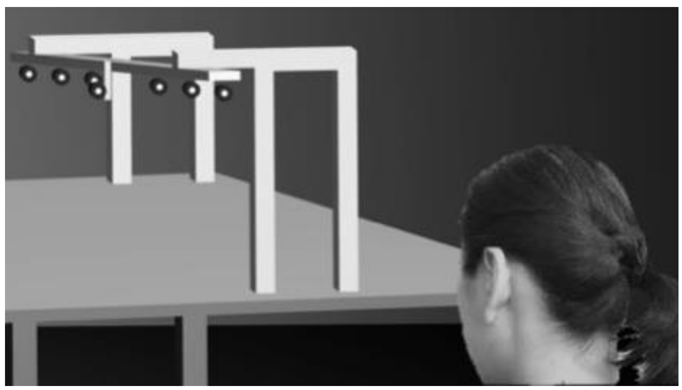


Figure 7. Illustrations of the novel apparatus designed and constructed for this dissertation. **A.** View of apparatus from side. The left of the figure is the farthest stimulus, located at 450cm from the participant. The right of the figure is the nearest stimulus, located at 150cm from the participant. **B.** View of apparatus from directly behind participant. Single small LED's scaled for size and brightness at the different distances (150, 200, 250, 300, 350, 400 & 450cm from participant) will be viewed in complete darkness to isolate distance cues.

Interestingly, this apparatus also allows for each canister to be oriented downward or upward, toward the participant eye. The stimulus located at 300cm from the participant is located at eye-level to the participant in the visual field. 3D printed platforms (Figure 8) were created with calculated angle offsets, so each stimuli counteracts the 5 degree decline (6 inches) in the apparatus, and orients the canister to face participant eye-level regardless of distance from the observer, further eliminating cues to height in the visual field. Each angle of offset is shown below in Table 6.

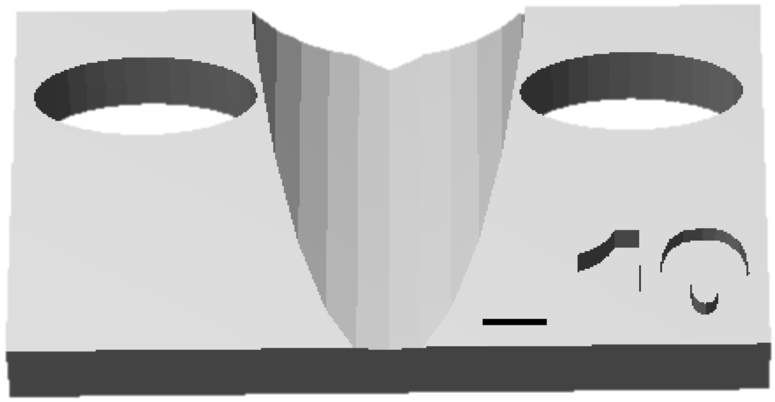


Figure 8. Example of 3D printed platform. This platform was created to offset the apparatus decline of 5° so the LED bulb is oriented toward the eye level of the participant. This specific platform is a replica of that which is adhered to the apparatus at 150cm from the participant.

Table 6

Degree of Angle Offset for Each LED Stimulus

Distance from Participant (cm)	Degree of Angle Offset
150	10°
200	7.5°
250	6°
300	5°
350	4.385°
400	3.75°
450	3.33°

Angle offsets were computed so that each individual LED stimulus would be oriented toward the eye-level of the participant in the experiment.

Participants are shown a standard stimulus that is their anchor for distance estimation that is located 300cm (~100 Shanda Units) from the participant. This standard canister with LED is attached to a Firgelli Automations L16 Miniature Linear Actuator (Victoria, British Columbia, CA) and between trials the entire canister and LED are moved vertically in the visual field upward or downward to be perceptually equal in height with the experimental LED stimulus for every trial (Figure 9, below). For example, in a given trial, if the upcoming experimental LED is located 450 cm away from the participant, the actuator will be sent a signal to extend downward to the full length prior to the "standard light" being activated. Conversely, in the following trial, if the upcoming experimental LED is located 150cm away from the participant, the actuator will be sent a signal to contract the full length prior to the “standard light” being activated. During every trial the actuator moves upwards or downwards to match the experimental stimuli height in the visual field for that particular trial. The linear actuator apparatus is run via Digital to Analog board (Measurement Computing Company, Norton, MA), simply by applying a strategic digital voltage via Matlab Daqtoolbox (Math Works, R2017b), which is then converted to an analog signal, which then extends the actuator. Conversely, by sending a conflicting digital signal via Matlab, then converted to an analog signal, the polarity of the actuator is reversed and the actuator retracts a given amount specified by the original digital signal input.

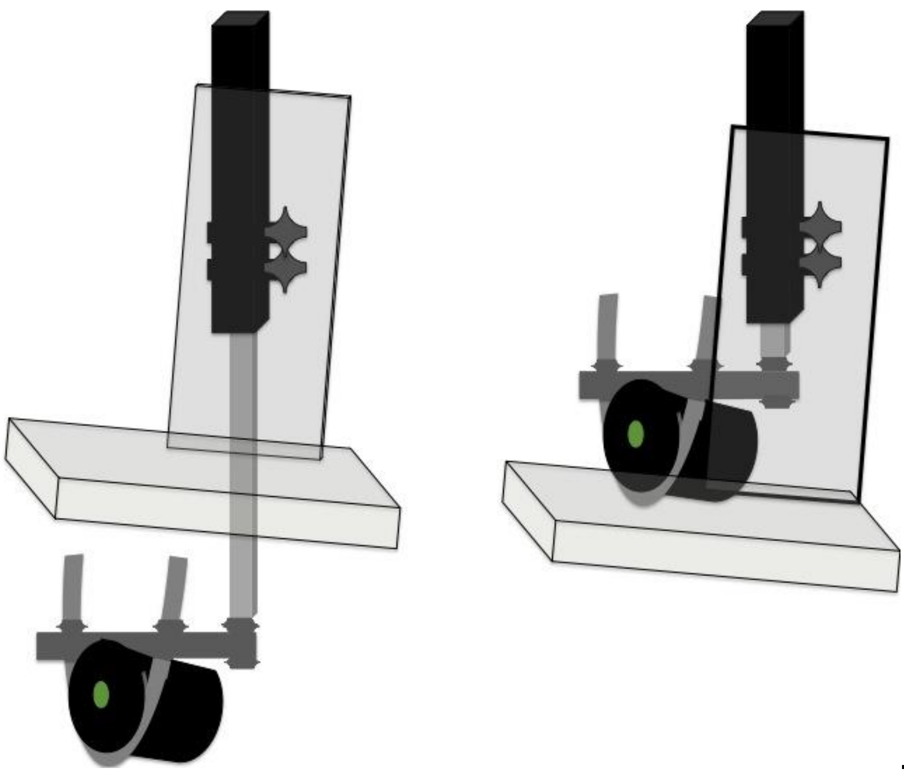


Figure 9. Depiction of standard stimulus. The standard stimulus was raised or lowered vertically by the Firgelli Linear Actuator. Between trials, the standard stimulus automatically moves vertically in the visual field to match the perceived height of the experimental stimulus that is to be viewed in the next trial.

Finally, the apparatus location with in the laboratory environment helps to disorient participants. The location of the apparatus is not perfectly perpendicular to the participant's assumptions of the experimental room shape. Participants will be seated with their head in a chinrest facing 30° to the left of perpendicular of the room shape, but directly perpendicular to the apparatus and stimuli. This positioning requires the participant to estimate distance without their shoulders and core of the body being perfectly square to the doorway of the room that contains the experimental apparatus. This experimental setup may render participant expectations of room size and shape inaccurate, thereby eliminating assumed room size as a possible cue to maximum distance. All visual experiments are conducted in an imperceptibly dark room (~0 lux), further eliminating visual cues to distance.

Procedure

Half of the participants completed Experiment 1 first, and the other half of the participants completed Experiment 2 first. At the time of entry to the lab for the first experiment, participants filled out consent forms and completed vision exams to check visual acuity and stereo acuity. Participants also underwent an alcohol-use screening questionnaire, medications questionnaire, and participant weight and height were recorded for use in experiment two. Each participant was then given a set of instructions and a 2D task to complete on the computer to insure participant understanding of the instructions for the experiment. The participants saw Figure 10 on the computer screen and were told to assume the vantage point of the female observer on the left of the figure. They were then told that a stimulus in front of them in their environment (known as the standard stimulus) was located exactly 100 "Shanda Units" from the individual. This stimulus remained at this distance from the observer in all trials. The participant task was to determine the distance from themselves, in Shanda Units, using the standard stimulus as an anchor. Participants then input their guesses in Shanda Units into the boxes above and below the stimuli using a keyboard and a mouse. The experimenter then verified the participant responses to insure distance magnitude accuracy. For example, if a participant was assigning a distance to a stimulus that was between the participant and the standard stimulus, the value should be less than 100 Shanda Units. If a participant was assigning a distance to a stimulus that was farther than the standard stimulus, the value should be greater than 100 Shanda Units. The conversion table of objective distance to equal corresponding subjective Shanda Units used for the actual experiment has been provided in Table 7, below.

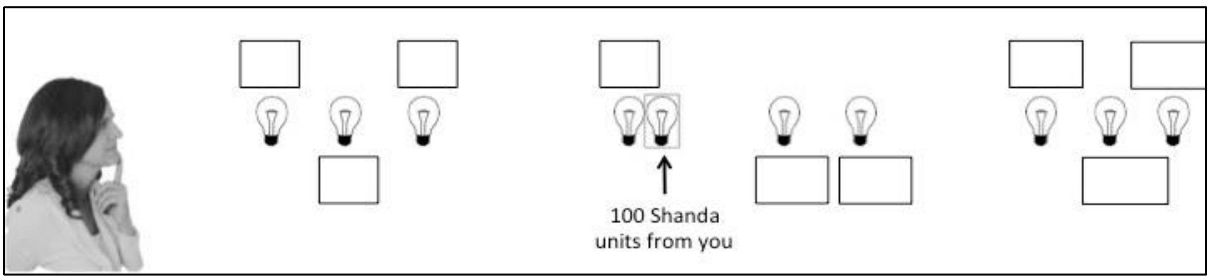


Figure 10. Computerized experimental task. This task was used to indicate if participants were able to understand directions for how to complete the distance estimation task. Participants were told to assume the view of the female observer to the left, and then were asked to use the mouse and keyboard to indicate the distance from themselves to each of the stimuli in the environment, using the standard stimulus as an anchoring point (see text).

Table 7

Conversion Table for Distances

Objective Distance	150cm	200cm	250cm	300 cm =Standard	350cm	400cm	450cm
Equal Subjective Distance	50 Shanda Units	66 Shanda Units	83 Shanda Units	100 Shanda Units	116.6 Shanda Units	133.3 Shanda Units	150 Shanda Units

Distance estimations given in Shanda Units for objective distances of stimuli on the experimental apparatus. Note the linearity of stimuli distances nearer to the participant than the standard as well as the linearity of stimuli distances farther than the standard stimulus.

After completion of this task, another 2D rendering on the computer (Figure 11) was shown to the participants, and they completed the same set of directions as the previous computerized task, only the vantage point of the participant had been changed to a more accurate aerial 2D depiction of the real experimental setup (see Figure 7b.). Participants were again asked to assume the role of the participant at the bottom center of the rendering and use the mouse and keyboard to input distances, in "Shanda units," that stimuli appear from themselves, by using the standard stimulus as an anchoring point. The experimenter then verified the participant responses to insure distance magnitude accuracy (see above for explanation). Again, these two procedures were completed to insure participant understanding of the task requirements, and all experimental directions with specific regard to proper communication of distance units.

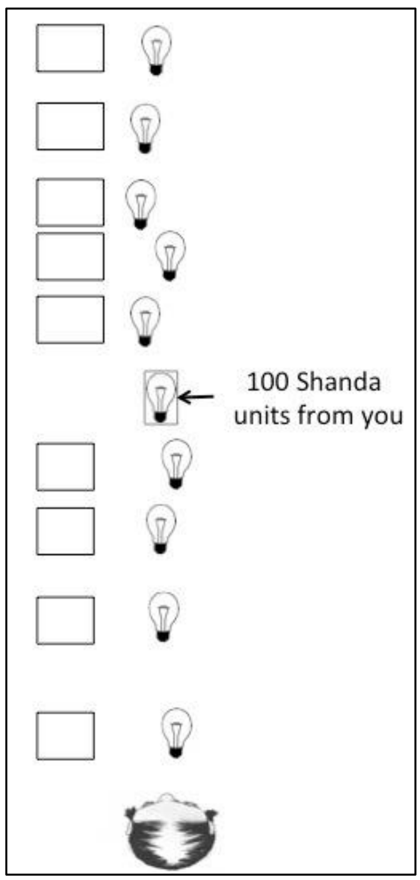


Figure 11. Second computerized experimental task. Example of second experimental task used to indicate if participants are able to understand directions for how to complete the distance estimation task. Participants are told to assume the position of the observer on the bottom center, and are then asked to use the mouse and keyboard to indicate the distance from themselves to each of the stimuli in the environment, using the standard stimulus as an anchoring point (see text).

Next, participants were then brought into the experimental laboratory room and seated comfortably in a chair at a table with a chinrest of predetermined height and orientation. Immediately in front of the participant is a door with the experimental set up (Figure 7b.) behind it in an adjacent room. The experimenter reiterated the directions, telling participants that stimuli will be shown in the adjacent room behind the closed door in a 3D environment, then extinguished the lights and exited the laboratory room. The experimenter then entered the experimental room in complete darkness from a separate door and opened the door directly in front of the participant to expose her/him to the experimental environment. The experimenter then exited the experimental room in complete darkness and sat at a computer in an adjacent room to record participant responses.

To begin a trial, participants were shown a standard stimulus located 300cm from the participant for 10 seconds. The participant was reminded that the stimulus was located 100 Shanda Units away from the participant. After 10 seconds, the standard stimulus was extinguished. Immediately, an experimental light, one of 6 other stimuli, selected at random, was illuminated for the participant to view for a 10-second duration. The participant task was to verbally indicate the distance (absolute) from themselves to the experimental stimulus "in Shanda-units" (see conversion in Table 7, above). Participant responses were recorded in Matlab by the experimenter in the next room listing to verbal responses through an intercom. Each trial lasted ~20 seconds in total duration. For each condition, observers completed 5 trials for each stimuli distance, resulting in 30 absolute distance estimations per viewing condition. Each participant completed all conditions in a randomized order following a Latin-square design.

Conditions

Participants were run through each of five different viewing conditions in the a randomized order. These conditions were called, No Cue, Accommodation, Vestibular, Vergence, and Full Cue. Each of the aforementioned conditions was created to systematically study the impact of important cues to distance. Table 8 shows which visual cues were available and which visual cues were not available by condition. A reminder to the reader, all viewing conditions took place in an imperceptibly dark room (~0 Lux). Each of the viewing conditions will be described in greater detail next.

Table 8

Scalar Visual Cues by Viewing Condition

	No Cue	Accommodation	Vestibular	Vergence	Full Cue
Cues Available		Accommodation	Accommodation Vestibular	Vergence	Accommodation; Vergence Vestibular
Cues Not Available	Accommodation; Vergence; Vestibular	Vergence; Vestibular	Vergence	Accommodation; Vestibular	

Description of visual cues available and not available for the experiment in each condition. All conditions are depicted in order from least cues available to most cues available from left to right.

The No Cue condition is the condition participants complete that contains the least amount of visual cues of all the viewing conditions. In the No Cue condition, participants were seated at in a stationary chin rest and asked to wear a special pair of pinhole glasses like those seen in Figure 12. Pinhole glasses have normal rims, and polarized lenses on the outside, but have small evenly spaced holes surrounded by black paint on the inside of the lens. These glasses forced participants to view stimuli through one of the individual holes, thereby eliminating peripheral rays entering their eyes. The eye has restricted visual input coming in, especially at the sides of the pupil; however, participant visual acuity was not negatively affected. Pinhole glasses are important to this experiment because the glasses removed an important visual cue, known as accommodation. Vergence, another visual cue thought to be important for distance estimation, was also eliminated from this condition. Vergence was eliminated from this condition by only allowing the participant to view the stimuli with one eye. In order to accomplish this, a mask was placed over the left lens of the pinhole glasses. Therefore, vergence cues were eliminated so that only one eye is available to move the fovea to the stimulus. The participant was seated in a stationary chin rest, and told to keep their head steady and still, so vestibular cues would not be available.

Figure 12. Pinhole glasses. Example of pinhole glasses used in the Vergence and the No Cue viewing conditions. In the Vergence condition, viewing stimuli through pinhole glasses eliminated the eye's ability to change the optical power of the lens (accommodate). Viewing stimuli through pinhole glasses removed the important distance cue of accommodation from the viewing condition. In the No Cue viewing condition, the left lens of the glasses is occluded with an opaque shield. Viewing stimuli through only one lens of the pinhole glasses removed both accommodation cues as well as vergence cues.

The next condition participants completed is the Accommodation condition. The Accommodation condition is very similar to the No Cue condition, only that the pinhole glasses were not worn, and instead, a participant was asked to wear an eye patch. By occluding one eye, participants will lose over 60 degrees of their visual field (Spector, 1990), however, the stimuli were located directly in front of the non-occluded eye, so worries about a limited field of vision are unwarranted. The bigger issue is that by occluding one eye, participants were left without vergence cues, which are hypothesized to be important to distance estimations. In this condition, participants will still have accommodation cues, to determine how much of an influence accommodation verses vergence has on participant accuracy of distance estimations. The eye patch kept vergence eye movements removed from the participant, while allowing accommodation to occur. Participants were able to change the optical power of their eyes for all near and distant stimuli. This condition, when compared to the No Cue Condition will provides data describing the contribution of accommodation cues in distance estimation accuracy.

The next condition is the Vestibular condition. As stated in the introduction, the question of whether or not monocular head bobbing gives accurate absolute distance cues is unproven, but it is thought by some to be an important cue to absolute distance. It is already known that the cue of motion parallax is a relative depth cue (Gibson, Gibson, Smith, & Flock, 1959; Park, 1964; Rogers & Graham, 1979). It has also been established that even micro-movements of the head, yield accurate relative depth information (Aytekin & Rucci, 2012). In this experiment, if participants had two stimuli lights on at the same time, and were allowed to monocularly view the lights while moving their head side to side, the cues given by motion parallax would easily differentiate the nearer vs. the farther of the two stimuli, even with minimal movement on the part of the participant. However, this visual condition and the associated absolute distance task were designed to experimentally investigate whether head bobbing, and the associated vestibular cues caused by moving the head are an effective cue to accurate absolute distance information. This condition is similar to the Accommodation condition in that participants are asked to view the stimuli with an eye patch covering their left eye. Participants are seated in a chinrest and oscillated from left to right at the participant's desired pace for the full duration (10 seconds) of the trial. Remember, the two stimuli for each trial are never on at the same time; the standard stimulus is extinguished prior to the onset of the experimental stimuli, insuring the distance task is absolute, not relative. The participant's chin movement doubled as a measure of their head location during this task. Head location was recorded using a large open frame linear motion potentiometer (LCPL-300; Eti Systems, Carlsbad, CA). The potentiometer is 30cm in length, and is the base for a chinrest, which slid left and right of center (15cm). A Digital to Analog converter box (Measurement Computing Company, Norton, MA) converted a digital voltage from MATLAB to an analog voltage to the potentiometer. The D/A converter box has 11-bit analog inputs, which means the 30cm potentiometer contains 2,048 possible voltage readings, roughly dividing each centimeter into ~68 possible readings, which is quite precise. MATLAB sampled the potentiometer voltage changes every 20msec, as the participant moved their head from left to right over the entire trial duration of 10 seconds. The participant was required to maintain an average velocity of 3cm/second in order for the trial to not be repeated. Later, the voltages were converted to distance locations along the potentiometer's length, and participant head movement was be graphed as distance traveled compared to time, appearing as a sinusoidal wave. Figure 13, below, shows an example of the head movement data and the quantitative aspects of participant head movements that were of interest.

The three aspects of participant head movement that are of interest include velocity, deviation from center, and frequency. The velocity of head movements are calculated according to the following formula:

$$V = \frac{X_f - X_i}{time} \tag{6}$$

The velocity (V) is equal to the final position of the participant head (X_f) minus the initial position of the participant's head (X_i), divided by the amount of time (t) the head was traveling. In the example graph below (Figure 13), for the time period from 500 to 1000 milliseconds, the participant moved their head from 30cm to 0cm. The velocity for this example movement is 0.03cm/msec.

Information about the participant's deviation from center is also an important facet of head movements to track and quantify. In the example graph below (Figure 13), deviation from center is quantified as distance traveled to the left or the right of center and given in centimeters. For example, in the example graph below, a participant moved in one direction for 15cm and then continued to move past the center in the same direction another 15cm. Participant deviation from center informs exactly how far participants' heads traveled leftward and rightward from center and is important data for comparison within participants.

Finally, the frequency of participant's head movements was measured. The amount of times the participant makes a head movement from the center to one side of the potentiometer, then a head movement all the way to the opposite side of the potentiometer and then back to the center yields one full cycle of a head movement. Frequency is traditionally measured in Hertz, or cycles per second. In the graph below (Figure 13), frequency is depicted as being measured by head movements from one side of the potentiometer, to the other side of the potentiometer and back. In this example, one complete cycle takes 2,000msec to complete, which equates to a frequency of 0.5 Hz (one half cycle every second). Measuring this aspect of head movement yields information about frequency of movement, which is valuable for comparison between subjects.

Some subjects may make faster head movements with higher velocities, farther deviations from center, and higher frequencies within the given 10 seconds. Other subjects may make slow head movements with lower velocities, smaller deviations from center, and lower frequencies within the given 10 seconds. Comparing the accuracy level of these participants may further quantify aspects of head movements with regard to distance estimation accuracy. By comparing the participant accuracy in the Vestibular condition against the participant accuracy in the Accommodation condition, it will be rather simple to determine whether or not "head-bobbing" helps participants to estimate absolute distance.

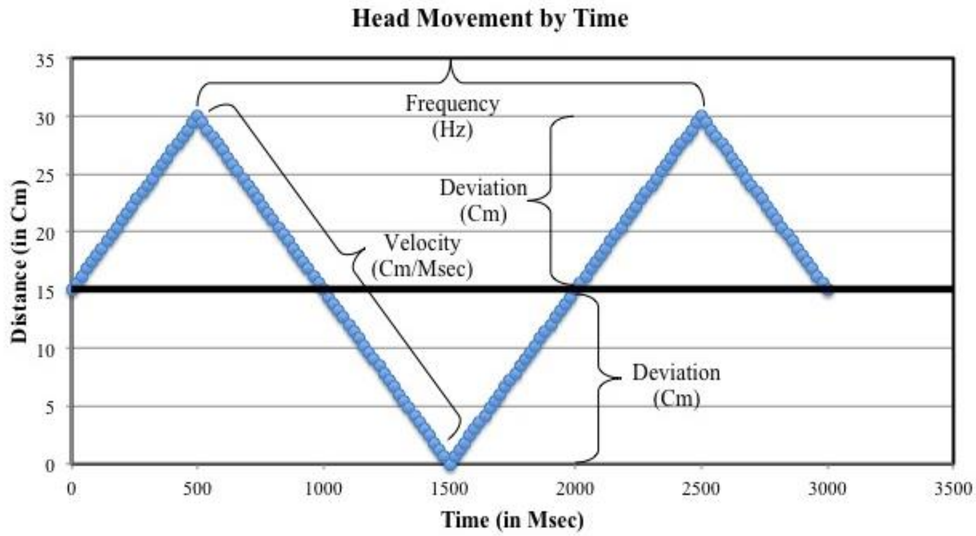


Figure 13. Head movement measurements. The distance a participant's head travels over three seconds in the Vestibular condition is depicted. The quantities of velocity, average deviation from the center, and frequency of participant head movements are of interest for categorizing participant head movement in tasks of distance estimation.

