Summer 8-1-2021

How Well Do You Know Your Reach?

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Recommended Citation

Surber, Tyler, "How Well Do You Know Your Reach?" (2021). *Dissertations*. 1906.
https://aquila.usm.edu/dissertations/1906

HOW WELL DO YOU KNOW YOUR REACH?

by

Tyler Addison Surber

A Dissertation
Submitted to the Graduate School,
the College of Education and Human Sciences
and the School of Psychology
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

Approved by:

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August 2021

Published by the Graduate School

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ABSTRACT

How does the relationship between an actor's body proportions (eye-, shoulder-, and arm length) and environmental properties (object distance) affect the perception of whether an object is within reach? Experiment 1 demonstrated that participants are more accurate at judging their own eye height than shoulder height. Experiment 2 revealed that participants can accurately perceive the angular direction to a target object's location. Interestingly, their pointing errors were significantly smaller when measured from the shoulder as a reference point than from the eye. In Experiment 3 we verified this finding using a functionally meaningful affordance task of reaching to a target object. The study tested whether participants rely on a particular complex variable that specifies the target object's location in space. This variable may serve as an invariant informational pattern that determines what is reachable. In Experiment 3 it was shown that the invariant that includes arm length, body height, and angle of declination to the target successfully predicted affordance judgments, but only when measured from the shoulder as a reference point. Affordance judgments were more accurate using the shoulder than the eye as a reference. Implications for the embodied nature of affordance perception are carefully considered in light of the present evidence.

ACKNOWLEDGMENTS

I would like to acknowledge my mentor Dr. Alen Hajnal, for his guidance and support throughout this project. Additionally, I would like to express my appreciation to Dr. Mark Huff, Dr. Richard Mohn, and Dr. Aaron Fath for their contributions to this paper. I would also like to express my gratitude to all the Perception Action Cognition Lab members that I have had the pleasure to work with throughout my time here. Finally, I would like to say thank you to Joseph Clark for helping me develop my coding abilities, and all the help he provided while constructing the virtual environments used in this study.

DEDICATION

I would like to dedicate this dissertation to my wife Sara Jordan Banks and son Bennett Holmes Surber. I would not be where I am today without your love and support. I will never be able to express how thankful I am to have you two in my life. I look forward to seeing what the next chapter of our lives has in store for us.

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CHAPTER I – Introduction

Reaching objects within our environment is something we must regularly do. Whether it is grabbing coffee off the top shelf or getting a new roll of paper towels from underneath the sink, reach is integral to our everyday activities. Interacting with objects in the environment is achieved by perceiving affordances, or possibilities for action, available to an actor (Gibson, 1979). Whether an action is possible depends on the layout of the environment and whether that layout supports or constrains behavior, specifically the actor's capabilities and biodynamics in that situation. For example, reaching for the coffee cup on the top shelf is dependent on the height of the actor in conjunction with their arm length, and the height of the coffee cup from the ground. Other factors include whether the cup is located behind other items on the shelf or if it is in the front, the number of skeletal degrees of freedom needed to accomplish the action, and so on. To rectify these various factors and decide on a possible action, an organism must be able to perceive the environment scaled to its capabilities (Carello, et al., 1989) or have knowledge relevant to that action (Robinovitch, 1998).

Carello et al. (1989) conducted four experiments investigating participant's ability to perceive whether an object was within reach across various situations and factors. They found that participants were sensitive to how various changes to the environment would affect their reaching capabilities. In Experiment 1 participants tended to overestimate their reaching ability, however they were less likely to do this when they could use multiple degrees of freedom (i.e., bending at the waist). This might imply that participants restricted to using a single degree of freedom (i.e., outstretched arms) might be unable to consider reach without multiple degrees of freedom. Evidence for this can be found in Mark et al. (1997), where it was found that participants tended to switch from using a single degree of freedom to multiple relatively quickly. Participants seem to prefer using multiple degrees of freedom even when just an outstretched arm would suffice. Related to this, Fischer (2000) found that when participants completed the task in a supine position, they tended to overestimate less than when standing up. The idea here is that due to being in the supine position participants had a reduced ability to call upon additional degrees of freedom such as leaning; therefore, participants were less likely to overestimate. This shows that an observer has awareness of how their body can move in the service of a possible action.

Additionally, Carello et al. (1989) found that participants were aware that changes to the surface on which the object of interest was placed altered their ability to reach the target. In Experiment 2 participants were presented with tables at different heights relative to the floor and asked to determine the furthest point they could reach. When the table was presented closest to the floor participants overestimated but were aware that their reach was reduced at this height. In Experiment 3 participants were presented with tables at different distance relative to them. This manipulated how much torso movement participants were able to make when making their reachability judgements. (i.e., 0 cm prevented hip movements, while 36 cm allowed participants their full range of torso movements). Participants were sensitive to this change. As the table moved further away from them, they estimated their reach to be further. These experiments show that participants are intuitively aware of how changes within the environment can affect their capabilities.

Finally, Carello et al (1989) looked at the effects of postural stability on reaching judgements. They found that if required to stand, putting a balance constraint on the task, participants underestimated their reaching capabilities. This is known as the postural stability hypothesis and has been replicated several times (Robinovitch, 1998; Fischer, 2000; Gabbard, Cordova, & Lee, 2007). However, there are conflicting reports when it comes to perceiving reachability while standing. Specifically, some researchers have found overestimation (Fischer, 2000; Rochat & Wraga; 1997; Masoner et al., 2020), while others have found underestimation (Robinovitch, 1998; Carello et al., 1989).

We can conclude that participants are able to accurately perceive how changes to their capabilities and the environment affect their perception of reach (Carello et al., 1989). This can be explained using the principles of ecological theory of perception. Specifically, the constraints imposed by the environment form an invariant relationship with the capabilities of the observer that determines whether an action is possible. An example of this invariant relationship was found by Warren (1984) where perception of the climb-ability of a set of stairs at different riser heights was scaled to participants' leg length. The invariant nature of this relationship can be expressed using a ratio of riser height over leg length called a π number.

The current study seeks to examine the variables that form the invariant relationship between an observer and the environment for the affordance task of reaching. Potential sources of information include eye- and shoulder