Another viewing condition participants completed is the Vergence condition. Participants are seated with their head in a stationary chin rest. Participants will use both of their eyes to view the stimuli, however, participants will be viewing the stimuli through the pinhole glasses (Figure 12). In this condition, both lenses have pinholes and will be available, as neither lens will be occluded with the opaque plastic piece. To reiterate, these glasses eliminate the accommodation cue but allow vergence eye movements to occur. Vergence has been shown to be an effective cue to distance (Mon-Williams and Teresilian, 1999) in distances of 60cm or less. While it is more uncertain how participants will do outside of 120cm, all of the stimuli in this experiment are within the 6-meter parameter limits for the eyes creating a different visual angle from vergence, which may mean that participants are rather accurate at determining distance with this cue. Upon comparing the accuracy levels of this condition with the Full Cue condition (discussed next), the importance and role of vergence in distance estimation will be understood.

Finally, participants will also complete the condition with the most available visual cues, the Full Cue condition. In the full cue condition, a participant was seated with their head in a chin rest that allowed the participant to oscillate left and right at their desired pace. Both eyes are available, which allowed the participants to have vergence and accommodation cues to distance, as well as vestibular cues available as the participant moves their head left and right. All three of these cues are likely impactful cues to distance estimation and are expected to be utilized in this condition to yield high accuracy scores, and the combination of these cues should be more accurate than each of the individual cues in isolation. Direct comparisons between this condition and the Vergence condition and the Accommodation condition will indicate which cues participants are using to complete this distance estimation task accurately. It is rather inconceivable that participants will not do well in this condition. On a final note, it is important to remember that having two eyes also gives retinal disparity or stereoscopic vision. Retinal disparity is a difference in image location of an object seen by each eye, which results in depth information. As a reminder to the reader, disparity cues are not involved in this condition, as disparity cues are relative depth cues, which rely on absolute distance information, and therefore not an applicable cue for this task or condition.

The five viewing conditions above have been selected purposefully to isolate visual cues within each condition to determine which cues participants utilize for absolute distance information. Each viewing condition is an independent variable, with the dependent variable in this experiment being distance estimation accuracy. By comparing these five experimental conditions, specific cues contributing to distance estimation, responsible for participant differences in accuracy by condition, will be known.

Preliminary Analyses

Prior to moving on to the results section, this author feels it necessary to discuss different possible outcomes of the No Cue condition, and provide the reader with a theoretical understanding of what these hypothetical outcomes could mean for participant behavior as well as the experimental setup should they occur. This information will help to frame the following results section and provide clarity to the reader.

In the No Cue condition, a number of possible outcomes could occur. Each outcome will be discussed and specifically speak to what that outcome translates to as far as participant behavior during this task. Having a familiarity with each possible outcome will help the reader to interpret the collected data when there are multiple viewing conditions with which to understand and keep track. For easy comparison of multiple possible outcomes, Figure 14 was created. On the y-axis, the subjective estimations of the distances are plotted, and on the x-axis, the true objective distances are plotted. To begin, please draw your attention to the line labeled, “A”, in Figure 14A., below. The data to form this line is exactly veridical. A participant providing data similar to this line would be very accurate in their distance estimates. This is a problem for the No Cue condition, because participants should not be able to estimate distance accurately in this condition and if they are doing so, many important visual cues are uncontrolled. The apparatus would need to be thoroughly inspected and the research program would need to be considered more thoughtfully. A participant providing data similar to the line, labeled “B”, would indicate the output of a participant who was unable to do the task. Every stimulus she/he sees would not appear different than the standard distance. Participants with data similar to the line labeled “B” are likely guessing very close to the standard distance with very little variation in their responses. These participants cannot do the task and are indicating that every stimulus appears exactly as far away from them as the standard distance. Data appearing close to the line “B” in the No Cue condition would be ideal. This would insure the apparatus is not giving any visual cues to the participants. Participants with data similar to the line labeled “C” are likely to be overestimating near distances and underestimating far distances, keeping their guesses tightly aligned with the standard distance, without much deviation. These people do have some cues informing their response, just not many and not very accurate ones. Participants with data similar to the line labeled “D” are incapable of doing the task. These participants are seeing every near stimulus as far and every far stimulus as near. These participants are either answering incorrectly or truly perceiving the stimuli backward from the objective distance. One might expect participants to show a variant of this kind of data in the No Cue condition, as they may be guessing randomly.

Data for the No Cue conditions may look many other ways when graphed. Figure 14B. shows three more hypothetical versions of data that could be present in the No Cue condition. For reference, the blue veridical line has again been graphed and labeled “A”. Participants with data similar to the orange line labeled, “E”, are also able to complete this task for near distances, and are somewhat accurate, however, these participants never perceive the stimulus as being farther than 300 for any distances. These participants may tend to have an overall bias to perceive stimuli as near. They could also be suffering from a “contraction bias” (Gogel & Tietz, 1973; Gogel, 1978) whereby participants have a tendency to underestimate distance in reduced-cue environments. Participants with data similar to the black line labeled, “F”, are also completing the task, but again are overestimating near distances and underestimating far distances, staying close to the “Standard” distance. Participants with data similar to the green line labeled, “G”, are also able to complete the task. These participants are doing something similar to those providing data for lines “G” and “C”, where they are overestimating near distances and underestimating far distances, while staying close to the “Standard” distance. A comparison of lines “C”, “F”, and “G” in Figure 14.A and 14.B lead one to wonder if in fact these three hypothetical viewing conditions differ. The slopes of the lines appear to be similar, but it is unknown whether they differ significantly from one another, and require the slopes of each of the different viewing conditions to be investigated.

The slopes of each of the lines in this experiment may be compared to determine whether or not differences in viewing condition effect accuracy. In graphing these lines, we can visually determine that their constants and slope coefficients are different. A simple linear regression line can be fit for each of the three lines one is interested in comparing to the veridical blue line, “A” which as a slope of 50 and a y-intercept of 0. For comparison, the purple line, “C” has a slope of 8.33 and a y-intercept of 241.67. The black line “F”, has a slope of 32.5 and a y-intercept of 62.5, and line “G”, has a slope of 25 and a coefficient of 150. These slopes (regression coefficients) can be then be compared using multiple t-tests with a Bonferroni correction to determine whether or not the slopes of the five different viewing conditions differ significantly. Multiple t-tests are proposed due to the categorical nature of the cues in each viewing condition.

In summary, five main evaluations of the data will be made. The first, comparing average deviation from the true objective distance addresses the first goal of this research program, which is to determine which visual cues are important for accurate distance estimation. The following four evaluations of the data (average absolute deviation, average absolute deviation from the standard stimulus, and average distance sign accuracy), and the computation of DSDI values for every participant in every viewing condition will address the second goal of this research question, which is to help quantify the differences in distance estimation accuracy as a result of variable visual cues.

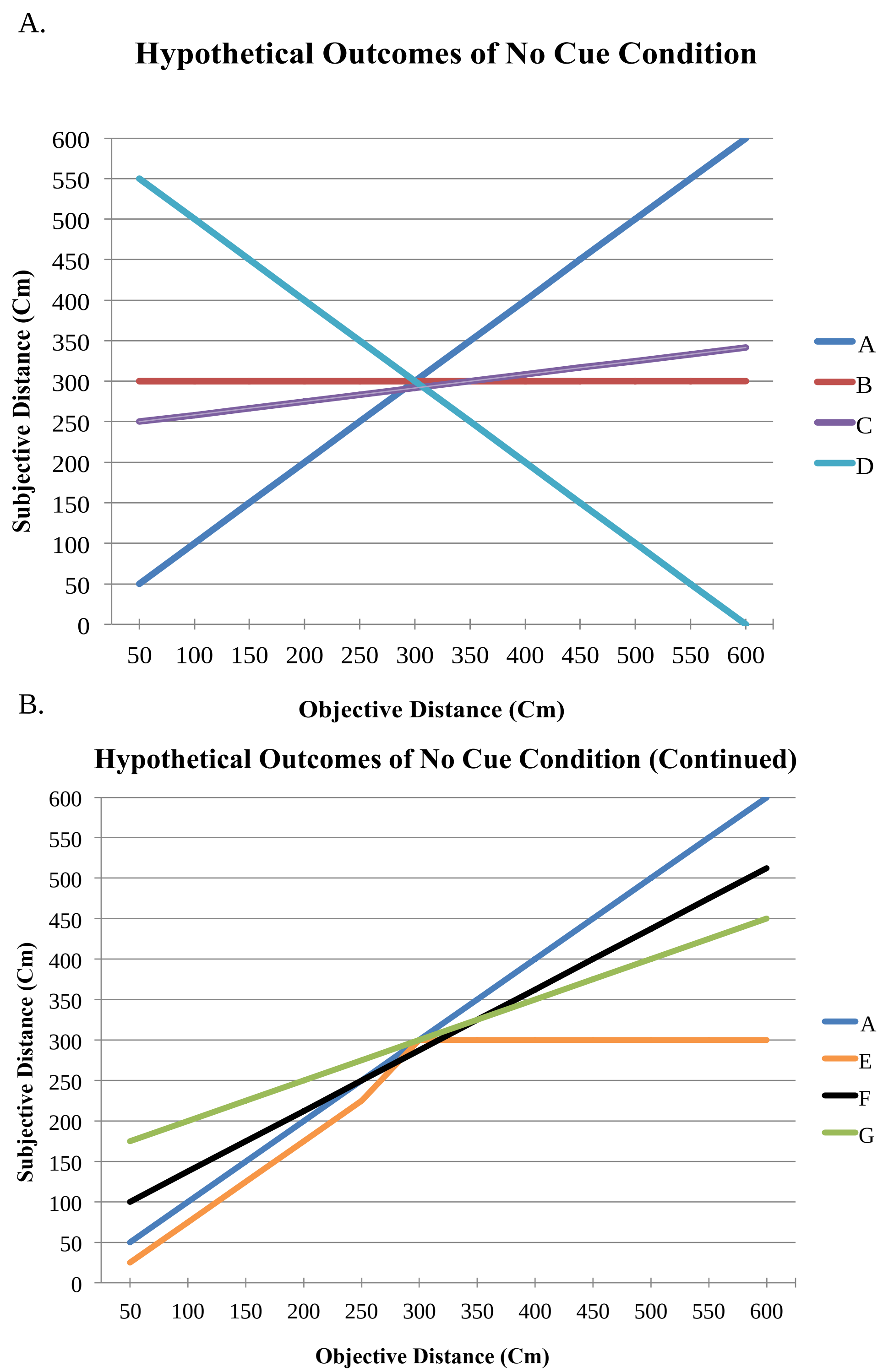


Figure 14. Possible outcomes of the No Cue condition. A. Hypothetical outcomes of the No Cue Condition. B. Hypothetical outcomes of the No Cue Condition, continued. The implications of collecting data that appears similar to those presented in this figure is discussed in the text.

Results

Analyses were conducted in Microsoft Excel, MATLAB R2016b (The Mathworks, Natick, MA) and SPSS 21 (SPSS II, New York, NY).

Average Subjective Distance Estimations

For each viewing condition for each observer, the estimations from each distance were averaged. Each observer's average estimations for each viewing condition were then aggregated and averaged among all observers. Figure 15, below, shows the average subjective distance estimation for all five viewing conditions plotted against the objective distances.

Overall, participant distance estimation in conditions of restricted cues deviated markedly from veridical. At objectively near distances, participants overestimated the distance to the stimulus, and at objectively far distances, participants underestimated the distance to the stimulus. Observer responses in the Accommodation, Vestibular, and Vergence conditions mimicked the overall trend of the responses given in the No Cue condition. In fact, these results are not significantly different.

Recall from the Hypothetical No Cue condition above (Figure 14.A & 14.B), that when the slope of the line is zero, participants are unable to discriminate the different distances and were unable to accomplish this task. The slopes of the central portion (distances 200-350) of the Accommodation, Vestibular, Vergence, and No Cue viewing conditions are not zero, but slightly positive (average slope = 0.189), indicating that participants were able to do the task, though experienced difficulty in doing so. This informs us that in each of these visual conditions, participants minimally used the single visual cue that was available to them to estimate distance.

In comparison to the single visual cue conditions, the responses for the Full Cue condition are more accurate. The central portion (distances 200-350 cm) of the Full Cue condition has a more substantial positive slope (0.589) than the single visual cue conditions or No Cue condition. This indicates that participants in the Full Cue condition were better able to estimate distance, and did so more accurately. Specifically, participants in the Full Cue condition performed significantly better than participants in the No Cue condition $t(19) = 3.309$, $p = 0.001$; the Accommodation condition $t(19)= 2.608$, $p=0.17$; and the Vergence condition $t(19) = -3.935$, $p = 0.001$. The Full Cue condition and the Vestibular condition $t(19) = 2.070$, $p = 0.052$ were not significantly different.

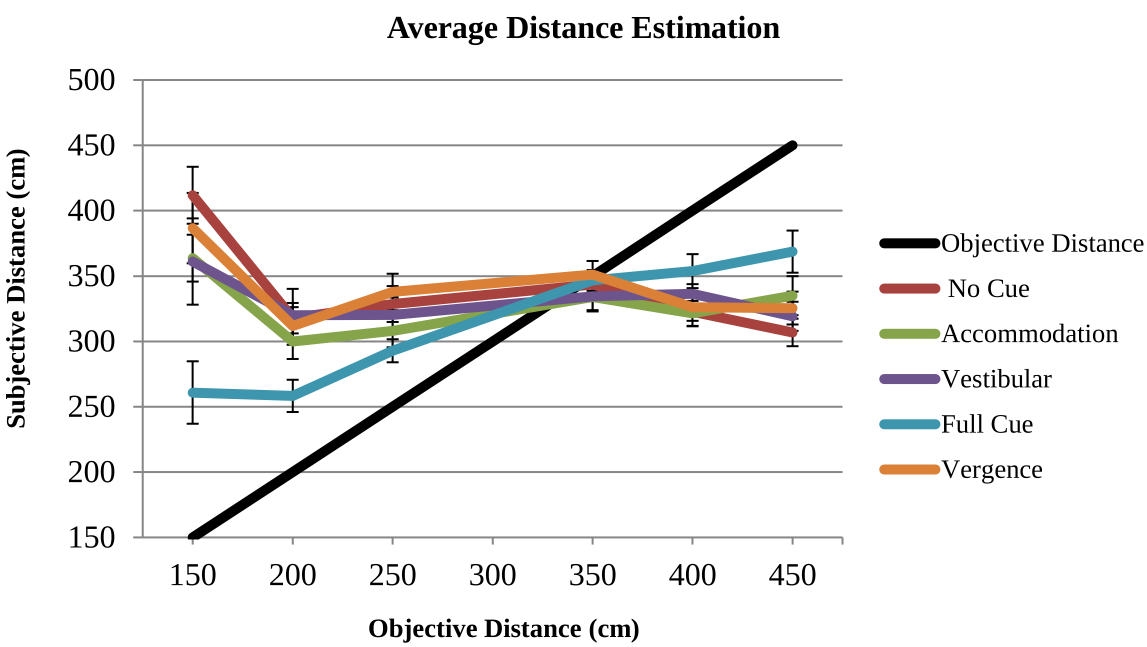


Figure 15. Average Distance Estimation. The average distance estimations for each viewing condition graphed against the objective distance of each stimulus. Error bars reflect standard error.

Absolute Deviation from Objective

For each viewing condition for each observer, the absolute deviation from the objective distance was averaged. Each observer's average absolute deviation for each viewing condition were then aggregated and averaged among all observers. Figure 16, below, shows the average absolute deviation from objective for all five viewing conditions plotted against the veridical distances. The absolute deviations were selected due to the fact that on any given trial, participants could overestimate or underestimate the distance from themselves to the experimental stimuli. Because of these differing possibilities, absolute deviations were used to give a value of error regardless of sign.

Overall, the deviations from the objective for all viewing conditions followed the same general trend. Participants had the largest deviations for the stimuli located at the nearest distance (150cm) and the farthest distance (450cm). The least amount of absolute deviation from the objective distance occurred at the distances of 250cm and 350cm.

In the reduced cue viewing conditions, participants struggled to estimate distance accurately, and had large absolute deviations from the objective distance the stimulus was located. Overall, the No Cue condition had the majority of the highest deviations, however, depending on the distance, other reduced-cue conditions also shared in high deviations. For example, at the location of 250cm, the Vergence condition had the highest absolute deviation. In most of the reduced cue conditions, participants deviated significantly from the true objective distance of the stimuli, particularly for the closest stimuli (150cm), which they perceived as appearing significantly farther than the actual distance. Indeed, participants reliably perceived this stimulus as the farthest stimulus, instead of the nearest.

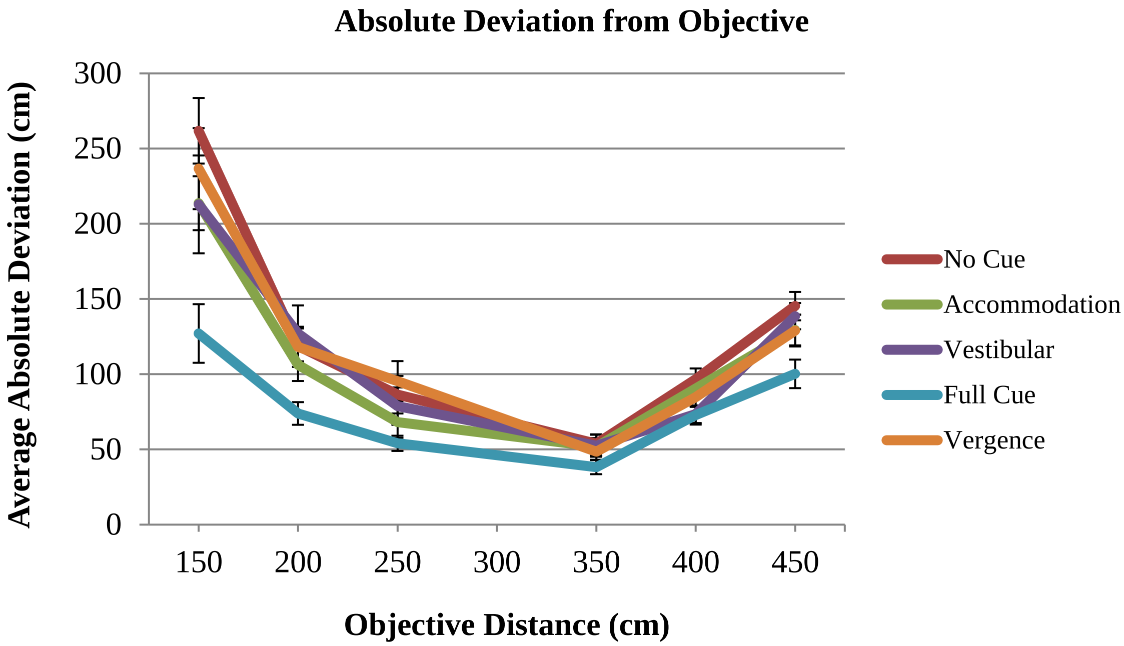


Figure 16. Average Absolute Deviation from Objective. Comparison of absolute deviation of distance estimates in the five different viewing conditions. Participant performance varied greatly for the stimuli that were objectively located closer to the participant. Participants in the No Cue, Accommodation, Vestibular, and Vergence conditions perceived the closest stimuli as very far from them compared to participants in the Full Cue condition. However, for the farthest stimulus, participants who were in the No Cue or reduced cue conditions perceived the stimuli with less absolute deviation when compared with the Full Cue condition. Error bars on the subjective estimations for all conditions reflect standard error.

In the Full Cue condition, participants deviated less (77.72cm; SE=8.76) from the true distance of the stimuli at every distance compared to the average of the reduced cue conditions (117.36cm; SE=12.08). Specifically, participants in the Full Cue condition had significantly smaller deviations than themselves in the No Cue condition $t(19) = 6.044$, $p = 0.000$; the Accommodation condition $t(19) = 5.512$, $p = 0.000$; the Vestibular condition $t(19) = 3.719$, $p = 0.001$; and the Vergence condition $t(19) = -5.158$, $p = 0.000$. Similar to the reduced cue conditions, the largest deviation for the Full Cue condition was also for the nearest stimulus, located 150cm from the participant.

Participants in both the Full Cue and the reduced cue conditions were the most accurate at their estimations nearest to the standard stimulus at a distance of 300cm. This finding is likely a result of participants being able to compare the stimuli located at 250 and 350cm to the standard shown immediately before each of these stimuli. However, it could also be evidence of a differing strategy for estimating distance in a reduced-cue environment, though it is difficult to be certain. If participants have very little visual information, a strategy to reduce the amount of error in their estimations would be to keep their distance estimations close to the known value of the standard, and therefore only deviate by a maximum of 150cm for any given distance. If participants were using this strategy, the results would appear slightly different than the average absolute deviation scores from the objective distance. Namely, all deviations should be compared to the standard distance, and should be less than 150cm for every stimulus, regardless of distance. To determine whether or not participants were using this strategy, the absolute deviations from the standard stimulus were calculated.

Absolute Deviation from Standard

For each viewing condition for each observer, the absolute deviation from the standard distance of 300cm was averaged. Each observer's absolute deviation from the standard was then aggregated and averaged among all observers. Figure 17, below, shows the average absolute deviation from standard for all five viewing conditions plotted against the veridical distances.

Overall, participant deviations from the standard distance of 300cm were not greater than 150cm. For all viewing conditions, for all distances, the greatest amount of deviation from the standard stimulus was ~130cm. The stimulus with the highest deviation from the standard stimulus was located at 150cm, again the nearest stimulus to the participants. Participants in every single viewing condition deviated the greatest from the standard stimulus position of 300cm for their estimate of this stimulus. Participants deviated from the standard distance the least at the middle distances (250 and 350cm). Finally, participants tended to maintain their deviation from the standard distance for their estimations of the farthest stimuli, however, the Accommodation condition and the Full Cue condition increased their deviation from the standard distance for the stimuli located the farthest away (400 and 450cm). Figure 17 depicts a comparison of absolute deviation from the standard in the five different viewing conditions.

On average, the reduced-cue visual conditions did not differ in their deviations from the Full Cue visual condition. In fact, participants in the No Cue condition averaged a deviation of 66.45cm (SE=10.64), while participants in the reduced-cue conditions of Accommodation, Vergence, and Vestibular Cues averaged a deviation of 64.88cm, (SE=11.12), compared to participants in the full-cue condition, who averaged a similar deviation of 64.26cm (SE=10.48). None of these differences are statistically significant, as in all comparisons the p-values are > 0.05. In the No Cue and reduced-cue conditions, it is thought that participants deviate less from the standard distance as a way of reducing errors, however, the same was likely not occurring in the Full Cue condition. Instead, participants in the Full Cue condition had enough visual cues to attempt to estimate the distance with accuracy and were attempting to do so (see Figures 15 and 16, above). The deviations from the standard distance of 300cm in the Full Cue condition and the reduced-cue conditions, though similar in magnitude, are likely an artifact of two different strategies to minimizing error.

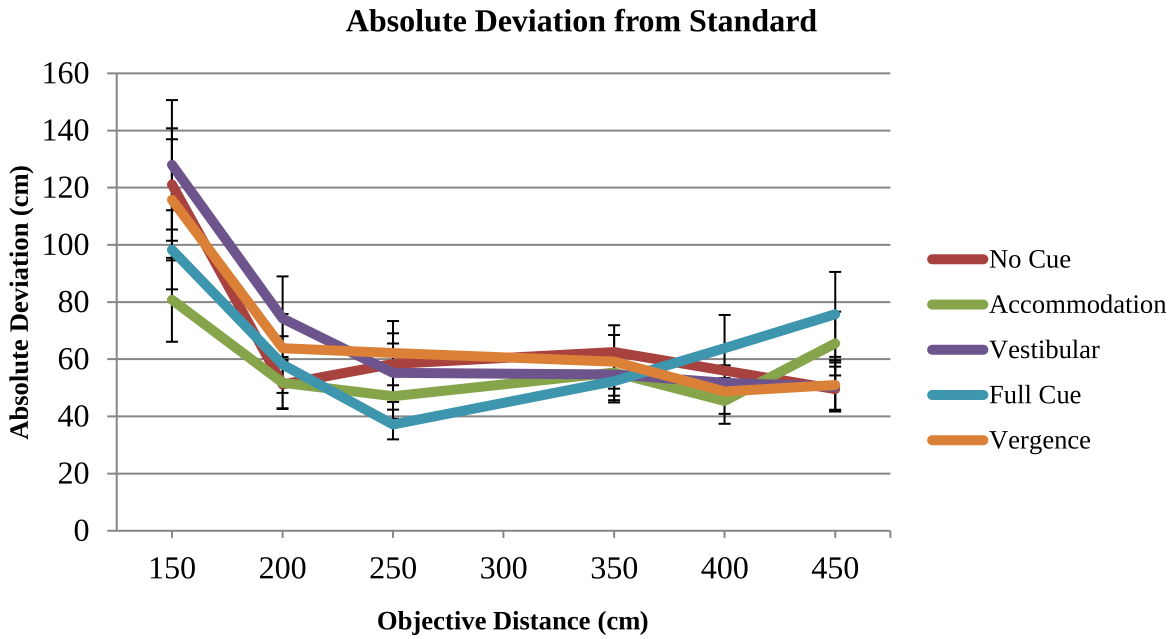


Figure 17. Absolute Deviation from Standard. Comparison of participant average estimate deviation from the standard stimulus (300cm) at each of the five distances. Participants in all conditions deviated away from the standard distance the greatest for the nearest stimulus (150cm). Participants in the full cue condition perceived stimuli as far away from the standard at the near and the far distances, but perceived the middle distances as being close to the standard. Participants in the No Cue and reduced-cue conditions perceived almost all of the stimuli as being near the standard stimulus. The differences in the two conditions graphed in this figure could indicate a potential difference in participant distance estimation strategy (see text).

Distance Sign Accuracy

Another important aspect that was investigated was whether or not participants were able to determine distance sign. In this experiment, distance sign was determined by perceptions of the experimental stimuli being nearer than the standard or farther than the standard. These are comparisons were made relative to the standard stimulus. Figure 18, below depicts the overall distance sign accuracy for far stimuli and near stimuli in each viewing condition.

Overall, participants were more accurate at determining the distance sign of the far stimuli than the distance sign of the near stimuli. In every viewing condition, participants were better able to accurately detect a far stimulus than a near stimulus. Participants were above chance for far stimuli (70%, SE= 0.05), but were below chance for near stimuli (average =32%, SE=0.062) in all viewing conditions, except the Full Cue viewing condition.

Participants in the Full Cue condition answered with 82% accuracy for far stimuli (SE=0.05) and 58% accuracy for near stimuli (SE=0.07). That is, participants were more accurate in correctly identifying the farthest 3 stimuli, relative to the standard stimulus compared with their accuracy in identifying the nearest 3 stimuli, relative to the standard stimulus. Participants in the reduced-visual cue conditions were very similar regardless of condition. Participants in the Accommodation, Vestibular, and Vergence cue conditions answered on average with 69% accuracy for far stimuli (SE=0.06) and 34% accuracy for near stimuli (SE=0.07). Interestingly, the Vergence condtion was relatively effective for identifying far stimuli (70.6%, SE=0.05), but was more similar to the No Cue condition for near stimuli (29%, SE= 0.06). Finally, participants in the No Cue condition answered with 62% accuracy for far stimuli (SE=0.05) and 27% accuracy for the near stimuli (SE=0.05).

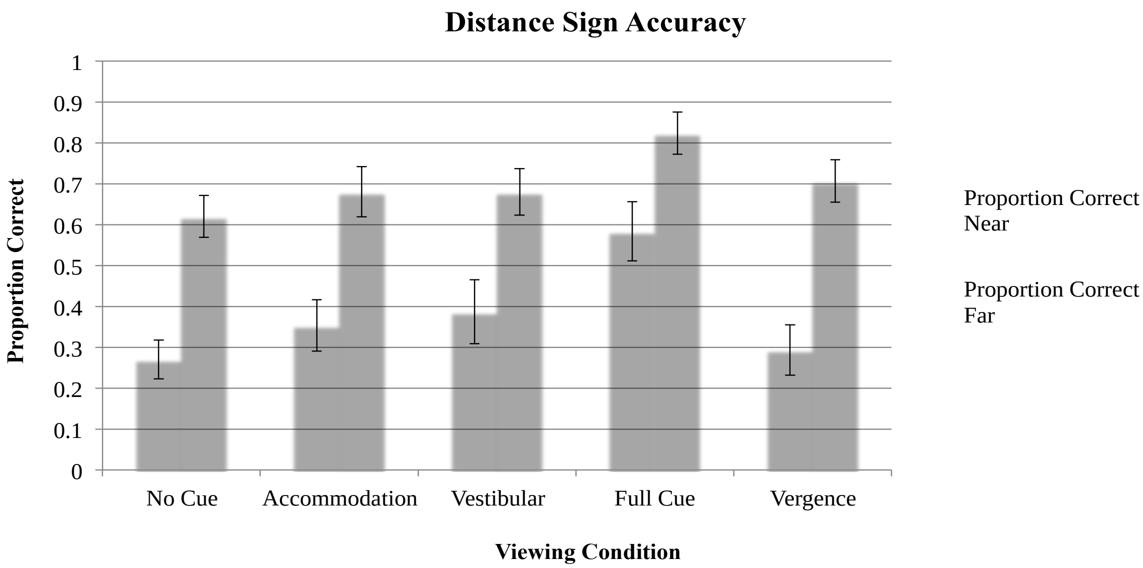


Figure 18. Distance Sign Accuracy. A comparison of the accuracy of distance sign between participants in the five viewing conditions. Distance sign in this experiment is defined as being nearer to the participant than the standard stimulus, or being farther than the standard stimulus from the participant. The Full Cue condition was the most accurate in reporting distance sign for both near and far stimuli. The reduced-cue conditions of Accommodation and Vestibular cues lead to similar reports of distance sign for near and far stimuli. The Vergence viewing condition was more accurate for far stimuli, but less accurate for near stimuli. The participants in the No Cue condition experienced more difficulty than other conditions with accurately reporting whether the experimental stimulus shown was nearer to or farther than the standard stimulus, particularly for the near stimuli.

The analysis of distance sign data provides confidence that the experimental setup was effective in eliminating most cues for the participants in the No Cue condition. The research team used this analysis as a test for flaws in the experimental setup in initial pilot phase testing. If participants in the No Cue condition answered depth sign estimates consistently better than chance at all distances, the experimental apparatus would need to be altered, as participants would be using some visual cues that the experimental team had not accounted for, and subsequently did not remove in the experimental setup. Further analysis of distance sign is reported in the Depth Sign Discrimination Index section, next.

Depth Sign Discrimination Index (DSDI)

Finally, in order to fully investigate whether the participant was biased in discriminating the stimulus as nearer than the standard or farther than the standard, a Depth Sign Discrimination Index, (DSDI) (Nadler, Angelaki, & DeAngelis, 2008) was calculated for each participant in each viewing condition. The DSDI was originally developed to categorize the firing pattern of single neurons within area MT of macaque monkeys, however, it lends itself well to this analysis due to the fact that this calculation takes into account participant inter-trial variation as well as calculating the magnitude of differences in responses between near and far (Nadler, Angelaki, & DeAngelis, 2008). The DSDI equation is given below:

$$DSDI = \frac{1}{3}\sum_{i=1}^{3} \frac{R_{far(i)} - R_{near(i)}}{\left|R_{far(i)} - R_{near(i)}\right| + \sigma_{avg.}} \qquad (7)$$

For each pair of distances symmetric around the standard (300cm), the difference in the response between far (ex: 450cm) and near (ex: 150cm) is computed. Then, the absolute value of these differences are added to the average standard deviation of the two responses and used to divide the initial difference between the far and near stimuli. Each pair (3) of distances symmetric around the standard are then summed, and divided by one third. The DSDI ranges from -1 to +1. A DSDI value of positive 1 would indicate that participants perceived far stimuli as far stimuli and near stimuli as near stimuli, with zero variability. Conversely, a DSDI value of negative 1 would indicate that a participant saw every far stimulus as a near stimulus and every near stimulus as a far stimulus for every trial and without any deviation. DSDI values that are very near zero indicate that the participant had difficulty in discerning whether the stimuli distance was nearer or farther than the standard stimulus, as would be expected in the No Cue condition.

The DSDI score is also a helpful analysis because it shows discrimination bias in the subjective responses of participants. Note, a participant may see objectively close stimulus as subjectively farther away and objectively far stimulus as subjectively close, giving them a high deviation score for accuracy, but a DSDI score that is near zero. Due to the robustness of the DSDI, it is useful to identify patterns in participant subjective responses, to identify bias, and to quickly compare participant responses in different conditions. In addition, all individual variability is taken into account with the DSDI.

Table 9

Average DSDI Scores

Viewing Condition	Average DSDI Score	Standard Error
No Cue	-0.0946	0.056
Accommodation	0.0473	0.098
Vestibular	0.1393	0.096
Full Cue	0.5075	0.082
Vergence	0.0099	0.096

DSDI scores were computed for participants in the all five viewing conditions. DSDI scores of near 1 indicate that participants had very little deviation in their responses, and their responses accurately included far stimuli perceived far and near stimuli perceived near. DSDI scores of near zero indicate that participants in that viewing condition had a large amount of average deviation in their responses, and their responses were relatively equally mixed with regard to distance sign; some near targets were perceived far and some far targets were perceived near.

DSDI scores of participants in the Full Cue condition (0.5075, SE=0.082) indicate that participants were consistently better able to accurately discriminate nearer or farther than the standard stimulus, with a small amount of variability. Specifically, participants in the Full Cue condition were more accurate at discriminating distance sign than the No Cue condition $t(19) = -6.688$, $p < 0.000$; the Accommodation condition $t(19) = -4.172$, $p = 0.001$, the Vestibular condition, $t(19) = 3.611$, $p = 0.002$; and the Vergence viewing condition $t(19) = 7.287$, $p < 0.000$. Participants in the No Cue and Vergence condition tended to have a DSDI score of near zero (-0.0946 and 0.0099; SE= 0.056 and 0.096), indicating that participants were less able to discriminate nearer or farther than the standard stimulus in these conditions, with a large amount of individual variability in their responses. Participants in the Accommodation and Vestibular viewing conditions were slightly above zero (0.0473 and 0.1393, SE= 0.098, 0.096), indicating that participants in these viewing conditions were able to determine distance sign in some cases, but struggled in others, with some variability.

The best way to depict DSDI data is by graphing the raw DSDI scores and observing patterns among and between the different viewing conditions. Figure 19, below, shows the individual DSDI for each participant for all five of the viewing conditions. In the No Cue visual condition, participant scores are tightly clustered around zero, indicating that participants did not have much visual information in this condition, and estimated some far distances as near and some near distances as far with variability. In the individual cue conditions, accommodation, vestibular, and vergence, participant scores are variable. The tight clustering pattern of the No Cue condition does not hold for these viewing conditions, as these viewing conditions have more variability, with some participants doing well and approaching +1, and others doing very poorly, nearly reaching -1. Participants in this condition were or inverting most of the stimuli. In the Full Cue condition, participants increased their accuracy and the majority cluster between 0.5 and +1, with an average of 0.51. Participants did well in this condition, and most of them had enough visual cues to be able to discern near stimuli vs. far stimuli with accuracy. The Full Cue condition was significantly different than the No Cue Condition, $t(19) = -6.688$, $p<0.000$, the Accommodation condition, $t(19) = -4.172$, $p = 0.001$, the Vestibular condition, $t(19) = -3.611$, $p = 0.002$, and the Vergence condition $t(19)= 7.287$, $p < 0.000$. This indicates that participants with three visual cues available had enough visual information to determine distance sign, whereas the same participants with no visual cues, or only a single visual cue available did not have enough information to determine distance sign.

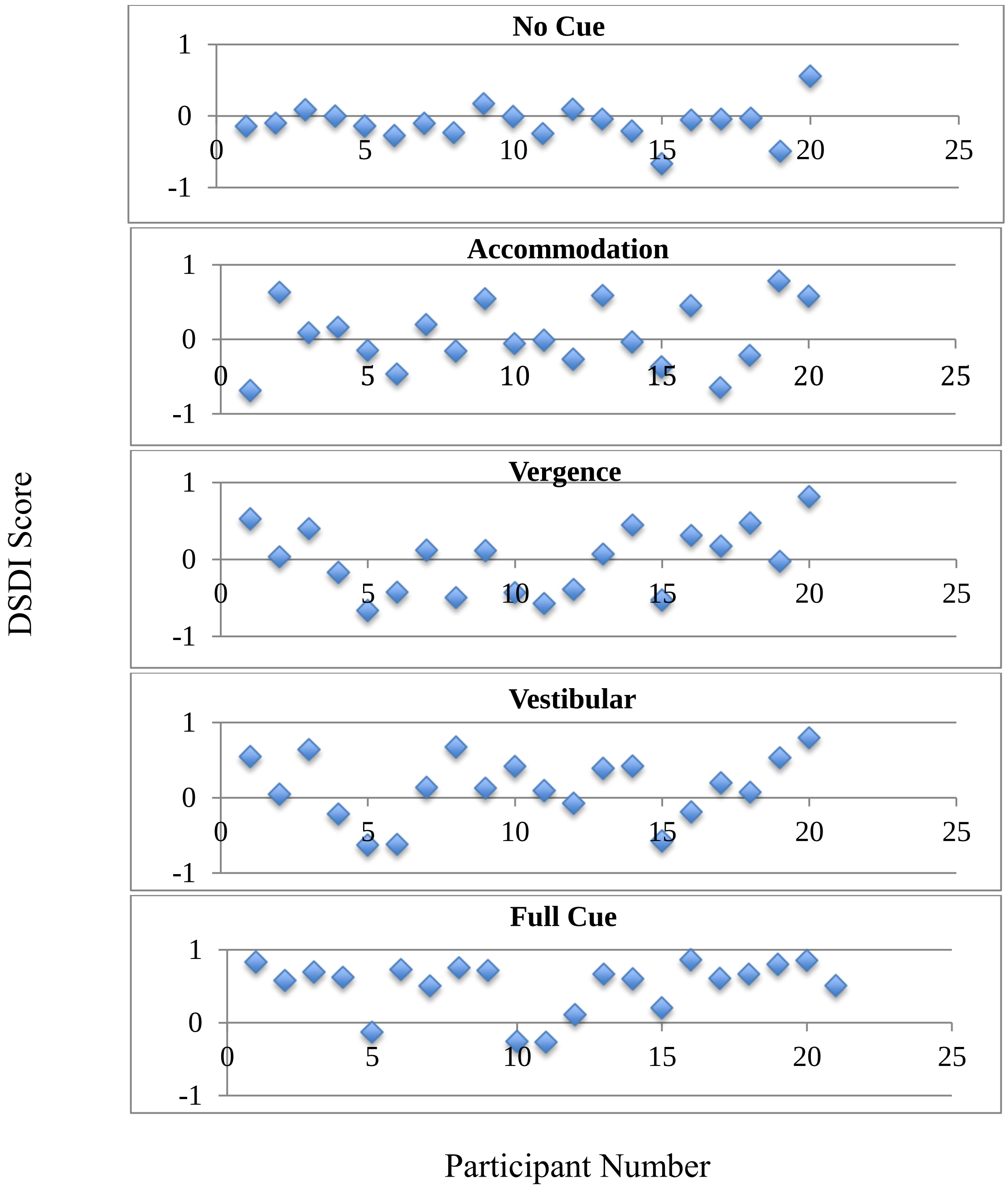


Figure 19. DSDI Comparison. For all 5 viewing conditions, the DSDI scores are shown along the y-axis, and the participant numbers are shown on the x-axis. Notice in the No Cue condition, the majority of the participant DSDI scores congregate between -0.50 and +0.50. In the singular-cue viewing conditions, Accommodation Vergence, and Vestibular, participants are more widely spaced between -1 and +1, indicating more variability in the individual responses and subsequent DSDI values. In the Full Cue condition, the majority of participant DSDI scores congregate between +0.50 and +1.

DSDI Correlation

It may be of interest to investigate whether a correlation exists between any of the DSDI scores for each of the viewing conditions. If a correlation was found, it could mean the internal physiological cues available in some viewing conditions are also being utilized in other viewing conditions, and therefore the DSDI scores for the two different viewing conditions would yield a high Person's r. For a one-tailed test, and (n-2) degrees of freedom (18), the r-critical value of the Correlation Coefficient is 0.378. Correlation coefficient values of r, greater than 0.378 are significant at the alpha=0.05 level. These values have been bolded in Table10, below.

Table 10

DSDI Correlation Table

	No Cue	Accommodation	Vestibular	Vergence	Full Cue
No Cue	1	0.266305334	**0.382033459**	**0.519783183**	0.187988976
Accommodation		1	0.277213	0.244869227	0.255711071
Vestibular			1	**0.556392967**	0.350104233
Vergence				1	**0.693711924**
Full Cue					1

Pearson's r values resulting from correlations between each viewing condition are shown.

Significant DSDI correlations exist among some of the visual conditions. For example, the Vergence cue and the Full Cue conditions are highly correlated. In the Vergence condition, only one visual cue, vergence is available, however in the Full Cue condition, vergence, vestibular, and accommodation are available. These two could be correlated because the vergence cue is common between both visual conditions. The Vergence cue is also highly correlated with the Vestibular Cue condition. In the Vergence condition, vergence is the only visual cue available, however, in the Vestibular condition, both the vestibular cue and the accommodation cues are available. Lastly, the Vergence cue is also significantly correlated with the No Cue condition. In the No Cue condition, no visual cues were available, but in the

Vergence condition, the vergence cue is available. One final significant correlation comes from the Vestibular and No Cue conditions being correlated. In the Vestibular condition, both vestibular cues and accommodation cues are available. However, in the No Cue condition, no visual cues are available.

Discussion

The goal of Experiment 1 was to determine which visual cues were utilized by the brain to accurately estimate distance. Individual visual cues, isolated by themselves did not do much to help participants accurately estimate distance in this experiment. However, the combination of cues which were available in the Full Cue condition yielded better results in the distance estimation task.

Overall, participants in the Full Cue condition were better able to estimate distance than those in the single visual cue conditions or the No Cue condition. The slopes of the all reduced cue conditions are similar and small, though the slope of the Full Cue condition is more positive, indicating that participants were most accurate with multiple visual cues incorporated together in the Full Cue condition than when the visual cues were isolated separately or when no visual cues were available.

The absolute deviation from objective distance is the largest for all participants at the nearest stimulus (150cm) although it is unclear why this is the case. The Full Cue condition had the smallest absolute deviation from the objective distance, again indicating that participants may need more than one individual visual cue in order to accurately estimate distance. Overall, the distances near the standard distance of 300cm were the most accurate for all viewing conditions, indicating that participants may not have been perceiving much difference in distance from what the standard was as well.

The absolute deviation from the standard distance was below 150cm for all distances and all viewing conditions, indicating that participants in reduced-cue viewing conditions may not have had a perception of farther than to near the known standard distance of 300cm. This situation is one that will give very accurate distance estimations for the stimuli that are located near the standard and lessen outlandish distance estimations for the stimuli that may or may not be located far from the standard. Participants could also be doing this implicitly, always offering estimations close to the standard distance to minimize the amount of error at the extreme distances as well, only having a maximum average absolute deviation average of ~135cm for any given stimuli. The fewer cues given to a participant in a magnitude estimation task, the more likely their responses are to center around the standard. In fact, this is a well-documented finding that participants employ in impoverished sensory conditions (Gogel, 1980; Künnapas, 1968). The absolute deviation from standard computation has elucidated a well-known phenomena, the "contraction bias" (Gogel & Tietz, 1973; Gogel, 1978), in which participants underestimate far distance estimations and overestimate near distance estimations, leading to a clustering of guesses near the middle of the closest and farthest distances, or near the standard distance. However, it is currently unclear whether or not participants simply do not have enough visual information to determine that a stimulus appears different than the standard, or simply because the standard is located in the middle of the ranges, that we see the lowest average deviations for the stimuli located nearest the standards.

In each viewing condition, all participants were more accurate at determining the distance sign of far stimuli than near stimuli. In the Full Cue condition, participants were the best at determining the distance sign, followed by the three singular visual cue conditions (Accommodation, Vestibular, and Vergence) and finally trailed by the No Cue condition. These findings indicate that again, the nearest stimulus, located at 150cm was very often, if not always judged to be farther than the standard stimulus at 300 by our participants, regardless of the viewing condition.

Finally, the DSDI for each participant indicated that, even with all of the variability within the sample of participants, some clear trends were able to emerge with regard to distance sign accuracy. The DSDI acts as a sensitive measure of participant distance estimation ability. In the Full Cue condition, participant DSDI values were large, clustering on average between +0.5 and +1. However, in the No Cue condition, participant DSDI values were tightly clustered around zero, indicating that participants had a difficult time discerning distance sign. In each of the reduced-cue conditions, participant answers were more variable, with the DSDI values between -0.5 and +0.5. This shows that some participants did well in these conditions, while others struggled. One fact does remain, and that is that the errors with the nearest stimulus continue throughout the single-cue viewing conditions as well as the no cue condition, though it is currently unclear as to why participants are perceiving the nearest stimulus as farther in all reduced-cue viewing conditions.

Two important findings have come from Experiment 1. The first interesting finding is that the Full Cue visual condition yielded more accurate estimations of distance than any of the reduced cue conditions. This finding tells us that the brain is more accurate when more than one visual cue is available. This may mean that the brain must have more than one visual cue to combine in order to estimate distance accurately. This finding would be especially interesting, given that similar findings have been published regarding depth perception (Landy, Maloney, Johnston, & Young, 1995; Nawrot & Stroyan, 2009). Equations for different types of depth perception have been proposed, but all require a combination of cues in order to determine depth, not one singular visual cue. While depth perception relies on accurate distance perception, it is interesting that the brain assimilates multiple visual cues together to be able to estimate both- depth and distance. The amount of weight given by the brain to individual physiologically based visual cues is low, but the individual contribution of these cues to distance perception as a whole has also not yet been quantified. Finally, the results of Experiment 1 show that visual cues necessary for distance estimation are better in combination with one another than they are by themselves. Another future avenue of research is to determine the pertinent combinations of visual cues, and quantify their ability to help one accurately estimate distance.

The second finding of interest is the curious situation where participants were greatly overestimating the closest stimulus in the experiment. Indeed, participants tended to perceive the nearest stimulus (located at 150 from the participant) as the farthest away in every viewing condition that was restricted in some way. However, observer estimates in the Full Cue condition were not as drastic. One reason participants may be performing this way could be due to the visual cue of height in the visual field during the reduced-cue viewing conditions. In conditions when few visual cues were available, participants may have been devising a strategy to pick up more information than in conditions when many visual cues were available. Notably, objects higher in the visual field, receding toward the horizon, do tend to be farther away, and objects that are lower in the visual field tend to be nearer. The experimental apparatus was composed in such a manner that put the nearest objects the highest in the visual field and the farthest objects the lowest in the visual field to counter visual cues of height in the visual field. However, participants may have been either consciously, or unconsciously aware of their eye height in the visual field. For example, participants may have been able to determine that two stimuli appeared higher than others shown to them, and attributed that quality to these two stimuli being the farthest away, not the nearest as was the case in this experiment. Though the experimental apparatus only slopes downward from the nearest stimulus to the farthest stimulus a difference of 6 inches in the visual field (subtending 3 degrees at 300cm), participants may be sensitive to this cue, particularly when their visual cues were impoverished. The results of the previous experiment do not help to ascertain whether or not height in the visual field was a potentially available or potentially usable cue. Therefore, an additional research experiment was created.

EXPERIMENT ONE SUPPLEMENT

Given the pattern of participant responses during experiment 1 regarding the nearest stimulus, the height in the visual field visual cue was further investigated to determine participant sensitivity to this cue.

Method

Observers

Half of the original participants (n=10) from the first experiment, picked at random, were invited back to the lab for a follow-up experiment. Six women and four men (average age = 26.4 years) returned to the lab to complete a psychophysical procedure.

Stimuli/Apparatus

The same experimental apparatus was used as in Experiment 1. Specifically, the standard stimulus, which was affixed to the linear actuator (see Figure 9.) was the only experimental light used for the experiment. The linear actuator was extended and contracted to seven pre-determined heights in the visual field. These heights perfectly coincided with the heights of the experimental lights in Experiment 1 (44.5, 45.5, 46.5. 47.5, 48.5, 49.5, 50.5 inches off the ground).

Removed cues

Similar to Experiment 1, many visual cues were already removed from the experiment. Recall from Table 1. that stimulus-based and environmentally-based cues, such as shadows, relative size, definition and textures, etc. were already removed from the experimental setup.

Cues held constant

Cues that were previously held constant in Experiment 1, such as brightness and size were also held constant in this experiment. For this follow-up experiment, the canister containing the LED bulb that was affixed to the linear actuator is the only light participants saw for this experiment. This makes the cues of size and brightness exactly the same for each trial, as only one light is being shown to the participant, and it is located always at the same distance away from the participant. Height in the visual field was allowed to vary in the previous experiment by moving the standard to match the height in the visual field of the comparison stimulus immediately before a trial began. The height cue was allowed to vary three inches above the visual horizon of the participant and three inches below the visual horizon of the participant during this experiment.

Procedure

Participants were brought into the lab and seated comfortably with their chin resting in a chin rest. The experimenter adjusted the height of the chin rest to insure the eye height of the participant was exactly 47.5 inches from the ground, coinciding with the middle height of the actuator. Participants were asked to maintain eye level within the visual space (e.g. a participant's comfortable visual horizon) during each trial. Participants were then shown the standard stimulus (Figure 9) at one of seven different heights in the visual field, (44.5, 45.5, 46.5. 47.5, 48.5, 49.5, 50.5 inches from the floor). These heights correspond to each height shown to the participants during the original experiment (three above and three below eye level), as well as one new middle height, which corresponded exactly with the participant's own eye height of 47.5 inches from the ground.

The task of the participant was to determine whether the location of the light being shown was above or below the exact horizontal midline of her/his vision. For each trial, a participant would indicate verbally whether the stimulus appeared above or below, and the experimenter would record her/his response. The stimulus light would then be extinguished and the linear actuator would then move to either fully extended height or a fully closed height, whichever was the opposite direction of the next upcoming trial. The actuator would then move to the height of the upcoming trial, and the LED light would be illuminated for 2 seconds before extinguished again, repeating the process. Participants completed 210 trials, being shown each stimulus height 30 times, with each trial lasting approximately 15 seconds. The total duration of the task for each participant was approximately one hour.

Viewing Conditions

This task was completed with only one viewing condition. All participants completed this task with unobstructed vision and both eyes available.

Design and Data Analysis

Participant responses “above” for each of the seven heights in the visual field were counted and then divided by 30, the total number of trials at each height. This gives a proportion of “above” responses for each of the seven heights in the visual field. Participants should have answered “above” for stimuli appearing at heights located 50.5, 49.5, and 48.5 inches from the ground, as all of these heights were above the visual field of the participant. Conversely, participants should not have answered “above” for any stimuli appearing at heights located at 46.5, 45.5, and 44.5 inches from the ground, as all of these heights were below the visual field of the participant. The participant responses at 47.5 inches were scrutinized, as this is the exact height in the visual field that is equal to that of the participant, and she/he should have answered “above” 50% of the time for stimuli appearing at this height and “below” 50% of the time if she/he had a very high discrimination threshold and was able to easily complete this task.

Results

Overall, participants tended to indicate that the stimulus appeared above their visual horizon more than they tended to indicate that the stimulus appeared below their visual horizon even though there were equal numbers of stimuli located “above” and stimuli located “below”. For example, at the lowest height presented to participants, at 44.5 inches from the ground, participants still answered “above”, on approximately 55% of the trials. Similarly, when shown the stimulus located at their visual horizon, located 47.5 inches from the ground, participants should have said “above” to 50% of the trials, but participants instead answered “above” in over 70% of the trials. As can be seen in Figure 20, below, participants struggled to be able to accurately discriminate height in the visual field, with the slope of the psychometric function appearing shallow.

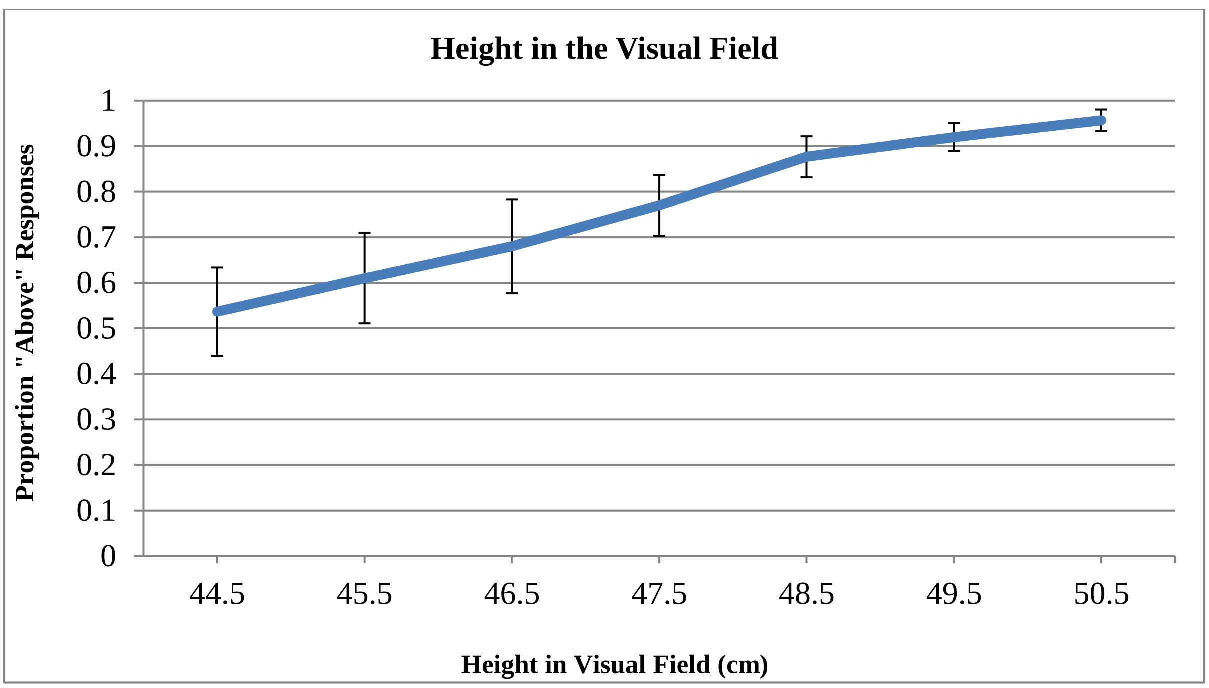


Figure 20. Height in the visual field. A psychometric function was created to determine the proportion of higher responses given by the participants at each of the heights in the visual field. Error bars reflect standard error.

Discussion

The majority of observers struggled to correctly identify the stimulus height in the visual field, with some participants indicating "above" for the majority of trials. One observer indicated "above" for all 210 trials. The psychophysical behavioral data indicates that the cue of height in the visual field during Experiment 1 was potentially available, but a poor cue to inform estimations. Participants in this experiment perceived the stimulus as farther away, which may be one of the reasons why participants perceived the nearest two stimuli as far away as well. It is currently unclear because in the original Experiment 1, both the standard stimulus and the nearest light were at the same height, which should have abolished use of the height cues.

Other visual cues available, but held constant during Experiment 1 were size and brightness. Both of these two visual cues were extensively measured and scrutinized during the experimental setup creation, as well as during the pilot-testing phase of the experiment. Aperture values and error can be reviewed in Table 3. Recall that all of the stimuli apertures were created in order to take up 0.1 degree of visual angle, regardless of the distance to the observer. Recall also, that the largest amount of error in any aperture was 0.028cm, or 3/10 of one millimeter. This error, though likely imperceptible to any participants in the experiment must be acknowledged. However, this tiny amount of error was on the farthest stimulus (450cm from participant), not the nearest stimulus (150cm from the participant), and therefore also does not definitively explain the curious perceptions' of participants during Experiment 1.

Brightness was the other visual cue that was available to participants during Experiment 1, but was also held constant. The measured values for luminance and illuminance of each stimuli used in the experiment can be reviewed in Table 5, and Figures 5 and 6. Much work was undertaken to insure the perception of brightness was not an available visual cue able to be utilized by participants. Luminance measurements, using the Konica Minolta LS-110 Luminance Meter (Chiyoda-ku, Tokyo, Japan) were closely related to a linear regression line with an R^2 value of 0.9577. However, in order for the LS-110 to be accurate, the surface area of the object being measured, must remain constant. Recall that the apertures used in the experiment precluded the surface area from being kept constant at the same distance, and therefore accurate luminance readings were unable to be obtained from the viewpoint of a participant during the experiment, and instead were taken 12 inches from the surface of the LED bulb with the 3 diffusion filters and brass aperture in place.

The second type of measurement that was taken was using a Tektronix J1811 LumaColor™ Photometer Illuminance Sensor Head (Tektronix, Inc., Wilsonville, OR) which is the preferred measurement device for LED bulbs. The most accurate measurements for an illuminance head must be taken within close proximity to the LED bulb in order to be certain the illuminance head is completely illuminated by the light. Recall that all measurements were taken 6 inches from the surface of the LED bulb with the 3 diffusion filters and brass aperture in place. The average illuminance readings were closely related to a linear regression line, with an R^2 value of 0.98929.

The two r^2 values obtained from the luminance and illumance measurement devices are very impressive, given that even minute errors in optical measurement techniques may result in errors of 50% or greater (Zaha, 1972). The two types of technology available to the research team were able to accurately measure the luminance and illuminance from 12 inches and 6 inches, respectively, but neither were capable of measuring the brightness from the exact viewpoint of the observer. This is problematic because it does not allow this researcher to either confirm or deny that the first two stimuli actually appeared the exact same brightness of any of the other stimuli presented during Experiment 1. Given the linear nature of the measurements at both 12 and 6 inches from both types of technology available, it is unlikely, though unproven, that noticeable differences in the brightness of the nearest two stimuli existed in Experiment 1. A second follow-up study could be proposed, similar in nature to Experiment 1.1, whereby the participant task is to simply indicate which of two lights shown to them in the dark room is brighter. The results of plotting participant responses into a psychometric function would yield evidence that the cue to brightness really was not held constant in the original experiment, and “leaked” visual information to participants.

EXPERIMENT TWO: INVESTIGATING THE EFFECT OF ALCOHOL ON DISTANCE ESTIMATION

Drunk driving has been a continuous problem since the mass production of automobiles (Newman & Fletcher, 1941). In the year 2014, more than 1.1 million drivers were arrested for driving under the influence of alcohol or narcotics (Department of Justice (US), 2015). Astonishingly, these arrests are only 1% of the 121 million self-reported incidences of alcohol-impaired driving undertaken by U.S. adults each year (Jewett, Shults, Banerjee, & Bergen, 2015). The disparity between those arrested and those engaging in driving under the influence is marked. Despite nationwide mass-media campaigns, school-based instructional programming, and stiff penalties - including jail time and revocation or suspension of licenses for repeat offenders, the number of drunk driving deaths still reach over 10,000 people in the United States every year (Department of Justice (US), 2015). The death toll and the incredibly high subjective reports of driving under the influence both reiterate the fact that drunk driving remains a continuing problem in our society. While much research has been conducted in the past, fundamental and unanswered questions remain about the way alcohol affects the human body. Answering these types of questions could help to shed light on why crashes continue to happen.

Literature Review

The physiological effects of alcohol on the human body have been investigated for over 100 years, and thousands of publications and research articles exist, however, this remains a difficult topic to succinctly summarize. Somewhat frustratingly, alcohol intoxication induces multifaceted dysfunction within the human body. Due to this fact, it has been difficult to pinpoint exactly which cognitive, perceptual, and muscular/movement systems may be affected in an intoxicated person. Rather than localize and impact singular behaviors, in some cases, alcohol affects bodily functioning wholesale. Further, inter-individual issues, such as differences in genetics, tolerance, and differential metabolism exist among participants. These differences, in combination of between-study issues such as accurate alcohol dosage techniques, when in the Blood Alcohol Content (BAC) curve participants were tested, differing blood alcohol measurement technology, and a lack of matched control groups, are all variables that have contributed to confounded findings or inhibited replication of previous studies, making generalizations about alcohol's effects a difficult task.

Large-Scale Motor Output

The effect of alcohol on large-scale motor behaviors (those typically involved in driving cars) is very well understood, due to over sixty years of research and the advent and validation of driving simulator technology. Dysfunction due to alcohol in steering abilities (Allen, Jex, McRuer, & DiMarco, 1975; Starmer, 1989), lane deviations (Calhoun, Pekar, & Pearlson, 2004; Weafer, Camarillo, Fillmore, Milich, & Marczinski, 2008), choice reaction time (Lyon, Tong, Leigh, & Clare, 1975; Maylor, Rabbitt, Sahgal, & Wright, 1987), physical coordination (Marczinski, Fillmore, Henges, Ramsey, & Young, 2012; Martin et al., 1985), and increases in brake latency (Liguori, D'Agostino Jr., Dwokin, Edwards, & Robinson, 1999; Liguori, Gatto, & Jarrett, 2002) are firmly established and reproducible findings.

The voluntary production and accurate timing of major motor movements like those described above requires accurate decision-making. Unfortunately, cognitive functioning required to make accurate decisions is also affected by alcohol. Usually, cognitive functioning is assessed by the performance of an intoxicated participant on tasks such as information processing and divided or sustained attention, which are all notorious for being affected by alcohol even at BAC levels below .05% (e.g. Mitchell, 1985; Moskowitz, 1984; Rohrbaugh et al., 1988). This is particularly problematic if you consider the legal driving limit for BAC is 0.08% in the United States. While all of these studies, and those mentioned above, contribute meaningfully to the our understanding of the effect of alcohol intoxication on human driving behavior, the problem with strictly focusing on large-scale behavioral outcomes and cognitive functioning is that the many smaller-scale motor behaviors, most of which combine together as scaffolding for the production of aforementioned behaviors, are overlooked.

Small-Scale Motor Output

Small-scale motor behaviors, particularly those involved in visual processing (automatic muscle reflexes and eye movements) actively contribute to the orientation of and feedback required to complete accurate whole-body motor behaviors, yet are less often researched with regard to alcohol. It is known that the coordination of fast eye movements (saccades), as well as conscious and reflexive visual tracking of objects with the eyes (pursuit), are sedated incrementally by doses of alcohol (E.g. Holdstock & Wit, 1999; Roche & King, 2010; Wilkinson, Kime & Purnell, 1974). Blekher, Miller, Yee, Christian, and Abel (1997) found that pursuit gain (a ratio of eye velocity to target velocity), saccadic accuracy, and both saccadic amplitude and rate were significantly reduced by alcohol. This decrement in pursuit eye movement impedes monocular depth perception from motion parallax (Nawrot, Nordenstrom & Olson, 2004). Interestingly, binocular depth perception is also impaired by alcohol at the legal driving limit (Watten & Lie, 1996; Wegner & Fahle, 1999). Given that both monocular and binocular depth perception rely on accurate distance estimation, it follows that visual cues important to accurate distance estimation are likely to be impaired by alcohol as well.

Vergence

One of the main visual cues thought to be important for accurate distance estimation is binocular vergence and has been studied in some capacity with regard to alcohol. The eye movements utilized to successfully land the fovea of each eye on a single target in space become impaired or less accurate after alcohol ingestion. Wist, Hughes, and Forney (1967) noticed a small but significant misalignment of the eyes of some participants completing a binocular fixation task. This small misalignment is due to a difference between the required vergence angle of the target and the complimentary convergence angle made by the eyes during binocular fixation. This misalignment was noted at a low BAC of just 0.05%, while leaving stereo acuity intact, indicating it was the eye movements that were affected by the alcohol. When investigating the resting state of vergence, Cohen and Alpern (1969) found that alcohol made the natural resting distance of the eyes shorter during relaxation, indicating an increase in convergence. Similar findings were also noted by McNamee, Piggins, and Tong (1981), but did not extend to misalignment of the eyes in the vertical plane during intoxication. Hogan and Gilmartin (1985) were also interested in the resting state of vergence, and found that overall, vergence became biased toward the resting state during taxing oculomotor tasks if the subjects were under the influence of alcohol. Further work has shown that the amount of time it takes for intoxicated participants to fuse two targets at far distances and near distances increases, however, intermediate targets near the resting point of vergence for a particular individual tend not to take additional time (Miller, 1991), demonstrating further evidence that alcohol has a narrowing effect on the range of vergence. Finally, while investigating alcohol's effects on heterophoria (misalignment of the eyes), a BAC of 0.10% and 0.05% caused participants eyes to move outward in an exophoric motion compared to their best possible sober near point of convergence, and in an inward or esophoric motion, compared to their best possible sober far point of convergence (Munsamy, Hamilton-Hoskins, Bero, Ximba, Govender, Soni, & Majola, 2016). These results replicate earlier findings by Miller, Pigion, and Takahama (1985) using distances of 6 cm for close targets and 30 cm for far targets.

Accommodation

The second main visual cue thought to be important for accurate distance estimation is accommodation, which has also been studied with regard to alcohol. However, in contrast to studies on vergence, the results of studies on alcohol and accommodation are sparse. The ability of the eye to focus at far distances and near distances is an automatic and crucial visual function. Miller, Pigion, and Martin (1985) tested the accommodative abilities of 7 participants at near distances of 30 cm and far distances of 6 m, at three levels of BAC: 0.00%, 0.05% and 0.13%. These authors found that accommodation for all target distances increased with intoxication indicating an excessive tightening of the ocular muscles controlling the shape of the lens while viewing stimuli. Additionally, each participant's dark focus of accommodation, or her/his resting accommodation also increased significantly, especially under the highest levels of intoxication. Unfortunately, the sample size for this experiment was small. Levett & Karrass (1977) found that accommodation latency increases (it takes more time to accommodate an object) when intoxicated. Hill and Toffolon (1990) found that accommodation is less accurate under the influence of a 0.08% BAC. The most recent work on the subject, by Watten and Lie (1996), did not find significant differences in the minimum distance to successfully accommodate a near target, nor the resting state of accommodation, nor the maximum distance to relax accommodation to maintain clear vision on a far target in their study of 22 participants. Watten and Lie were using BAC levels of participants at 0.0%, 0.05%, and 0.10%, which are comparable to those by Miller, Pigion, and Martin eleven years prior. There is no denying that these two studies are in direct conflict with one another. It may be pertinent to point out that the resting state of accommodation, also known as "tonic" or "dark" accommodation is the natural resting state of the focus of the eyes and varies significantly by individual. Liebowitz and Owens (1978) found that the resting state of accommodation varies among college-aged individuals from anywhere to 10 inches from the face of the eye out to an infinite distance. These large inter-individual differences could be one of the reasons for the discrepancy within these two studies.

Evidence presented on the effects of alcohol on vergence and to a lesser degree, accommodation suggests negative impacts on eye movement and focus. To summarize, convergence eye movements tend to become fatigued with alcohol and the ocular muscles tend to decrease their flexion abilities while divergent eye movements tend to struggle with full relaxation under the influence of alcohol. Tentatively, we may say that accommodation to both near and far targets tends to increase with alcohol, indicating a shortening of the accommodated distance. These changes in physiological visual cues may mislead the brain to inaccurately perceive distance, as has been previously established with depth perception under the influence of alcohol. However, only primary studies have been conducted thus far on the effect of alcohol on vergence and accommodation, and the application of these findings to a real world task, such as distance estimation has never before been conducted.

Both relative depth and absolute distance estimation are necessary for a driver (or anyone) to successfully navigate a cluttered and moving environment. Lacking accurate distance estimation abilities could lead to very serious consequences for those driving under the influence of alcohol. For example, if intoxicated drivers are unable to judge the distance of objects in their path, things may “suddenly jump out in front of the car” with disastrous consequences. It is therefore crucial to understand how distance perception is affected by alcohol.

Goal

The goal of the second experiment is to determine how distance estimation is affected by alcohol at moderate levels. In order to determine which visual cues participants rely upon under the influence of alcohol, the same experimental apparatus used in Experiment 1 will be utilized in this experiment to systematically eliminate stimulus-based and environmental cues in order to focus on and isolate the physiological cues used by the brain to accomplish this task. Each viewing condition from Experiment 1 will be repeated, allowing the experimental team to compare accuracy performance in each condition and make concrete comparisons with sober visual conditions, leading to conclusions about how alcohol affects distance estimation accuracy. To this author’s knowledge, no study has ever been conducted that investigates distance estimation under the influence of alcohol.

Method

Observers

The same twenty participants that completed Experiment 1 returned for Experiment 2. Using a between subjects design decreases variability from baseline performance in Experiment 1 to performance in Experiment 2, allowing direct comparisons of distance estimation accuracy. Ten women and 10 men over the age of 21, (average age =26.2) completed the study. Each participant had normal or corrected to normal visual acuity and stereo acuity. Each participant had a normal body mass index (calculated using participant height and weight given during Experiment 1), and no positive answers to the alcohol-screening questionnaire from Experiment 1. Each participant was paid $10/hour as compensation.

Stimuli/Apparatus

The same stimuli and apparatus used in Experiment 1 was also utilized for Experiment 2. To review, please see Figures 4, 7a, 7b, 8, and 9.

Procedure

Prior to entering the laboratory, participants were asked to fast for a minimum of 4 hours, assuring their stomach was empty. Upon entering the lab, participants were reacquainted with the absolute distance task via PowerPoint task at the computer, where they were asked to indicate absolute distance in Shanda Units with a mouse and keypad while using the standard stimulus as a guide (see Figure 11). Upon completion of this task, participants were given a Breathalyzer, using the Intoxilyzer 5000 (CMI, Inc. Owensboro, KY). This intoxilyzer works by passing participant breath samples through infrared light to a detector, and quantifies the number of alcohol molecules in each breath sample compared to samples of air from the testing room (zero reference point). The intoxilyzer then displays the number of grams per 210 liters of air, yielding a BAC reading. For example, 17 grams of alcohol per 210 liters of air = 0.081% BAC. Participants were required to have a 0.00% BAC to begin the experiment, insuring they did not have a residual BAC from any previous alcohol intake that day. Participants then re-reviewed the screening questionnaire to make sure they had not started a new medication known to interact with alcohol, they had not engaged in illicit street drug use or had not become pregnant since participation in Experiment 1, and then signed their consent. Shortly thereafter, participants removed their shoes and were reweighed. The weight of the participant was recorded and used to determine how much alcohol was required to intoxicate the participant to the desired BAC of 0.08% using the following standardized dosing formula,

$$\text{Alcohol Dose (mL)} = \text{W} * 0.74. \qquad (8)$$

The total dose of 100-proof vodka given to the participant (in mL) is equal to the participant's weight in pounds multiplied by 0.74. This calculation was double-checked via an Ethanol Dosage Control Sheet in the laboratory to make sure the calculation was completely accurate. The total alcohol dose (in mL) was divided into 4 equal doses. Participants were given the first dose mixed with equal parts orange juice and were required to consume it within 15 minutes. At each of 3 consecutive 15-minute intervals thereafter, participants were given another dose. One hour after starting the dosing process, participants usually reached the desired BAC of 0.08%. Throughout the experiment, participant BAC was checked and recorded every 15-minutes. This constant measurement informed the research team of the current BAC of the participant, and additional doses were given throughout the experiment to maintain a 0.08% BAC level for the duration of the experiment.

After the dosing was complete, participants were again reminded of the instructions for the experiment and seated in the chair and chinrest in the experimental room in complete darkness (See Figure 7b.). Participants were alone in the imperceptibly dark room and once the experimental door directly in front of them was opened and the experimenter was in place outside the experimental room, the trials began. The exact same stimuli and apparatus used in Experiment 1 was again utilized to present stimuli to the participants (Figure 4, Figure 7). The presentation of the standard light began the trial, followed shortly thereafter by the experimental light. The standard light and the experimental light appeared at equal height in the visual field (Figure 9). The participant task was the same as in Experiment 1, to verbalize a distance estimate of how far away from her/himself the experimental light was located. Participants again estimated the absolute distance between her/himself in Shanda Units, which was later converted to the objective distances of centimeters (Table 7). The experimenter recorded the participant's verbal distance estimations, which were heard through an intercom.

Conditions

Participants ran through each of the 5 viewing conditions previously completed in Experiment 1 (refer to Table 8), again in a randomized order. The following conditions were run in random order: No Cue condition, the Vestibular condition, Accommodation condition, Vergence condition and the Full Cue condition. In having participants complete each condition in a randomized order helped to insure that the effects seen in the different viewing conditions are actually due to different visual cues being available and not practice effects or the utilization of other cognitive strategies. The experimenter was mindful of a 15-minute timer and stopped between viewing conditions to check and record the BAC level of the participants. Participants were run through each viewing condition, and after completing the final condition, participants were able to relax within the laboratory, receiving a breathalyzer every 15 minutes until her/his BAC content reached 0.04%. At that time, the experimental team released the participant from the laboratory to a pre-arranged designated ride home, in nearly all cases, the experimenter. Participants were instructed to refrain from making any life-altering decisions for 2 hours after the completion of the experiment, by which time, the participant BAC should be safely back to 0.00%.

The design of this experiment was a fully randomized within-subjects experimental design. By running half of the participants first in Experiment 1 in the sober condition and half of the participants first in Experiment 2 in the intoxicated condition, and then switching, certain benefits exist. First, the amount of variability from pre-to post-intoxication conditions was decreased, and attributed to the alcohol rather than to individual differences. Secondly, direct comparisons are made regarding the influence of alcohol on distance estimation accuracy and visual cue condition. Finally, practice effects were eliminated from the experimental design.

Results

In this section, outcomes of each viewing condition will be presented. Analyses were conducted in Microsoft Excel, MATLAB R2016b (The Mathworks, Natick, MA) and SPSS 21 (SPSS II, New York, NY).

Average Subjective Distance Estimations

The first investigation that was made is a comparison of differences in the average of the subjective estimates compared to the objective distances in each viewing condition while under the influence of alcohol. Similar to Experiment 1, for each viewing condition for each observer, the estimations from each distance were averaged. Each observer's average estimations for each viewing condition were then aggregated among all observers. Figure 21, below, shows the average subjective distance estimation for all five viewing conditions plotted against the objective distances.

Overall, participant distance estimation in conditions of restricted cues deviated markedly from veridical. Nearly all of the viewing conditions appear to follow the same general trend, with the nearest stimulus appearing to be the farthest away, and the remaining distances all appearing to be at or near the standard distance of 300. At objectively near distances, participants overestimated the distance to the stimulus, and at objectively far distances, participants underestimated the distance to the stimulus.

Recall again from Experiment 1 above (Figure 14.A & 14.B), that when the slope of the line is zero, participants are unable to discriminate the different distances and were unable to accomplish this task. The slopes of the central portion (distances 200-350) of No Cue viewing conditions was actually below zero, (-0.15), indicating that participants were able to do the task in the No Cue viewing condition. Participants in the Vergence and Accommodation viewing conditions had similar slopes, very near zero, but slightly positive (average slope= 0.07), indicating that these participants were only slightly able to complete the tasks, and experienced great difficulty in doing so. This informs us that in each of these visual conditions, participants were only slightly able to use the single visual cue that was available to them to estimate distance. The Vestibular condition had a positive slope of 0.19, indicating that participants in this viewing condition were able to utilize vestibular information to complete the task. Finally, participants in the Full Cue condition did the best while intoxicated, with a slope of 0.248. This indicates that participants in the Full Cue condition were better able to estimate distance, and did so more accurately, but only compared to some viewing conditions. Specifically, participants in the Full Cue condition performed better than participants in the No Cue condition $t(19) = 3.891$, $p = 0.001$; and better than participants in the Vergence condition $t(19) = -4.693$, $p < 0.000$. However, the participants in the Full Cue condition did not significantly differ in their average subjective distance estimations of themselves while in the Vestibular condition $t(19) = 1.661$, $p = 0.113$; or in the Accommodation condition $t(19) = 1.344$, $p = 0.195$.

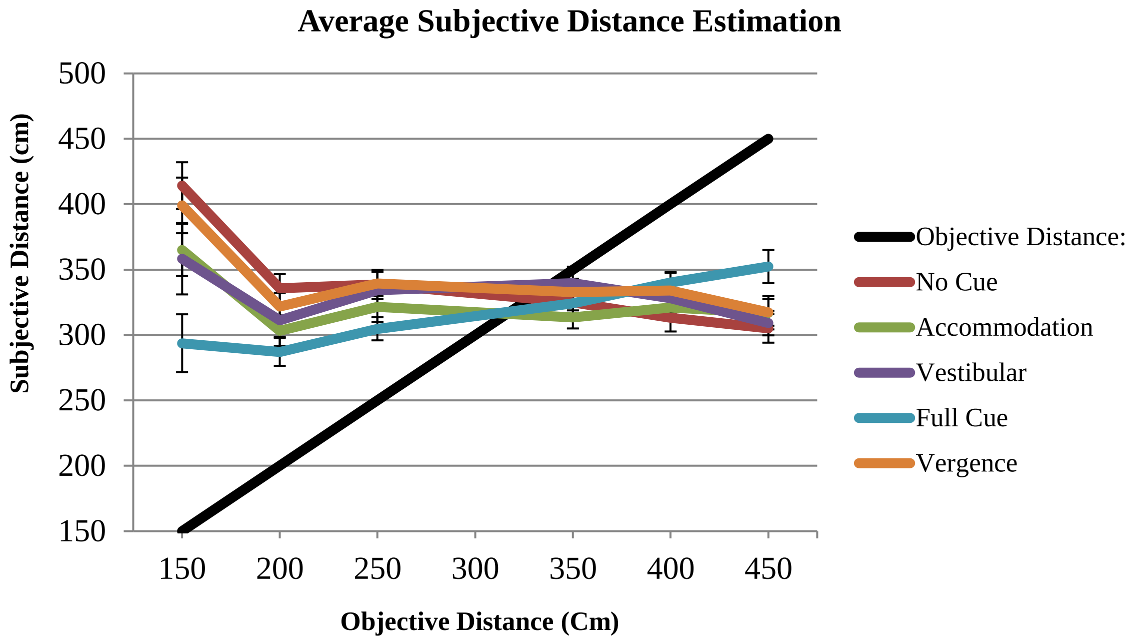


Figure 21. Average subjective distance estimations. A comparison of the average subjective distance estimations with objective distance for all conditions. The objective distance has been indicated by a black line. Conditions that are farther from the black line, indicating lower accuracy include the No Cue, Accommodation, Vergence, and Vestibular conditions. Due to alcohol interfering with the ability to accurately utilize cues available in the full cue condition, participant accuracy level decreased from their sober performance in that viewing condition.

Secondly, it is important to compare the findings of the current study to those of the previous study. One of the main investigations that was done compared the average subjective deviation in the intoxicated state to the deviations made while the participants were sober. Recall that half of these participants first completed this task while sober and the other half first completed this task while intoxicated. An interested reader may elect to compare Figure 18 with Figure 22 to visually reiterate how alcohol is hypothesized to change the accuracy of subjective distance estimations. A simple visual comparison of these two Figures shows alcohol’s devastating effects on distance estimation.

Overall, participants performed slightly worse on all visual conditions while under the influence of alcohol, though the differences were not significant, all p-values > 0.05. One may notice the small amount of positive slope from the singular-cue conditions (Accommodation, Vergence, and Vestibular) in Experiment 1 (average= 0.19) effectively disappeared in Experiment 2 (average =0.07) while participants were under the influence of alcohol. This change in sensitivity level for distance estimation accuracy is statistically depicted in the upcoming DSDI section. The No Cue condition in Experiment 1 had a slightly positive slope of 0.172, which regressed in Experiment 2 to -0.150. Perhaps nowhere more than in the Full Cue condition can one notice small deleterious effects of alcohol on distance perception. While sober, the slope of the Full Cue condition was 0.589, but in the intoxicated condition, this slope fell to 0.248 and began to blend in with the other viewing conditions. Again, it is likely that by adding alcohol, both vergence and accommodative abilities of the participants were decreased, impacting their overall accuracy on the distance estimation task.

Average Absolute Deviation from Objective

The second comparison that was made investigated the average absolute deviation from the objective distance. For each viewing condition for each observer, the absolute deviation from the objective distance was averaged. Each observer's average absolute deviation for each viewing condition was then aggregated and averaged among all observers. The average absolute deviation from objective can be thought of as a measure of estimate error. Figure 23, below, shows the average absolute deviation from objective for all five viewing conditions plotted against the veridical distances. Recall that the absolute deviations were selected due to the fact that on any given trial, participants could overestimate or underestimate the distance from themselves to the experimental stimuli. Because of these differing possibilities, absolute deviations were used to give a value of error regardless of sign.

Overall, the deviations from the objective for all viewing conditions followed the same general trend found in Experiment 1. Participants had the largest deviations for the stimuli located at the nearest distance (150cm) and the farthest distance (450cm). The least amount of absolute deviation from the objective distance occurred at the distances of 250cm and 350cm.

The No Cue visual condition had the majority of the highest deviations (average = 132.77cm, SE=10.50), however, depending on the distance, other reduced-cue conditions also shared in high deviations. For example, at the location of 350cm, the Vestibular condition had the highest absolute deviation, but overall fell toward the middle of the viewing conditions with regard to deviation (average =118.42, SE=12.61). As for the remainder of the singular cue viewing conditions, in the Accommodation visual condition, participants still struggled to estimate distance accurately, but the Accommodation condition was one of the better visual conditions for average deviation (114.76, SE=10.85). The Vergence condition had large absolute deviations (average = 123.31, SE=11.29) from the objective distance the stimulus was located, particularly at the nearest and farthest stimulus locations.

The Full Cue visual condition had the lowest amount of deviation (average = 86.80, SE= 9.64) from the objective distance for every stimulus distance. Specifically, the participants in the Full Cue condition had significantly lower absolute deviations than themselves in the No Cue condition, $t(19) = 5.269$, $p < 0.000$; the Accommodation condition, $t(19) = 4.027$, $p = 0.001$; the Vestibular condition, $t(19) = 3.567$, $p = 0.002$; and the Vergence condition $t(19) = -4.644$, $p < 0.000$. Similar to the reduced cue conditions, the largest deviation for the Full Cue condition was also for the nearest stimulus, located 150cm from the participant.

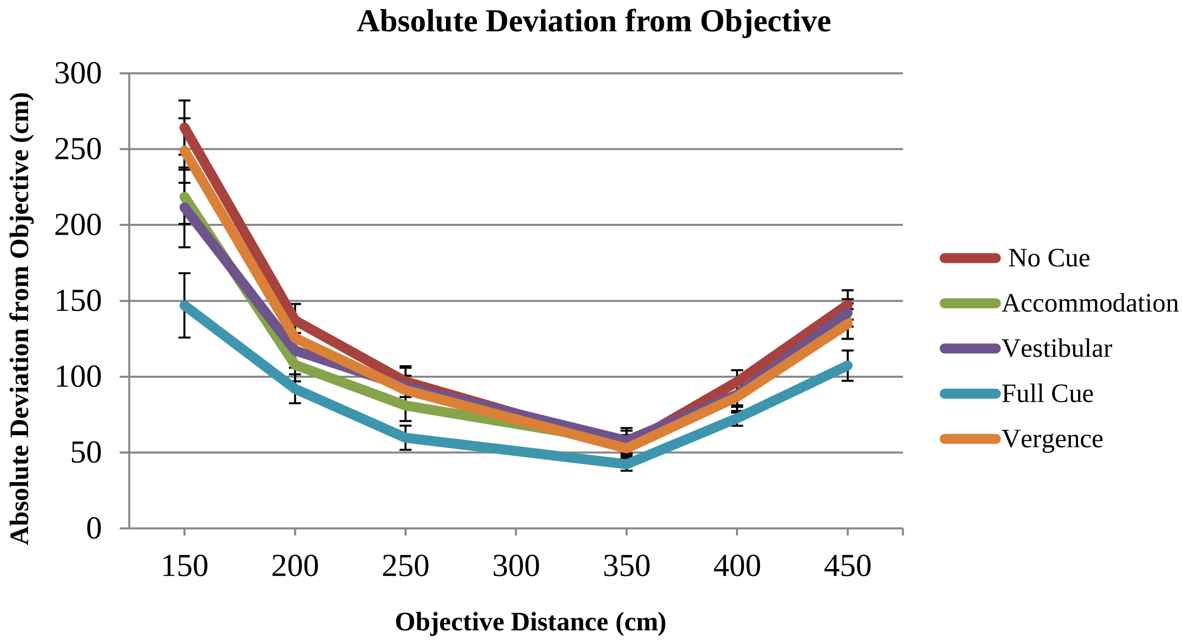


Figure 22. Average absolute deviation. A comparison of the average absolute deviation by objective distance for each viewing condition while participants are under the influence of alcohol. As the red line of the No Cue condition shows, the deviation is greatest for nearest and farthest distances when no cues are available. All of the remaining viewing conditions are in very close proximity to the No Cue condition, indicating that participants deviated widely from the objective distance due to the fact that the cues they were relying on in Experiment 1 to accomplish this task were degraded by alcohol, decreasing their sensitivity to distance estimation.

The next investigation compares the average absolute deviation to the objective distance made while the participants were sober. An interested reader may elect to compare Figure 16 with Figure 22 to visually reiterate how alcohol changes the accuracy of subjective distance estimations. One must look closely to see any noticeable differences in the absolute deviation from objective from Experiment 1 to Experiment 2. The two graphical representations in Figures 16 and 22 are incredibly similar. The same general trend shows participant absolute deviation very high for the nearest stimulus, then decreasing greatly toward the stimulus located at 350cm, before increasing again to the farthest stimulus at 450cm. The same values for the error occur and the same order of the viewing conditions hold from highest deviation (No Cue) to lowest deviation (Full Cue). The only noticeable difference is that the absolute deviation for the Full

Cue condition increased by roughly 25 cm in the intoxicated condition compared with the sober condition. All other viewing conditions appear similar, regardless of alcohol intoxication and are not significantly different from themselves. The sober No Cue condition, compared with the intoxicated No Cue condition yielded insignificant differences, $t(19) = -1.182$, $p = 0.252$. The same general trend followed for Accommodation, $t(19) = -.774$, $p = 0.448$, Vestibular, $t(19) = -.632$, $p = .535$, and the Vergence condition, $t(19) = -1.171$, 0.256. However, the sober Full Cue condition was statistically better than the intoxicated Full Cue condition, $t(19) = -2.643$, $p=0.016$.

Average Absolute Deviation from Standard

The third major comparison investigated was the average absolute deviation from the standard. For each viewing condition for each observer, the absolute deviation from the standard distance of 300cm was averaged. Each observer's absolute deviation from the standard was then aggregated and averaged among all observers. Figure 23, below, shows the average absolute deviation from standard for all five viewing conditions plotted against the veridical distances.

Recall from Experiment 1 that in reduced-cue visual conditions, participants tended to estimate distance more conservatively, and hover their estimations around 300cm, the known distance to the standard stimulus. Overall, when participants are under the influence of alcohol, their distance estimation's average deviation from the standard distance of 300cm was not greater than 115cm, indicating that alcohol also contributed to the reduction of visual cues. This means that for all viewing conditions for all distances, the greatest amount of deviation from the standard stimulus was 115cm. Again, the nearest stimulus, located 150cm from the participant garnered the greatest amount of deviation from the standard, regardless of viewing condition. The farthest stimulus, located 450cm from the participant received a similar deviation (~60cm) as nearly every single other distance for all viewing conditions.

On average, the reduced cue visual conditions did not differ in their deviations from the Full Cue condition. The Full Cue condition did have the lowest deviation, (average = 54.1, SE= 7.82), however, the Accommodation condition had a similar deviation (average=59.04, SE=8.56). The No Cue, Vestibular, and Vergence conditions were all very similar, with a combined average deviation of 66.87 (SE=10.08).

Next, a comparison will be made of the average absolute deviation from the standard between the sober condition of Experiment 1 with the intoxicated condition of Experiment 2. Comparing these two conditions graphically in Figures 17 and 23, respectively, a similar trend is apparent. The deviations in both the sober and intoxicated conditions are the highest for the nearest stimulus, located at 150cm, and for nearly every subsequent stimulus distance, the average absolute deviation from the standard is ~60, in both Experiment 1 and Experiment 2. The main noticeable difference between the sober and the intoxicated condition is the fact that in Experiment 2, the alcohol decreased some of the deviation for the nearest stimulus, reducing the deviation down from a maximum of 135 to a maximum of 115. This is likely due to the fact that participants have little to no information, and the alcohol reduces the utility what little remnants of visual cues were still available. Therefore, intoxicated participants are more likely to bias their judgments more conservatively (Gogel, 1969, 1972, 1978; Gogel & Tietz, 1973), resulting in the least variation from the standard distance. In all conditions, participants remain conservative in their guesses and deviate from the standard distance by relatively small amounts. Regardless of cues available, participant guesses, on average, tend to only be about 60cm away from the standard at any given distance. These findings suggest that the SDT (Gogel, 1969, 1972) and the Contraction Bias (Gogel & Tietz, 1973; Gogel, 1978) are occurring in the intoxicated condition as well and influencing participant absolute deviation scores similarly to how these biases influenced these participants in the sober condition of Experiment 1.

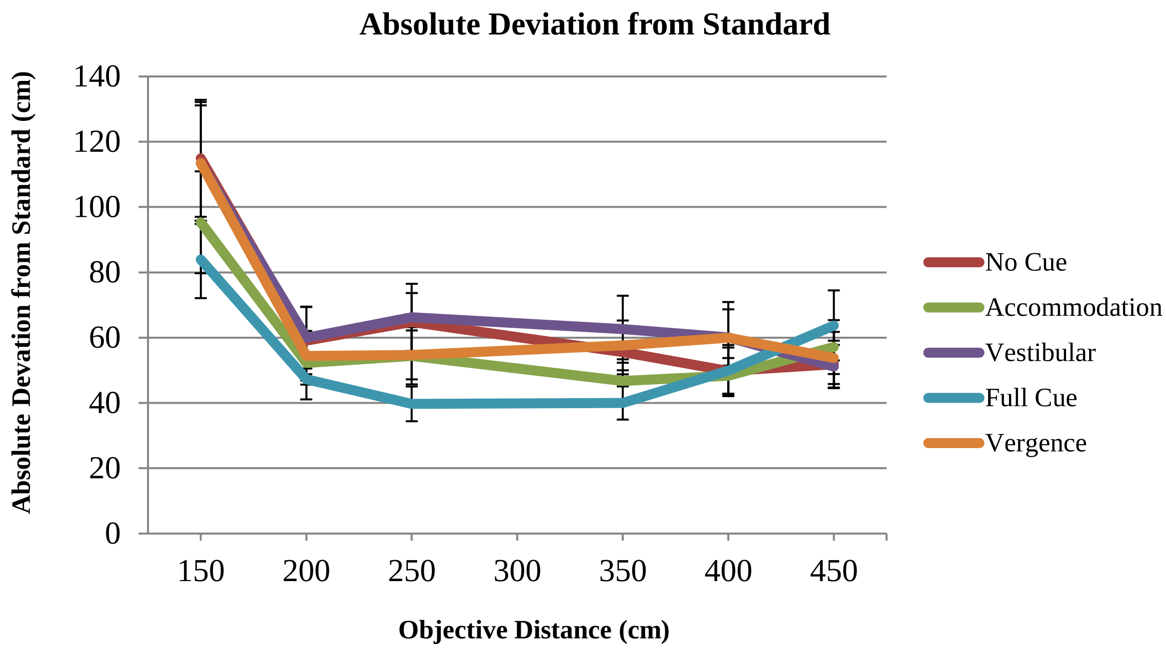


Figure 23. Average absolute deviation from standard. Comparison of the average absolute deviation from the standard stimulus in all viewing conditions. The same overall trend is occurring in the data of each viewing condition, with participants deviating little from the standard distance. This evidence suggests that participants are remaining conservative with distance estimates when she/he has few visual cues to rely upon, as is seen in the No Cue condition. The same pattern is true for conditions in which visual cues are available, suggesting that participants are either unable to use the cues provided or the visual cues are degraded and are no longer useful to complete this task as a result of the alcohol ingestion.

Distance Sign

The fourth comparison investigated the average distance sign accuracy for all viewing conditions. The comparison of distance sign is an important one, as it shows whether or not participants are able to accurately determine whether the stimulus they are viewing is nearer to them or farther from them than the standard stimulus they saw immediately prior. Figure 24, below depicts the overall distance sign accuracy for far stimuli and near stimuli in each viewing condition for participants in Experiment 2.

Overall, participants were more accurate at determining the distance sign of the far stimuli than the distance sign of the near stimuli. In every viewing condition, participants were better able to accurately detect a far stimulus than a near stimulus. Participants were above chance for far stimuli (average=62%, SE= 0.06), but were below chance for near stimuli (average =32%, SE=0.06) in all viewing conditions.

Participants in the Full Cue condition answered correctly 74% of the time (SE=0.042) for far stimuli and answered correctly 48% of the time (SE=0.077). This condition was the best for distance sign accuracy for both near and far stimuli. Participants in the singular-cue visual conditions did similarly to the Full Cue condition for far stimuli, with Vestibular and Vergence correctly identifying an average of 64% of the far stimuli (SE=0.061), but worse than the Full Cue condition for the near stimuli, answering an average of 30% (SE=0.06) of near stimuli. In the Accommodation condition, participants were able to correctly identify 35% of the near stimuli (SE=0.06), which was better than the No Cue condition, in which participants were only able to identify 18% of the near stimuli (SE=0.03). However, the participants within the Accommodation condition did slightly worse at identifying far stimuli (average=54%, SE=0.07) compared to the participants in the No Cue condition (average =55%, SE=0.06).

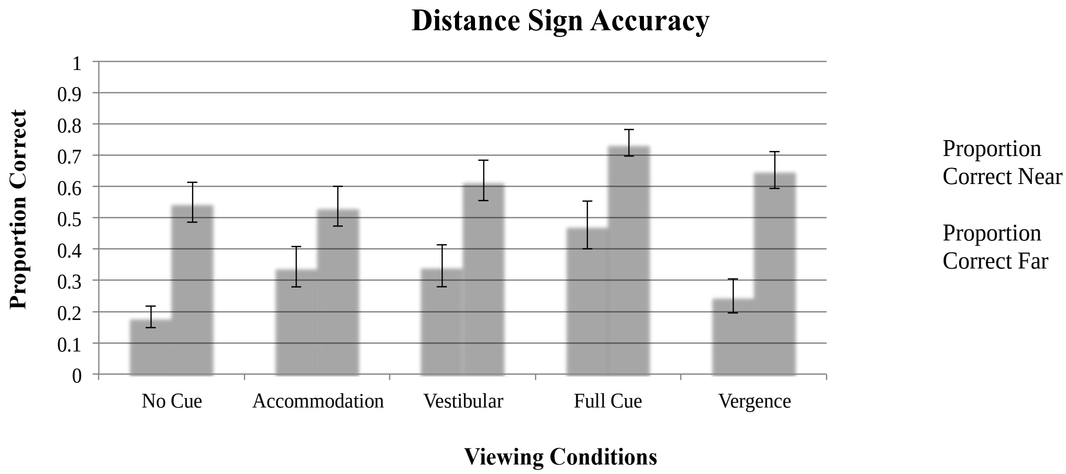


Figure 24. Distance Sign Accuracy. A comparison of the accuracy of distance sign between participants in the five viewing conditions. The Full Cue condition allowed participants to be the most accurate in reporting distance sign for both near and far stimuli. The reduced-cue conditions of Accommodation and Vestibular cues lead participants to make similar reports of distance sign for near and far stimuli. The Vergence viewing condition allowed participants to be more accurate for far stimuli, but less accurate for near stimuli. During the No Cue condition, participants had less visual information than other conditions, which decreased their ability to accurately report whether the experimental stimulus shown was nearer to or farther than the standard stimulus, particularly for the near stimuli.

The next investigation compared the change in the average distance sign accuracy from the sober condition to the intoxicated condition. The changes in distance sign accuracy occurred in every viewing condition for both near and far stimuli. Participants in the sober condition were better able to correctly identify distance sign than those in the intoxicated condition. In the intoxication condition, particular decrements occurred to the Accommodation condition, in which the far condition was reduced, the Vestibular condition, in which the far condition was reduced, and both the far and near conditions in the Full Cue condition were reduced with the introduction of alcohol. Further statistical investigation of distance sign accuracy was conducted in the Depth Sign Discrimination Index section, next.

Depth Sign Discrimination Index

Finally, DSDI values are again calculated for each participant in each viewing condition and averaged together. A reminder to the reader, a DSDI value is computed in order to determine if participants are biased in any way and to have a quick overall measure of their distance sign accuracy. A DSDI value was calculated for each participant for each viewing condition. Recall that a large positive DSDI value indicates a participant made accurate distance sign estimations with little variation. A large negative DSDI value indicates that a participant mistakenly perceived far stimuli as near and near stimuli as far with little variation. A DSDI value of near zero indicates that participants were near guessing accuracy of 50% for distance sign estimation with a moderate amount of trial-to-trial variability. Table 11, below, shows the DSDI values calculated for each intoxicated participant in each viewing condition, averaged together.

Overall, the DSDI values were very near zero or negative numbers, with the exception of the Full Cue condition. This indicates that participants struggled with distance sign accuracy for all viewing conditions, with the exception of the Full Cue condition. The Full Cue condition has a positive value, indicating that participants in the Full Cue condition were able to complete the task and accurately determine distance sign when presented with a stimulus in Experiment 2. The No Cue condition has a negative value, indicating that participants in the No Cue condition struggled to complete the task and accurately determine distance sign. Each of the single cue conditions are negative and relatively near zero. This indicates that participants struggled in these conditions and had a medium amount of variability in their distance sign accuracy.

Table 11

Average DSDI Scores

Viewing Condition	Average DSDI Score	Standard Error
No Cue	-0.263	0.245
Accommodation	-0.102	0.336
Vestibular	-0.015	0.403
Full Cue	0.282	0.455
Vergence	-0.098	0.375

Average DSDI Value per viewing condition under the influence of alcohol. Participants in all viewing conditions have problems accurately determining distance sign of stimuli and have moderate deviation in their responses, creating DSDI values that are negative or near zero, with the exception of the Full Cue condition.

Again, the best way to depict DSDI is by graphing the raw DSDI scores and observing patterns among and between the different viewing conditions. Figure 25, below, shows the individual DSDI for each participant for all five of the viewing conditions.

DSDI scores for participants in the No Cue condition are clustered between 0 and -0.5, indicating that participants struggled in the No Cue condition and had a moderate level of variability in their responses. Participants in the Vestibular, Accommodation, and Vergence conditions had DSDI values that ranged more widely between -1 and +1. This indicates that there was variability in the sample, with some participants doing well in these singular cue conditions, and others doing more poorly. DSDI scores for participants in the Full Cue condition are clustered around +0.5, indicating that the Full Cue condition was the easiest condition for participants to determine the distance sign. Specifically, participants in the Full Cue condition had DSDI values that were more accurate than the values in the No Cue condition $t(19) = -4.913$, $p < 0.000$; the Accommodation condition $t(19) = -3.462$, $p = 0.003$; the Vestibular condition $t(19) = -2.597$, $p = 0.018$; and the Vergence condition $t(19) = 3.751$, $p = 0.001$.

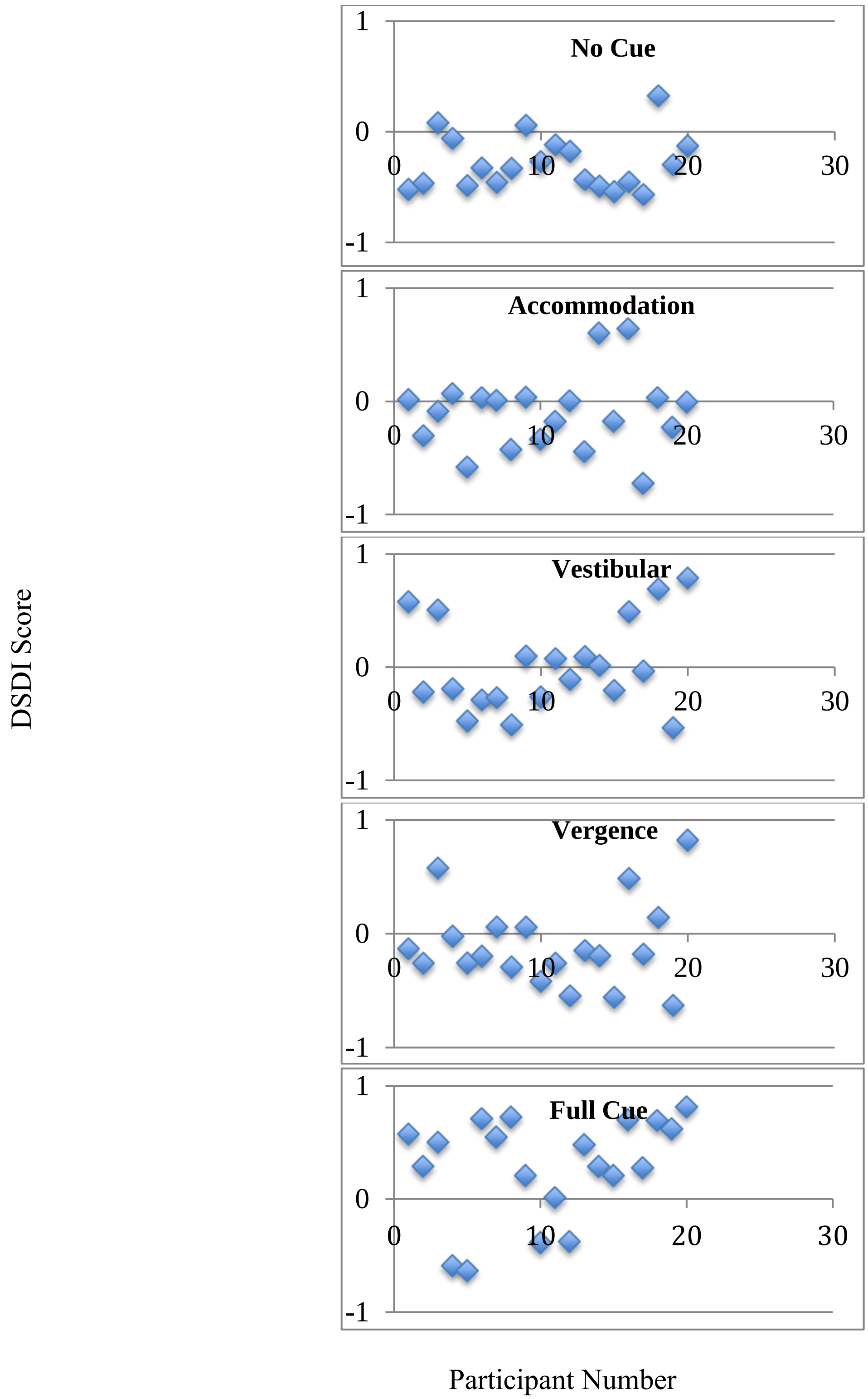


Figure 25. DSDI comparison. For all five viewing conditions, the DSDI scores are shown along the y-axis, and the participant numbers are shown along the x-axis.

A comparison of Table 9 to Table 11 will help the reader to determine how the alcohol influenced the participant DSDI values. Simply put, the DSDI values in the sober conditions were less negative than the DSDI values in the intoxicated condition. Alcohol had a tuning effect on the DSDI, that is, the addition of alcohol turned down the discrimination abilities of participants regardless of the viewing condition. For example, in the sober condition, Full Cue DSDI scores were 0.508 (SE= 0.082), however, in the intoxicated condition, Full Cue DSDI scores were 0.282 (SE=0.455). These differences are statistically significant, $t(19) = 3.258$, $p = 0.004$. Another example involves the No Cue condition. In the sober condition, No Cue DSDI scores were -0.095 (SE=-0.056), however, in the intoxicated condition, No Cue DSDI scores were -0.263 (SE=0.245). These scores were also significant, $t(19) = 3.211$, $p = 0.005$. Alcohol diminished the sensitivity of depth sign in each of these two conditions, but alcohol did not significantly change the sensitivity of single-cue viewing conditions, as all p-values > 0.05.

DSDI Correlations

It may be of interest to investigate whether a correlation exists between any of the DSDI scores for each of the viewing conditions. If a correlation was found, it could mean the internal physiological cues available in some viewing conditions are also being utilized in other viewing conditions, and therefore the DSDI scores for the two different viewing conditions would yield a high Person's r. For a one-tailed test, and n-2 degrees of freedom (18), the r-critical value of the Correlation Coefficient is 0.378. Correlation coefficient values of r, greater than 0.378 are significant at the alpha=0.05 level. These values have been bolded in Table 12, below.

Table 12

DSDI Correlation Table

	No Cue	Accommodation	Vestibular	Vergence	Full Cue
No Cue	1	0.16155154	**0.41022751**	0.37702951	0.00625349
Accommodation		1	**0.42226392**	0.37943417	0.23594617
Vestibular			1	**0.76025025**	**0.41301068**
Vergence				1	**0.41482426**
Full Cue					1

Pearson’s r values resulting from correlations between each viewing condition.

Significant DSDI correlations exist among some of the visual conditions in the intoxicated condition. For example, the Vergence condition and the Vestibular condition are highly correlated. Both of these cues require eye movements, which may be a reason they are correlated. Full Cue and Vergence are also correlated. The relationship among these two viewing conditions could be a result of Vergence being available in both conditions. Full Cue and Vestibular are also correlated. These two viewing conditions may be correlated for the same reason as just mentioned- the Full Cue condition contains Vestibular cues, leading them to have a similar relationship. There are also two remaining significant correlations, that between the No Cue condition and the Vestibular condition, as well as the correlation between the Vestibular condition and the Accommodation condition.

Discussion

Overall, the results of Experiment 2 show that alcohol negatively affects distance estimation abilities by eliminating the efficacy of the vergence cue, the accommodation cue, as well as the vestibular cue. Regardless of analysis or viewing condition, participants performed worse in the alcohol condition than in the sober conditions. Specifically, the results indicate that participants who are in viewing conditions that are reliant upon either accommodation, vergence, or vestibular cues perform poorly, closely mirroring the No Cue condition. Alcohol has been shown in previous studies to potentially impair the ability of the eyes to make accurate vergence eye movements, to interfere with the workings of the inner ear leading to consequences in the vestibular system, as well as slowing accommodation. In Experiment 2, the viewing conditions that rely on vergence, such as the Vergence and Full Cue conditions were negatively affected by shortening the farthest estimations toward the midpoint and also by elongating the shortest estimations toward the midpoint. Alcohol was also shown to impair participant performance on conditions that rely on accommodation, such as the Accommodation viewing condition and the Full Cue condition. Previous studies have shown that accommodation becomes erratic under the influence of alcohol, and may interrupt accommodation in some cases by not maintaining focus and in other cases by focusing the eye nearer than the stimulus. Both accommodation and vergence eye movements were negatively affected by alcohol, resulting in decrements in participant performance on the distance estimation tasks. The vestibular cue has also been shown to be susceptible to alcohol, and in the current experiment, was also decreased as an effective cue to distance estimation as a result of participant ingestion of alcohol.

Another overall finding is that the Full Cue condition outperformed all three single cue conditions, and the No Cue conditions on nearly every single analysis. Similar to the results in Experiment 1, it appears that multiple cues, or cues in combination with one another are required for participants to perform well on distance estimation tasks, as well as under the influence of alcohol. In addition, the analysis of distance sign accuracy showed that like sober participants, intoxicated participants were better able to detect far stimuli rather than near.

DSDI values for individual viewing conditions were attenuated by alcohol. The DSDI acts as a sensitive measure of participant perception of distance sign. Alcohol tuned the DSDI downward in all viewing conditions, making values that were positive in the sober condition, near zero or negative in the intoxicated condition. This change in participant DSDI scores indicates a struggle in discrimination of distance sign under the influence of alcohol. It is important to note here that alcohol did not wipe out the sensitivity of the DSDI completely, but rather turned down the sensitivity.

Likely, the fact that Accommodation, Vergence and Vestibular cues are affected by alcohol lead participants to struggle in the visual conditions during the intoxicated conditions. It was only when these cues could be combined together that participants did better on distance estimation tasks. This indicates that alcohol may affect all three of these cues, making a No Cue condition nearly impossible and a Full Cue condition, which is made up of these individual cues working together, the best option possible to complete with accuracy.

EXPERIMENT THREE: INVESTIGATING THE EFFECT OF TRAINING ON DISTANCE ESTIMATION

Distance estimation is a perceptual task that our brain accomplishes automatically. Knowing how near or how far away objects are informs the small and large motor outputs required to act on the objects surrounding us. Whether while walking, grasping a coffee cup, gazing out the window of the office, or driving an automobile, the brain is constantly using visual cues to determine the distance of objects within in the 3D environment and preventing one from colliding with these objects. This perceptual task is completed without conscious awareness, making the mechanisms controlling the perception somewhat mysterious.

Literature Review

Early attempts to determine which cues were important for absolute distance estimations were conducted within the laboratory. Dees (1966), attempted to test distance estimation using a motion-picture stereoscope under three different viewing conditions: stereopsis alone, stereopsis with motion parallax, and motion parallax alone (via simulated head motion). A motion-picture stereoscope is a device that projects a film image to each eye, creating a sense of depth through stereopsis. In the stereopsis alone condition, participants were allowed to view the stimuli with two eyes, in the motion parallax alone condition, participants were allowed to view the stimuli with one eye covered and "simulated head movements" recorded in the film were viewed. In the combination condition, both stereopsis and motion parallax were used together, and the "simulated head movement" films were viewed with two eyes. Participants were to order the stimuli in order from 1 (closest) to 10 (farthest) immediately after viewing. A training session was conducted prior to the experiment whereby participants were given immediate feedback of the true rank of the stimuli presented immediately prior. After a 5-minute break, participants were shown the same stimuli again in a randomized order and were asked again to rank the stimuli. The results of this study indicate that participant accuracy levels were the best for the stereopsis plus motion parallax viewing condition, but that participants who underwent training for the motion parallax condition alone were also accurate at this absolute distance task.

There are many problems with the experimental design of Dees, which likely lead to the mistaken assumption that motion parallax is a visual cue that can be utilized for absolute distance estimations. The first is that Dees does not present any pre-training data, only post training data, so it is unclear how accurate participants were prior to doing any training in his experiment. Secondly, looking at a film to determine absolute distance does not directly translate to "real life" distance estimation, so it is difficult to determine the reasoning behind using film as a stimulus. Dees was also negligent in controlling other cues to distance such as brightness and relative size. Finally, simulated head movements do not act in the same way that real head movements do, namely eliciting vestibular cues to the brain, and were not cross-validated, therefore it is not certain the eyes act in the same way when viewing a real stimulus as they do on film. These flaws are fundamental, but unfortunately, lead to further research.

Ferris (1972) was interested in furthering the laboratory findings of Dees (1966), but rather than using "simulated head movements," Ferris was interested in eliciting motion parallax signals via actual head movement (and compensatory eye rotation). Ferris used a baseline, training, and testing experimental procedure, with 10 stimuli located between 4 and 15 feet and two different groups of participants who viewed two different backgrounds of the viewing apparatus. The first was a plain background and the second was a checkered background, the latter instituted to help participants in the motion parallax condition. During the training session, participants were shown stimuli at some of the different distances and given immediate feedback as to the actual distance the stimulus was located from her/him. Also during the training period, the participants in the motion parallax condition were informed about the relative movement of their head from side to side eliciting “more” cues to absolute distance if the participant paid attention to the apparent motion occurring in the foreground and background relative to the fixation. The results of the first experiment revealed that participants were better at estimating absolute distance under monocular viewing conditions when they were allowed to move their head left to right (motion parallax condition) when compared with participants estimating distance with their head stationary (stationary monocular viewing). Unlike Dees, Ferris kept brightness, retinal size, and height in the visual field constant in all of his experiments. In a second experiment, the training procedure was repeated but participants were not informed of additional information about the relative movement of foreground and background with regard to fixation, but were again given training on some of the stimulus distances used in the testing phase of the experiment. Two groups both making head movements (motion parallax viewing conditions) saw the silhouettes placed in front of either the white or textured background. The results of the second experiment showed that participants were better able to make accurate estimations with the textured background (hinting that the diverse background increased participant awareness of the relative motion). In a final experiment, Ferris added a strip nearer than the fixation point, a near reference directly in front of half of the participants, which was meant to increase participants’ notice of the perceived movement of objects relative to the fixation stimulus. The other half of participants did not have a near reference. Both sets of participants had white backgrounds during this experiment. First, participants were tested on their absolute distance estimation in a stationary head condition with a plain background. Then training using head movements was done, followed immediately by testing with head movement.

The results of the third experiment found that participants without head movements did not perform well regardless of the near reference. However, in the motion parallax condition in which participants were again trained and attention drawn to the relative movement of objects, both the near reference conditions and plain background participants performed very accurately. Though Ferris produced many publications in the early 1970s, many of the experiments, like those described above, contained flaws, which confused the conclusions.

Ferris felt that informing participants about the relative motion of the foreground and background of the stimuli during training would help to improve participant absolute distance estimation. In any condition of everyday life during which the observer or the stimulus window are translating, motion parallax information is being elicited and utilized by the brain. Informing participants about this cue likely did not help improve their absolute distance estimation, but rather, likely elicited their use of other, non-controlled visual cues. For example, participants reported that stimulus size appeared to be different at different distances, though the research team allegedly accounted for that cue by displaying different sized targets at the varying distances. In addition, the stimulus window used was a near target reference even before the third experiment was conducted, giving participants even more movement in their field of view in motion parallax conditions. Finally, Ferris did not rule out that vestibular signals were being elicited by the brain in the head movement conditions, and therefore the effects found in the motion parallax condition could have been from vestibular cues or other visual cues and not from motion parallax information. Finally, training participants and testing them in one condition and then re-training them in another condition using the same apparatus with distances within 20 feet informs participants of the parameter limitations, and therefore could inform any subsequent guesses. In the third experiment, the same group of participants were already very well trained and had been given feedback twice prior to the final test in the motion parallax condition. First participants were trained and then tested in the stationary monocular condition, and then trained and tested in the motion parallax condition. These participants had already viewed three variations of five stimuli within 20 feet of them prior to final testing in the motion parallax condition. Without counterbalancing the two conditions, unsurprisingly, better accuracy was achieved in the movement condition than the initial monocular stationary condition. The effects of training in this experiment are rampant and make it difficult to evaluate the conclusions of these sets of three experiments.

It is not entirely known which visual cues are being acquired and utilized as the eyes scan a scene to determine the distance of objects. This is a complex process confounded with many visual cues of different types- physiological, stimulus-based, and environmental. The result is that only careful and systematic isolation of individual cues will be able to help discern the answer for which cues are important for estimating absolute distance accurately. Previous research by this author in Experiments 1 and 2 have determined that physiological cues created by the movements of the eyes are important for accurate distance estimation under impoverished visual conditions. Previous research by others in the field, however, has suggested that merely training participants to use motion parallax visual cues, naturally occurring as they move through an environment, increases accuracy for absolute distance estimation. The problem with these suggestions is that geometrically, motion parallax cannot provide absolute distance estimation. In addition, previous studies have not been conducted in visually rich and complex environments, and distances of greater than 20 feet have not been evaluated.

The effect of training on the increase in accuracy in all viewing conditions is not surprising, as the effect of training produced a small impact on even monocular stationary viewing in previous research. The question of how much feedback improves accuracy is of interest to the present research due to the fact that participant accuracy consistently increased with training in both of the above experiments, leading researchers to conclude that motion parallax can be an effective cue to absolute distance. The goal of experiment three is to determine how training affects absolute distance estimation under three different viewing conditions. To extend the findings past those of previous studies, distances larger than 20 feet will be examined and the experiment will be conducted outside the laboratory in a real-world 3D environment. Previous research provides little ecological validity, as all research was conducted under "tightly" controlled conditions. A supplementary goal of experiment three is to be able to determine how individuals perceive distance in a natural environment.

Method

Observers

Forty-five participants over the age of 18 with normal or corrected to normal vision were asked to participate in the following proposed experiment. Twenty-six women and 19 men (Mean age: 20.28 years) were recruited to participate. Each participant was recruited through Sona-System, an online sign-up system for undergraduate students in psychology courses to read equitable recruitment postings and participate in ongoing psychological research at NDSU. Each participant was compensated with extra credit in the psychology class of her/his choice. For every 15 minutes of participation, one extra credit point was awarded, which is a psychology department standard. Prior to acceptance into this experiment, the visual functioning of each participant was assessed and met specific criteria. These criteria consist of scores better than 20/60 (6/12) on the Snellen visual acuity chart (Graham-Field, Atlanta, GA), and better than 1/35 on the Pelli-Robson Contrast Acuity chart (Haag-Streit, Essex, UK). Participants not meeting these visual criteria were excluded from participation.

Stimuli

In order to investigate the effect of training on distance estimation abilities, participants were outdoors viewing 30 specific and predetermined real-world 3D stimuli and physical landmarks on the NDSU campus. These stimuli consisted of naturally occurring objects, such as trees, as well as man-made objects such as garbage cans, bus stations, signs, stairs, doorways, etc. (Table 13). All stimuli were viewed from predetermined locations, at distances carefully measured from each stimulus in advance. The stimuli selected for this experiment are listed in Table 13, below. Each participant viewed the same 30 stimuli in the same order as they are listed in the table, regardless of the random assignment of participants into different viewing conditions. The actual distance of each of the stimuli from the viewing locations is also listed in the table (in yards). Additionally, the stop location and whether or not feedback was given to the participants on each particular trial is also indicated on the table, filling this table with all of the important parameters of Experiment #3.

Unlike Experiments 1 and 2, where every attempt was made to remove or isolate every cue to distance, this experiment has many visual cues available to participants, while specifically controlling some physiological cues. All visual cues possible for participants to use are listed in Table 14, below. Some visual cues that were not be available are retinal projection, due to the fact that all stimuli are stationary. Height in the visual field was also controlled by instructing participants to indicate the distance from her/himself to the base of the stimulus indicated by the experimenter. The base of all of the stimuli is the ground, and therefore though the height of the actual object may vary widely (a tall tree compared to a garbage can), participant focus and distance estimation will be to the base of each stimulus.

Table 13

Important Parameters of Experiment 3

Stop Number	Stimulus	Distance (In Yards)	Feedback Given?
1	1.) Lamp Post	16	No
1	2.) Minard Hall Dedication	23	No
2	3.) Fire Hydrant	38	No
2	4.) Cement Railing on Askanese	76	No
3	5.) Stop Sign	46	No
3	6.) Blue Emergency Light	52	No
4	7.) Drain Pipe on Old Main	90	No
4	8.) Garbage Can	7	No
5	9.) Garage Door Window	82	No
5	10.) Green Electrical Box	69	No
6	11.) Light Pole	17	Yes
6	12.) Back of stop sign	81	Yes
7	13.) Skinny Tree	24	Yes
7	14.) Vice President Parking Sign	57	Yes
8	15.) Second Parking Pole	5	Yes
8	16.) Federal Vehicles Sign	79	Yes
9	17.) C-Lot Staff Parking Sign	39	Yes
9	18.) Ladd Hall Black Door	62	Yes
10	19.) No Parking sign	46	Yes
10	20.) Garbage Can	95	Yes
11	21.) FLC Dedication Plaque	50	No
11	22.) Light Pole on Blvd	32	No
12	23.) Corner of Geosciences	16	No
12	24.) Engineering Sculpture	72	No
13	25.) Campus Map Sign	66	No
13	26.) Garbage Can	47	No
14	27.) Bus Stop Edge	85	No
14	28.) Morrill Hall Sign	99	No
15	29.) Garbage can	21	No
15	30.) Large tree	7	No

Description of important parameters of Experiment 3. A description is given of the stop location, stimulus, objective distance from participant, and whether or not feedback was given during that trial. Note: Stimuli 1-10 are located within the distances of 5-100 yards, stimuli 11-20 are located within the distances of 5-100 yards, and stimuli 21-30 are located within the distances of 5-100 yards.

Table 14

Available Cues in Experiment 3

Visual Cue to Distance	Natural Occurrences
Arial Perspective	Far stimuli may appear to have a more similar contrast to the background, may appear to have less contrast in the details of the stimulus itself, and may even appear bluish or less saturated in color.
Sharp Focus/Blur	Near objects are more sharply in focus while farther objects tend to have less distinct features, and appear blurrier.
Definition & Textures	Near objects are more clearly defined and appear texturized, whereas distant objects have less distinct features and a more uniform texture in appearance.
Shadows	Many shadows will occur in the environment, indicating to participants not only where the light source is but perhaps how far away the stimulus is located.
Relative Size	Objects will vary greatly in size.
Brightness	Participants will be ushered around campus at many different times of the day dependent upon availability of the experimental team. Brightness will be allowed to vary naturally among participants and among viewing conditions.
Familiar Size	The size of these objects should be highly familiar to participants, as they pass by these objects many times per day.
Eye Level	Near objects will cast the eyes downward, and far objects will keep the eyes at or above resting eye level.

Environmental, stimulus-based, and one physiological visual cue that are available to participants during experimental trials in Experiment 3. In direct contrast to Experiments 1 and 2, all of these visual cues were available and no attempt was made to control them.

Procedure

Participants entered the laboratory and signed a consent form. At this time, the participants had their visual acuity and their stereo acuity checked by a member of the experimental team. After passing the vision exams, the participant and the experimenter exited the laboratory and walked out the east-facing doors of Minard Hall toward the first stop location.

The experimenter held an I-pad to record the verbal distance estimations of the participants. The I-pad contained an app called, Presentation, (Neurobehavioral Systems Inc., Albany, CA) that not only records verbal distance estimations, but also contained a route map and stopping locations clearly pictured in order to decrease confusion on the part of the experimenter. A mock-up of the I-pad used by the experimenter is shown in Figure 26. It was the job of the experimenter to lead the participant around a predetermined route located on campus and ask the participant to estimate the distance to each of the various landmarks serving as stimuli for this experiment. These stimuli and their objective distance, in yards, are conveniently listed for the reader's reference in Table 13.

The task of the participant was to estimate the distance from their physical body to the stimuli pointed out to them by the experimenter (absolute distance) in yards. Yards were selected for the measurement increment for this experiment due to undergraduate familiarity with the non-metric distances. With the help of the experimenter, participants stopped around the campus at precise locations indicated by dark numbers drawn on the sidewalk and made absolute distance estimations to two different stimuli at each location prior to moving to the next location. It is important to note that the participants were stationary (but see Monocular Viewing condition, below), and not walking or moving while they made their estimations. Additionally, the first stimulus was located roughly 180 degrees away from the second stimuli location. Simply put, the participant made a half turn to view the second stimuli at each location. The reason this protocol was implemented was so as to not influence the distance estimations given by the participant. Participants would be able to adjust their second estimation in accordance with their first estimation if both stimuli were located in the same field of view, depending on if this second stimuli was nearer or farther from the participant than the first stimuli. This type of task would be an example of a relative depth task, not an absolute distance task, and therefore having a new field of view for every estimate was carefully worked through in the stimuli selection process.

Figure 26. Experimenter’s I-pad for Experiment 3. The I-pad was used for recording participant absolute distance estimations at each stopping point. The map on the top center depicts with a red X stopping point #6, located near the babbling brook on the NDSU campus. Stimulus number 12 is the yellow dot on the map to the left of the red “X”. A photo of that stimulus is also shown on the lower left corner of the I-pad screen. The participant guessed a distance (in yards) of how far away the lamppost resided and the experimenter recorded this value using the numbers located in the center of the I-pad. The number 17 appeared after the entry, which is the actual distance from the participant to the lamppost. This number appeared to alert the experimenter to provide actual feedback to the participant in this trial. Next, the experimenter asked the participant to turn 180 degrees to their right and estimate the distance to the back of the stop sign depicted as the yellow dot on the right side of the map, as well as circled in the photo in the lower right. The process was then repeated, the answer recorded, and feedback given.

To review, there are 15 stops along a predetermined path on campus, and each participant stopped at the same 15 stops. With the help of the experimenter, the participant made distance estimations to each stimulus assigned to the stop, then turned 180 degrees, made another distance estimation to a second stimulus, and then continued to the next location.

At the first five stops (10 distance estimations) the participant did not receive feedback; the experimenter simply recorded their estimations. This portion of the experiment was considered the baseline. During the second five stops (10 distance estimations) the experimenter provided feedback to the participant immediately after she/he verbalized a distance estimate, so this portion of the experiment was considered the feedback portion of the experiment. During the remaining five final stops (10 distance estimations), no feedback was given, and the experimenter again, simply recorded the estimations. This portion of the experiment was considered the test. Unknown to each participant, at each of the five stops, the distance that each stimulus could reside is between 5 and 100 yards (see Table 12). These distance parameters were selected so as to not induce ceiling effects on the accuracy of the participants after they are given feedback. As stated in the introduction, with only 40 options of distances, it may be easier to guess the correct distance, without actually using the visual cues afforded to a participant. In this experimental design, there are over 100 possible answers (in yards) for the distance to each of the stimuli, increasing the possibility of variation among estimations. Once the participant walked to all 15 locations and estimated the distance to all 30 stimuli, she/he returned to the lab with the experimenter and was compensated for her/his time participating in the experiment, which lasted in total ~45 minutes.

Conditions

Each participant was placed into one of three predetermined viewing conditions prior to participating in the experiment. The three viewing conditions are Binocular Viewing, Monocular Movement, and viewing through Night Vision Goggles. These viewing conditions coincided with conditions from Experiments 1 and 2, namely that the binocular viewing condition was considered a Full Cue condition, the monocular movement condition is considered a Vestibular and Accommodation condition, and the night vision goggles condition was considered a No Cue condition. Each viewing condition and the associated physiological visual cues available or absent are succinctly summarized in Table 14, below. When participants left the lab with the experimenter at the beginning of the study, participants viewed each stimulus with two eyes available, one eye available and the other patched with an eye patch, or through night vision goggles.

Table 15

Cues Available by Viewing Condition

Viewing Conditions:	Visual Cues Available:		
	Accommodation	Vergence	Vestibular
Binocular Viewing	Yes	Yes	No
Monocular Movement	Yes	No	Yes
Night Vision Goggles	No	No	No

Physiological visual cues were available or absent in each viewing condition of Experiment 3.

Binocular viewing

In the binocular viewing condition, participants were able to view each stimulus with both eyes. This condition had the available visual cues of accommodation and vergence, but participants were viewing the stimuli at each location while standing stationary. Therefore, participants in this viewing condition were not eliciting any movements during the distance estimation task and did not be create any vestibular cues.

Monocular movement

In the monocular movement condition, participants were able to view each stimulus with only one eye. Participants were allowed to sway side to side laterally at their own comfortable pace in order to elicit vestibular cues while viewing the stimuli and estimating each distance. In doing so, participants elicited very clear relative depth percepts. Since one of the eyes were patched, participants in this condition did not have the physiological cue of vergence but accommodation from the unpatched eye was available, as were vestibular cues created from the head movement and compensatory eye movements.

Night vision

In the third condition, participants viewed each stimulus through Morovision MV/PVS-7 Night Vision Goggles (see Figure 27). As seen in Figure 27, night vision goggles differ in appearance in a variety of ways from a more familiar form of goggle, binoculars. First, night vision goggles have a single input and two outputs, whereas binoculars have two inputs and two outputs. Secondly, night vision goggles project the entire field of view on a high-resolution screen projected in monochromatic green inside the device in front of two output goggle lenses. This means that viewing through the night vision goggles eliminates accommodation cues as well as vergence cues. In contrast, binoculars have two inputs and two outputs and must be manually focused while providing vergence cues for fixation. Participants viewed the stimuli in this viewing condition while stationary and were not moving; therefore no vestibular cues were elicited.

Figure 27. Morovision MV/PVS-7 Night Vision Goggles. These goggles were utilized in one viewing condition of Experiment 3. If used while standing stationary, night vision goggles eliminate the physiological cues of vergence, accommodation, and vestibular cues.

Design and Data Analysis

The design of this experiment is a between subjects experimental design, where participants viewed stimuli in one of three viewing conditions. The experimental design is one such that accuracy increases in any of the viewing conditions informs the researchers which cues are being utilized. It must be stated that there are a number of uncontrolled cues in this experiment, compared to the previous two experiments, however, nearly all physiological cues were be kept controlled, thus enabling one to draw conclusions about differential cue utilization if there were significant differences in participant accuracy. As well, the use of feedback for training is the only variable that will be changing from the second 10 estimations to the third 10 estimations. This design will help to determine whether or not participants are utilizing the feedback information and applying it to new estimations. That said, the following information should be kept in mind by the reader as a reference frame for all subsequent investigations: if participants in the binocular cue condition are the most accurate, accommodation and/or vergence are the visual cues being utilized. If participants in the monocular cue condition are the most accurate, accommodation and/or vestibular cues are the visual cues responsible for distance estimation accuracy. Finally, if participants in the night vision goggles condition are the most accurate, vergence, accommodation, and vestibular cues are not helpful in a distance estimation task in a real world, 3D environment. Similarly, if participant averages for the first 10 distance estimations are the same as or more accurate than participant averages for the final 10 distance estimations, there is no effect of feedback. Conversely, if participant averages for the first 10 distance estimations are less accurate than participant averages for the final 10 distance estimations, there is an effect of feedback.

Results

Subjective Distance Estimations

To begin, the average subjective distance estimations will be compared to the objective distance estimations. Participant distance estimation accuracy was investigated similarly to data collected inside the laboratory for Experiments 1 and 2. First, the overall average subjective distances will be compared with the objective distances for each participant in each viewing condition. The size of the error between the objective and subjective estimates is an indication of accuracy, with the smaller space between the objective and subjective estimates indicating less accuracy than a larger space. Figure 28, below, depicts the objective distances compared to the average subjective distance estimations for all three viewing conditions for all 30 stimuli.

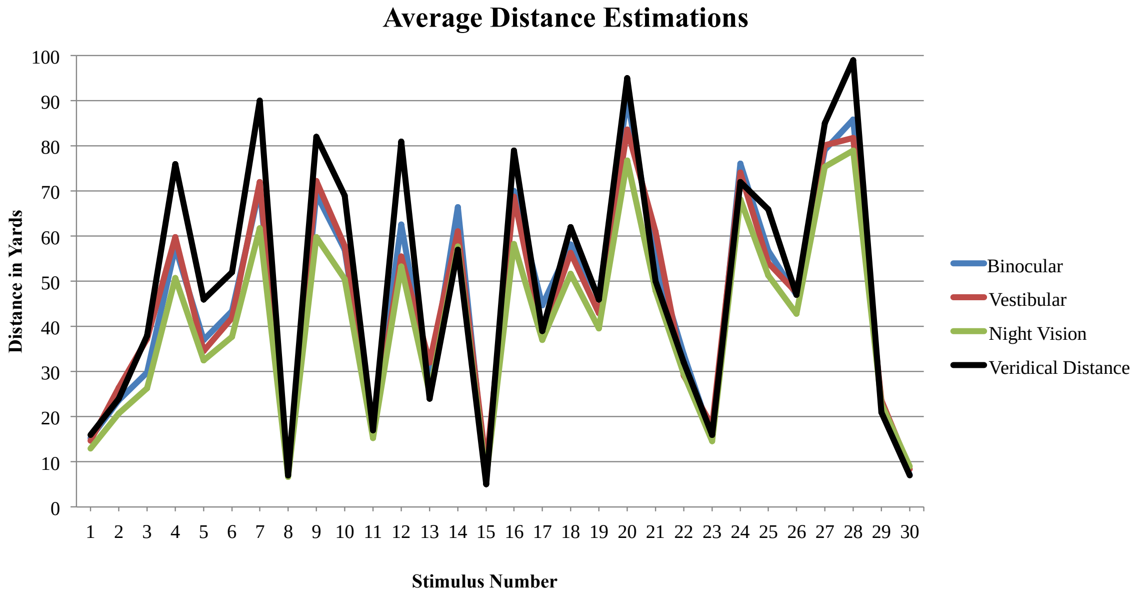


Figure 28. Average distance estimations. For each stimulus in each viewing condition, the average distance estimations are compared to the objective/veridical distance. For nearly every stimulus, the binocular condition was the most accurate, followed by the vestibular condition, and finally the night vision condition.

Overall, as this graph shows, participant distance estimation accuracy is overall relatively accurate in all three viewing conditions. The accuracy appears to be the best for the binocular viewing condition, followed by the monocular viewing condition, and finally the night vision viewing condition. The individual physiological cues helped, but the Night Vision goggles condition did almost as well, indicating that observers could be using a variety of other, pictoral depth cues, and not just the physiological ones. In short, the physiological cues did help, but the results in the night vision goggles condition show that it is possible to also use other cues to do the task. Interestingly, very few stimulus locations were overestimated, as it appears that most participants underestimated the actual distance to the stimuli. This fact is particularly true with most of the green lines in the night vision condition considerably under the objective distance. The night vision condition was void the physiological cues of accommodation, vergence, and vestibular, which is why it is likely more variable than the other two conditions.

Absolute Deviation from Objective

Next, the absolute deviation for the subjective estimates was computed. Each participant's subjective distance estimations for each of the 30 distances were subtracted from the objective distances of those stimuli in order to yield a deviation score. The absolute value of this score will be taken in order to improve comparisons between participants, and to determine how much total deviation existed between participants in each viewing condition. Figure 29, below, shows the average absolute deviation participants made in each viewing condition (in yards).

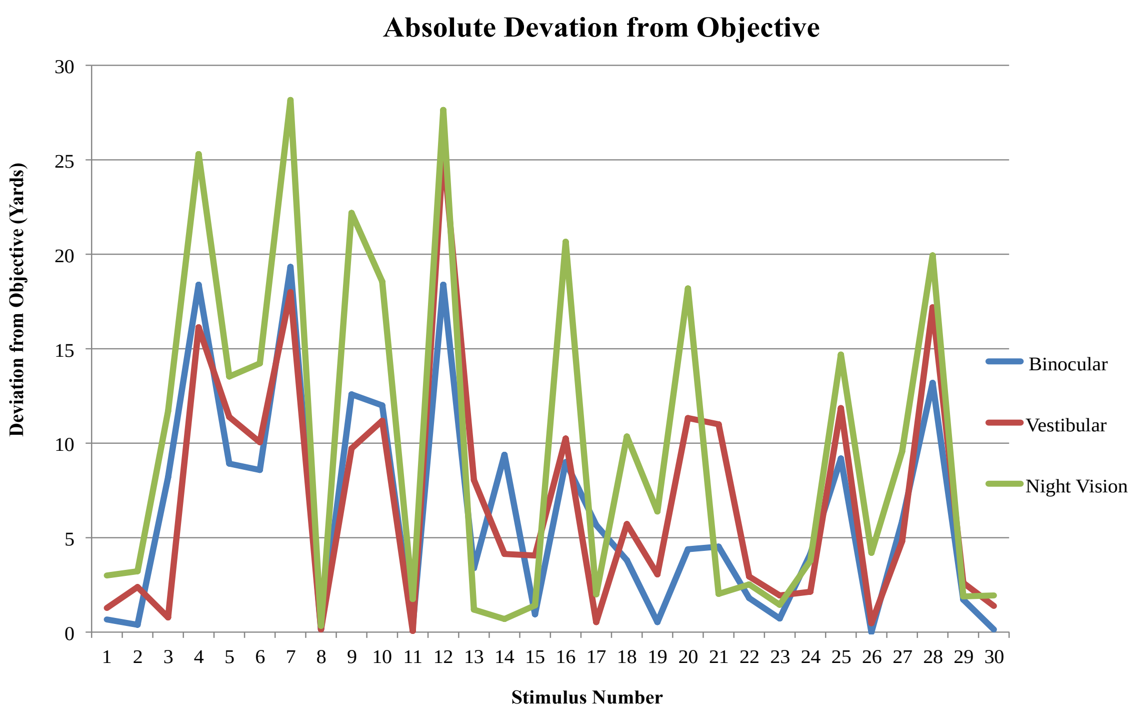


Figure 29. Average absolute deviation from objective. The average absolute deviation (in yards) of each stimulus for participants in each viewing condition are depicted. Participants tended to be the most accurate, that is, have the smallest deviation on average, in the binocular viewing condition. Participants in the monocular viewing condition tended to also have relatively low deviations, followed by the night vision condition, in which participant deviation from objective distances was the largest.

Overall, participant deviations appear to be similar for the Binocular and the Vestibular cue conditions, at times the Binocular condition having a lower deviation, and at times the

Vestibular condition having a lower deviation. However, the Night Vision Goggle condition appeared to be the most variable, with larger deviations from the objective distance the stimulus resided for many of the stimuli. Participants in every viewing condition, on average, minimized their error to be below 30 yards. One can notice that participants had very large absolute deviations for some stimuli, for example, 4,7, 9, 12, 25 and 28. These estimations are to objectively far distances, as indicated by Table 12, above. Up until this point, the size of the deviation has not been compared with regard to the objective distance of the estimation.

Ratio

It may also be pertinent to examine the absolute deviations for each viewing condition as a function of objective distance. After a deviation score is created for each trial for each participant, the deviations can also be transformed into ratios in order to scale variability in participant answers. For example, if one participant badly misjudged a near object, for example, subjectively guessed one yard for an object that was objectively located 10 yards away from her/him, this error would be more egregious than guessing 91 yards when the object resided objectively 100 yards away from her/him. Therefore, participant variability in estimation should be scaled as a function of objective distance. In order to scale this variability, each deviation will be transformed into a ratio by taking the estimated distance subtracting the objective distance, and dividing the error by the objective distance. By dividing the error by the objective distance, the error is presented as a standardized measure, no matter the total objective distance. This ratio of error is standardized among all objective distances. For example, very low ratios (0 or 0.1) indicate that participant estimations are very accurate. In contrast, very high ratios (0.8 or 1.0) indicate that participant estimations are very inaccurate.

After a computation of deviation or ratio, each viewing condition will be compared to determine which viewing condition was the most accurate. This information will allow us to make determinations about the types of visual cues that participants may be using to complete the distance estimation task in the real world. This information will then be compared to the findings of Experiment 1 in order to make a final determination about whether or not the physiological cues utilized in the lab are also used outside in the real world. Figure 30, below, shows a graphical representation of these ratios for each stimulus in each viewing condition.

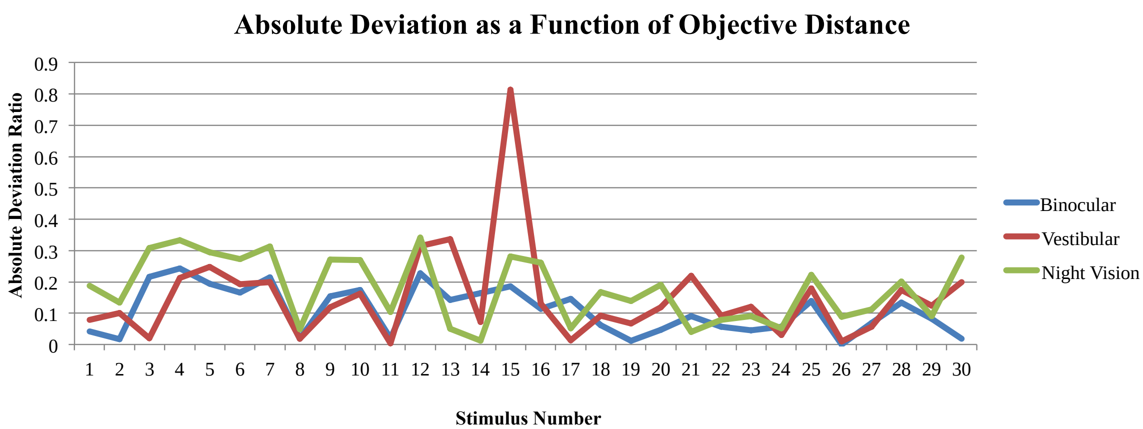


Figure 30. Ratios. The absolute deviation as a function of objective distance for each stimulus in each viewing condition. In order to scale the variability of participant estimates as a function of the objective distance, the difference between the participant subjective estimates and the objective estimates were taken, and then were divided by the objective distances of each stimulus. Very low ratios (0 or 0.1) indicate that participant estimations were very accurate. Very high ratios (0.8 or 1.0) indicate that participant estimations were not accurate.

Overall, the ratios for the majority of the stimuli in all viewing conditions were below 0.3, indicating that participants were relatively accurate. The Binocular and Vestibular viewing conditions had the lowest ratios, while the Night Vision Goggles condition had the highest ratios for most of the stimuli. One glaring exception to the overall trend of Figure 30 is in the Vestibular cue condition, for stimulus number 15. The objective distance for this stimulus is 5 yards, but one of the 15 participants in this viewing condition reported the stimulus as residing 30 yards away. This large outlier pulled the mean for this stimulus in this condition way out, ending up with a ratio of 0.80. This participant did have other rather outlandish estimations, though most were for stimuli that were far distances away, which the ratio calculation was able to cover.

Feedback

Providing direct and immediate feedback has been shown to increase participant's abilities to accurately estimate distance. In order to examine how feedback influenced the participants, the first 10 distance estimations (baseline) were averaged, then converted to absolute deviation ratios, and then examined by viewing condition. The additional conversion to ratios helped to standardize the deviations across different viewing distances. The same was done for the second 10 distance estimations (training), as well as the third 10 distance estimations (testing) for each viewing condition. Figure 31, below, compares the overall averages of the absolute deviation ratios of each viewing condition with the baseline, testing, and training set of stimuli.

As foreshadowed by Figure 28, participants in all of the viewing conditions were variable and erred in their distance estimations, particularly in the baseline phase of the experiment. Indeed, for all viewing conditions, the highest absolute deviation ratios occurred during the first five stops (10 estimations). For all viewing conditions, during the second 5 stops (10 estimations), or during the feedback phase of the experiment, participant absolute deviation ratios from objective decreased, compared to the baseline phase. Finally, for all viewing conditions, the final five stops (10 estimations) or the testing phase, participant absolute deviation ratios decreased again, compared to both the baseline and the feedback phases of the experiment. Providing feedback significantly helps to inform participant distance estimations on subsequent trails, regardless of viewing condition, $F(2,84) = 14.574$, $p < 0.000$, $\eta_p^2 = 0.258$.

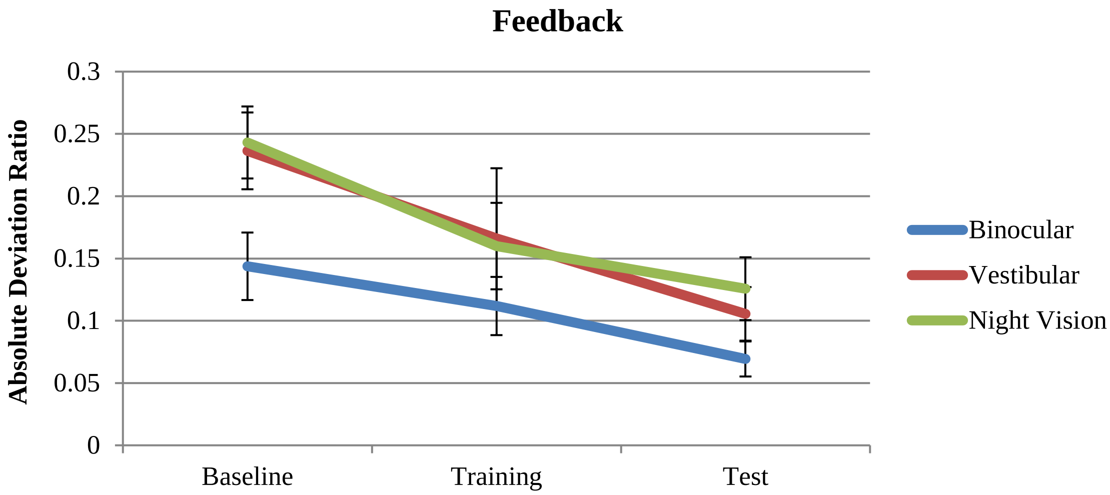


Figure 31. Feedback accuracy. Comparison of average deviation ratio by stimulus set. A comparison is made between the absolute deviation ratio value for the baseline, training, and testing stimuli in each viewing condition. All viewing conditions average large deviation ratios during the baseline (first 10 estimations), however, in each viewing condition, these deviations decrease during the training (second 10 estimations) portion, and continue to stay reduced in the testing (third 10 estimations) portion of stimuli presentation. Error Bars reflect standard error.

Discussion

The main goal of Experiment 3 was to determine the effectiveness of physiological visual cues for estimating distance in a real world, 3D environment. Overall, in Experiment 3, regardless of viewing condition, participants did not have huge deviations from veridical, and managed to keep their distance estimations within an error range of 30 yards or less. This could be due to the fact that many environmentally based and stimulus-based visual cues were available to them in the rich outdoor 3D environment. Participants were divided into specific viewing conditions, such as the Vestibular and Night Vision condition that precluded them from using some physiological cues, however, they were still able to accomplish the distance estimation task. The night vision condition results showed that most of the distances estimated by participants in this condition were underestimated. This is an interesting finding, and shows that the visual cues held constant for this viewing condition: vergence, accommodation, or vestibular cues, or a combination of all three cues, would likely help increase distance estimation accuracy.

The Vestibular and the Binocular viewing conditions tended to have similar accuracies and similar deviations, though importantly, different cues were being eliminated, (ie: vergence) or induced (ie: vestibular) in the Vestibular viewing condition. The fact that participants did similarly in these conditions indicates that either participants were using all of the other cues in the Vestibular condition and did not miss the vergence cue, or that participants in the Vestibular condition did not gain anything from moving their head and eliciting a vestibular signal.

A supplementary goal of Experiment 3 was to determine whether immediate verbal feedback given to participants would impact the accuracy of their subsequent distance estimations. In every viewing condition, participant's deviations decreased as a result of feedback. The difference between baseline and test was marked in the night vision goggle condition and the binocular viewing condition. Previous literature has focused on intentionally training participants with the use of feedback to improve distance estimation abilities through night vision goggles (e.g. Niall, Reising, & Martin, 1999). These experiments were undertaken as a response to military aviators experiencing poor distance estimation in large spaces as well as while using night vision goggles (e.g. Crowley, 1991). Taken together, studies like these underscore the need for Night Vision Goggle training programs in the military to help improve distance estimation accuracy. The results of the current study indicate that training with feedback decreases participant average deviation from objective. This study further shows that vergence, vestibular, and accommodation physiological cues (all not available while wearing night vision goggles) are valuable cues for the brain to estimate distance in a real-world environment, as participants in the binocular condition were less variable in their estimations.

The finding that feedback decreases absolute deviation in subsequent distance estimations is rather unsurprising given the preponderance of literature on training distance estimation abilities with verbal feedback for binocular (Gibson, Bergman, & Purdy, 1994), monocular (Ferris, 1972) and night vision (Reising & Martin, 1995) viewing conditions. The results of this study show that feedback and training have helped increase participant distance estimation abilities, and therefore rebut some previous literature surmising that absolute distance estimation can be accomplished with motion parallax training (Dees, 1966; Ferris, 1972, 1974). Instead, elicitation of the vestibular cue in an environment rich with stimulus-based and environmentally based visual cues, and feedback training was enough to decrease absolute deviation scores.

The results of this experiment not only expand our understanding of how the brain uses information provided by the visual system and incorporates feedback and training to increase the accuracy of participant distance estimation, but also shows physiological distance estimation cues utilized in an artificial and tightly controlled environment, such as the laboratory in Experiments 1 and 2, provide utility in accomplishing a distance estimation task on a larger scale in an environment rich with visual cues.

GENERAL DISCUSSION

The goals of the three studies of this dissertation are to provide a better understanding of how the brain computes absolute distance. The purpose of the first study was to determine which visual cues the brain uses to accurately estimate distance, as well as gain a quantitative understanding of how much each visual cue impacts accuracy. The purpose of the second study was to investigate the way individual distance cues are affected by alcohol. While some aspects of vision change with the ingestion of alcohol, other visual cues do not. Prior to this dissertation, it was unknown whether or not vital visual cues involved in distance estimation are changed or impaired by alcohol ingestion. Finally, the goal of the third study was to determine the influence of feedback/training on absolute distance judgments in a real-world, 3D environment. A secondary goal of the third experiment is to investigate the effectiveness of physiological cues, such as vergence, accommodation, and vestibular cues in helping the brain to accomplish an absolute distance task within a natural and stimulus-rich environment.

When taken together, the findings of the above three experiments greatly increase the scientific literature regarding the brain's ability to compute absolute distance. These studies offer new insight into how the brain computes absolute distance information about the 3D world in which we live.

The first study is an integral piece of the brain's puzzle that has previously been absent and is long overdue. While searching for previous work done on absolute distance estimation, it was not uncommon for searches to yield only one or two previously conducted studies with sizeable confounds. Previous research efforts (Künnepas, 1968) have been confounded by the availability of uncontrolled visual cues, rendering them confusing and untrustworthy. Previous experimental designs attempted to investigate the role of one or two individual visual cues, but did not take a task-oriented holistic approach, as seen in Experiments 1 and 2. In the first and second experiments, a new experimental apparatus was painstakingly constructed to negate all environmental and stimulus-based cues. Implementing this novel apparatus, along with manipulating viewing conditions, allowed for direct deciphering regarding which cues the brain is using to complete distance estimation. The findings of the first experiment impact the field of visual neuroscience not only by laying important groundwork for future creation of a scientific model of distance estimation, but by also providing valuable information about the brain's use of visual cues that may be inserted into models of depth perception, which have been in existence and regular use for greater than thirty years.

The second experiment is also novel to the literature base for this field, even more so than the first experiment. To this author's knowledge, there is absolutely no published research on how alcohol affects the brain's ability to compute absolute distance. The results of Experiment 2 will be the first of their kind to be published. The scientific field now knows how alcohol acts upon the brain's use of physiological visual cues in an environment devoid of common environmentally-based or stimulus-based cues. The second experiment used the same apparatus as the first experiment, maintaining the high rigor for visual cue compartmentalization established in the first experiment. By comparing the performance of participants in the first experiment to the performance of participants under the influence of alcohol in the second experiment, the effects of alcohol on the brain's ability to judge distance have been elucidated. The effects of alcohol on the visual system are very important to understand, as self-reports of driving under the influence are still incredibly high in the United States (Jewett, Shults, Banerjee, & Bergen, 2015). The findings of Experiments 1 and 2 may inform public policy and driver safety moving forward.

The third experiment discerned the role of feedback in influencing the accuracy of absolute distance estimation using real world 3D stimuli. The experimental usage of training and feedback has been a common practice previously, but the effectiveness of feedback mistakenly lead some researchers in the past to make unwarranted conclusions about relevant cues in distance estimation tasks (Dees, 1966; Ferris 1972). Experiment 3 has determined the influence of feedback in various viewing conditions as well as investigated whether findings from the first two experiments are helpful in informing how the brain computes distance in a real-world 3D environment. Without Experiment 3, this series of experiments would be lacking ecological validity. While some experimental behaviors or perceptions are often elicited in tightly controlled artificial laboratory settings, it is rare that investigators take the additional step of insuring that these behaviors are also elicited in the real world. Experiment 3 added ecological validity to the findings of Experiments 1 and 2 as well as extends our knowledge of how the brain computes absolute distance information for long distances and while moving. Excitingly, this experimental program also allows one to draw conclusions about the applicable role that these visual cues play in signaling our brain throughout our everyday lives as we work, move, and live in a real world 3D environment.

These three studies, when taken together, provide a necessary impact on the field of visual neuroscience. It is clear that these studies will add a plethora of much-needed depth to the sparse literature regarding absolute distance computation. It is the hope of this author that the addition of these studies may spur on additional research from the scientific community in order to fine tune our understanding of the applicable parameters for the computation of absolute distance. As previously mentioned, the creation of a new model utilizing this information would be very beneficial to the field. Additionally, testing relative depth models by varying the parameters now known to influence distance estimation may also help to improve our understanding of relative depth computation. A further application of the results of these studies may be to help improve distance estimation in virtual reality environments. Improvement of distance and depth percepts in virtual reality devices has been slow despite increases in screen quality technology. To illustrate just one small example, Witmer and Kline (1997) found that participants verbally underestimated stimuli distances by 25% while viewing a real world stimulus binocularly, while participants verbally underestimated distances in a virtual environment by 50%. The findings of these three experiments could greatly influence future VR technology and may also lead to improvements in night-vision goggles or training paradigms to help improve distance estimation via feedback.

Overall, this dissertation seeks to improve our fundamental understanding of the mechanisms the brain uses to unconsciously and accurately compute distance in our everyday lives. The implications for this dissertation are important not only for the field of neuroscience, but for the field of visual technology as well.

REFERENCES

Allen, B. P. (1999). Shadows as sources of cues for distance of shadow-casting objects. *Perceptual and motor skills*, *89*(2), 571-584.

Allen, R. W., Jex, H. R., McRuer, D. T., & DiMarco, R. J. (1975). Alcohol effects on driving behavior and performance in a car simulator. *IEEE transactions on systems, man, and cybernetics*, (5), 498-505.

Atkinson, J., & Braddick, O. (2008). Vision disorders and visual impairment.

Aytekin, M., & Rucci, M. (2012). Motion parallax from microscopic head movements during visual fixation. *Vision research*, *70*, 7-17.

Baird, J. W. (1903). *The influence of accommodation and convergence upon the perception of depth*.

Barnes, G. R. (1980). Vestibular control of oculomotor and postural mechanisms. *Clinical Physics and Physiological Measurement*, *1*(1), 3.

Blakemore, C., & Donaghy, M. (1980). Co-ordination of head and eyes in the gaze changing behaviour of cats. *The Journal of physiology*, *300*, 317.

Blekher, T., Miller, K., Yee, R. D., Christian, J. C., & Abel, L. A. (1997). Smooth pursuit in twins before and after alcohol ingestion. *Investigative ophthalmology & visual science*, *38*(9), 1768-1773.

Bronstein, A. M. , & Gresty, M. A. (1988). Short latency compensatory eye movement responses to transient linear head acceleration: a specific function of the otolith-ocular reflex. *Experimental Brain Research*, *71*, 406-410.

Buizza, A., Leger, A., Droulez, J., Berthoz, A., & Schmid, R. (1980). Influence of otolithic stimulation by horizontal linear acceleration on optokinetic nystagmus and visual motion perception. *Experimental Brain Research*, *39*(2), 165-176.

Calhoun, V. D., Pekar, J. J., & Pearlson, G. D. (2004). Alcohol intoxication effects on simulated driving: exploring alcohol-dose effects on brain activation using functional MRI. *Neuropsychopharmacology*, *29*(11), 2097.

Carey, D. P., Dijkerman, H. C., & Milner, A. D. (1998). Perception and action in depth. *Consciousness and Cognition*, *7*(3), 438-453.

Cohen, M. M. & Alpern, M. (1969). Vergence and accommodation: VI. The influence of alcohol on the AC/A ratio. *Archives of Opthalmology*, *81*(4), 518-525.

Coren, S., Ward, L. M., & Enns, J. T. Sensation and perception, 2004.

Cormack, R., & Fox, R. (1985). The computation of retinal disparity. *Attention, Perception, & Psychophysics*, *37*(2), 176-178.

Coules, J. (1955). Effect of photometric brightness on judgments of distance. *Journal of experimental psychology*, *50*(1), 19.

Cutting, J. E. (1997). How the eye measures reality and virtual reality. *Behavior Research Methods*, *29*(1), 27-36.

Dees, J. W. (1966). Accuracy of absolute visual distance and size estimation in space as a function of stereopsis and motion parallax. *Journal of Experimental Psychology*, *72*(3), 466.

Department of Justice (US), Federal Bureau of Investigation (FBI). Crime in the United States 2014: Uniform Crime Reports. Washington (DC): FBI; 2015 [cited 2017 June 10].

Egusa, H. (1982). Effect of brightness on perceived distance as a figure—ground phenomenon. *Perception*, *11*(6), 671-676.

Egusa, H. (1983). Effects of brightness, hue, and saturation on perceived depth between adjacent regions in the visual field. *Perception*, *12*(2), 167-175.

Farnè, M. (1977). Brightness as an indicator to distance: relative brightness per se or contrast with the background? *Perception*, *6*(3), 287-293.

Ferris, S. H. (1972). Motion parallax and absolute distance. *Journal of experimental psychology*, *95*(2), 258.

Fisher, S. K., & Ciuffreda, K. J. (1988). Accommodation and apparent distance. *Perception*, *17*(5), 609-621.

Foyle, D. C., & Kaiser, M. K. (1991). Pilot distance estimation with unaided vision, night-vision goggles, and infrared imagery. *SID International Symposium Digest of Technical Papers,* XXII. 314-317.

Gibson, J. J. (2014). *The ecological approach to visual perception: classic edition*. Psychology Press.

Gibson, E., Bergman, R., & Purdy, J. (1994). Distance over ground. *An Odyssey in Learning and Perception*, *50*, 221.

Gogel, W. C. (1972). Scalar perceptions with binocular cues of distance. *The American journal of psychology*, 477-497.

Gogel, W. C. (1978). Size, distance and depth perception. *Handbook of perception*, *8*, 299-333.

Gogel, W. C. (1969). The sensing of retinal size. *Vision research*, *9*(9), 1079-1094.

Gogel, W. C., & Tietz, J. D. (1973). Absolute motion parallax and the specific distance tendency. *Attention, Perception, & Psychophysics*, *13*(2), 284-292.

Grant, V. W. (1942). Accommodation and convergence in visual space perception. *Journal of Experimental Psychology*, *31*(2), 89.

Gruber, H. E. (1954). The relation of perceived size to perceived distance. *The American Journal of Psychology*, *67*(3), 411-426.

Held, R. T., Cooper, E. A., O'brien, J. F., & Banks, M. S. (2010). Using blur to affect perceived distance and size. *ACM transactions on graphics*, *29*(2).

Hogan, R. E., & Gilmartin B. (1985). The relationship between tonic vergence and oculomotor stress induced by ethanol. *Opthalmic & Physiological Optics*, *5*(1), 43-51.

Holdstock, L., & Wit, H. (1999). Ethanol Impairs Saccadic and Smooth Pursuit Eye Movements Without Producing Self‐Reports of Sedation. *Alcoholism: Clinical and Experimental Research*, *23*(4), 664-672.

Ittelson, W. H. (1951). Size as a cue to distance: Static localization. *The American journal of psychology*, *64*(1), 54-67.

Jewett, A., Shults, R.A., Banerjee, T., & Bergen, G. (2015) Alcohol-impaired driving among adults— United States, 2012. *MMWR Morbi Mortal Wkly Rep.* 64(30), 814-17.

Komoda, M. K., & Ono, H. (1974). Oculomotor adjustments and size-distance perception. *Attention, Perception, & Psychophysics*, *15*(2), 353-360.

Künnepas, T. (1968). Distance perception as a function of available visual cues. *Journal of experimental psychology*, *77*(4), 523.

Landauer, A. A., & Epstein, W. (1969). Does retinal size have a unique correlate in perceived size?. *Attention, Perception, & Psychophysics*, *6*(5), 273-275.

Landy, M. S., Maloney, L. T., Johnston, E. B., & Young, M. (1995). Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision research*, *35*(3), 389-412.

Leibowitz, H.W., & Owens, D. A. (1978). New evidence for the intermediate position of relaxed accommodation. *Documenta Opthalmologica, 46*(1), 133-147.

Liguori, A., Gatto, C. P., & Jarrett, D. B. (2002). Separate and combined effects of marijuana and alcohol on mood, equilibrium and simulated driving. *Psychopharmacology*, *163*(3), 399-405.

Liguori, A., D'agostino, R. B., Dworkin, S. I., Edwards, D., & Robinson, J. H. (1999). Alcohol effects on mood, equilibrium, and simulated driving. *Alcoholism: Clinical and Experimental Research*, *23*(5), 815-821.

Lyon, R. J., Tong, J. E., Leigh, G., & Clare, G. (1975). The influence of alcohol and tobacco on the components of choice reaction time. *Journal of studies on alcohol, 36*(5), 587-596.

Marczinski, C. A., Fillmore, M. T., Henges, A. L., Ramsey, M. A., & Young, C. R. (2012). Effects of energy drinks mixed with alcohol on information processing, motor coordination and subjective reports of intoxication. *Experimental and clinical psychopharmacology*, *20*(2), 129.

Marotta, J. J., Behrmann, M., & Goodale, M. A. (1997). The removal of binocular cues disrupts the calibration of grasping in patients with visual form agnosia. *Experimental Brain Research*, *116*(1), 113-121.

Martin, N. G., Oakeshott, J. G., Gibson, J. B., Starmer, G. A., Perl, J., & Wilks, A. V. (1985). A twin study of psychomotor and physiological responses to an acute dose of alcohol. *Behavior genetics*, *15*(4), 305-347.

Mather, G. (1996). Image blur as a pictorial depth cue. *Proceedings of the Royal Society of London B: Biological Sciences*, *263*(1367), 169-172.

Maylor, E. A., Rabbitt, P. M. A., Sahgal, A., & Wright, C. (1987). Effects of alcohol on speed and accuracy in choice reaction time and visual search. *Acta psychologica*, *65*(2), 147-163.

Mcnamee, J. E., Piggins, D., & Tong, J. (1981). Confirmation of the influence of alcohol on heterophoria using a vision screener. *Optometry and vision science, 58*(9), 761-765.

Miles, F. A., & Busettini, C. (1992). Ocular Compensation for Self‐Motion. Visual Mechanisms. *Annals of the New York Academy of Sciences*, *656*(1), 220-232.

Miller, R. J. (1991). The effect of ingested alcohol on fusion latency at various viewing distances. *Perception and Psychophysics, 50*(6), 575-583.

Miller, R.J., Pigion, R., & Martin, K. D. (1985). The effects of ingested alcohol on accommodation. *Attention, Perception, and Psychophysics*, *37*(5), 407-414.

Miller, R. J., Pigion, R., & Takahama, M. (1985). The effects of alcohol on accommodative, fusional, and dark vergence. *Attention, Perception, and Psychophysics*, *39*(1), 25-31.

Mitchell, M. C. (1985). Alcohol-induced impairment of central nervous system function: behavioral skills involved in driving. *Journal of studies on alcohol, supplement*, (10), 109-116.

Mon-Williams, M., McIntosh, R. D., & Milner, D. A. (2001). Vertical gaze angle as a distance cue for programming reaching: insights from visual form agnosia II (of III). *Experimental brain research*, *139*(2), 137-142.

Mon-Williams, M., & Tresilian, J. R. (1999). Some recent studies on the extraretinal contribution to distance perception. *Perception*, *28*(2), 167-181.

Mon-Williams, M., Tresilian, J. R., & Roberts, A. (2000). Vergence provides veridical depth perception from horizontal retinal image disparities. *Experimental brain research*, *133*(3).

Mon-Williams, M., Tresilian, J. R., McIntosh, R. D., & Milner, D. A. (2001). Monocular and binocular distance cues: insights from visual form agnosia I (of III). *Experimental Brain Research*, *139*(2), 127-136.

Morrison, J. D., & Whiteside, T. C. (1984). Binocular cues in the perception of distance of a point source of light. *Perception*, *13*(5), 555-566.

Moskowitz H. (1984) Attention tasks as skills performance measures of drug effects, *British journal of clinical pharmacology,* (18) 51-61.

Munsamy, A. J., Hamilton-Hoskins, R. S., Bero, T., Ximba, P. P., Govender, D., Soni, M., & Majola, L. (2016). The effect of acute ingestion of alcohol at 0.05% and 0.10% blood respiratory alcohol concentration on heterophoria. *African Vision and Eye Health, 75*(1), 1-7.

Nadler, J. W., Angelaki, D. E., & DeAngelis, G. C. (2008). A neural representation of depth from motion parallax in macaque visual cortex. *Nature*, *452*(7187), 642.

National Center for Statistics and Analysis. (2016, December). *Alcohol-impaired driving: 2015 data*. (Traffic Safety Facts. DOT HS 812 350). Washington, DC: National Highway Traffic Safety Administration.

Nawrot, M. (2003). Depth from motion parallax scales with eye movement gain. *Journal of Vision*, *3*(17), 17-17.

Nawrot, M., Nordenstrom, B., & Olson A. (2004). Disruption of eye movements by ethanol intoxication affects perception of depth from motion parallax. *Psychological Science, 15*(12), 858-865.

Nawrot, M., Ratzlaff, M., Leonard, Z., & Stroyan, K. (2014). Modeling depth from motion parallax with the motion/pursuit ratio. *Frontiers in psychology*, *5*.

Nawrot, M., & Stroyan, K. (2012). Integration time for the perception of depth from motion parallax. *Vision research*, *59*, 64-71.

Nawrot, M., & Stroyan, K. (2009). The motion/pursuit law for visual depth perception from motion parallax. *Vision research*, *49*(15), 1969-1978.

Ooi, T. L., Wu, B., & He, Z. J. (2001). Distance determined by the angular declination below the horizon. *Nature*, *414*(6860), 197-200.

O'Shea, R. P., Blackburn, S. G., & Ono, H. (1994). Contrast as a depth cue. *Vision research, 34*(12), 1595-1604.

O'Shea, R. P., Govan, D. G., & Sekuler, R. (1997). Blur and contrast as pictorial depth cues. *Perception*, *26*(5), 599-612.

Owens, A. D., & Leibowitz, H. W. (1980). Accommodation, convergence, and distance perception in low illumination. *Optometry & Vision Science*, *57*(9), 540-550.

Paige, G.D. (1989). The influence of target distance on eye movement responses during vertical linear motion. *Experimental Brain Research,* 77(3), 585-593.

Paige, G. D., & Tomko, D. L. (1991). Eye movement responses to linear head motion in the squirrel monkey. I. Basic characteristics. *Journal of Neurophysiology*, *65*(5), 1170-1182.

Pentland, A. P. (1987). A new sense for depth of field. *IEEE transactions on pattern analysis and machine intelligence*, (4), 523-531.

Reising, J. D., & Martin, E. L. (1995). *Distance Estimation Training with Night Vision Goggles Under Low Illumination*. DAYTON UNIV OH RESEARCH INST.

Roche, D. J., & King, A. C. (2010). Alcohol impairment of saccadic and smooth pursuit eye movements: impact of risk factors for alcohol dependence. *Psychopharmacology, 212*(1), 33-44.

Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception*, *8*(2), 125-134.

Rohaly, A. M., & Wilson, H. R. (1999). The effects of contrast on perceived depth and depth discrimination. *Vision research*, *39*(1), 9-18.

Rohrbaugh, J. W., Stapleton, J. M., Parasuraman, R., Frowein, H. W., Adinoff, B., Varner, J. L., ... & Linnoila, M. (1988). Alcohol intoxication reduces visual sustained attention. *Psychopharmacology*, *96*(4), 442-446.

Schwarz, U., Busettini, C., & Miles, F. A. (1989). Ocular responses to linear motion are inversely proportional to viewing distance. *Science*, *245*(4924), 1394-1396.

Spector, R. H. (1990). Visual Fields. In H. K. Walker, W.D. Hall, & J. W. Hurst (Eds.) *Clinical Methods: The history, physical, and laboratory examinations*. Boston: Butterworths.

Starmer, G. (1989). Effects of low to moderate doses of ethanol on human driving performance. In K. Crow & R. Blatt (Eds.), *Human Metabolism of Alcohol (Volume 1): Pharmacokinetics, Medicolegal Aspects and General Interest* (pp. 101-133). Boca Raton, Florida: CRC Press.

Stroyan, K., & Nawrot, M. (2012). Visual depth from motion parallax and eye pursuit. *Journal of mathematical biology*, *64*(7), 1157-1188.

Surdick, R. T., Davis, E. T., King, R. A., Corso, G. M., Shapiro, A., Hodges, L., & Elliot, K. (1994, October). Relevant cues for the visual perception of depth: is where you see it where it is?. In *Proceedings of the Human Factors and Ergonomic Society Annual Meeting* (Vol. 38, No. 19, pp. 1305-1309). Sage CA: Los Angeles, CA: SAGE Publications.

Swenson, H. A. (1932). The relative influence of accommodation and convergence in the judgment of distance. *The Journal of General Psychology*, *7*(2), 360-380.

Tokita, T., Miyata, H., Masaki, M., & Ikeda, S. (1981). Dynamic characteristics of the otolithic oculomotor system. *Annals of the New York Academy of Sciences*, *374*(1), 56-68.

Viguier, A., Clément, G., & Trotter, Y. (2001). Distance perception within near visual space. *Perception*, *30*(1), 115-124.

Watten, R. G., & Lie, I. (1996). Visual functions and the acute ingestion of alcohol. *Opthalmic and physiological optics*, *16*(6), 460-466.

Weafer, J., Camarillo, D., Fillmore, M. T., Milich, R., & Marczinski, C. A. (2008). Simulated driving performance of adults with ADHD: comparisons with alcohol intoxication. *Experimental and clinical psychopharmacology*, *16*(3), 251.

Wegner, A.J., & Fahle, M. (1999). Alcohol and visual performance. *Progress in neuro-psychopharmacology and biological psychiatry*, *23*(3), 465-482.

Wilkinson, I. M. S., Kime, R., & Purnell, M. (1974). Alcohol and human eye movement. *Brain*, *97*(4), 785-795.

Wist, E. R., Hughes, F. W., & Forney, R. B. (1967). Effect of low blood alcohol level on stereoscopic acuity and fixation disparity. *Perceptual and motor skills, 24*(1), 83-87.

Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and virtual environments, 7*(2), 144-167.

Wundt, W. (1862). Beiträge zur Theorie der Sinneswahrnemung. Winter, Leipzig.

Zaha, M. A. (1972). Shedding some needed light on optical measurements. *Electronics*, *45*(23), 91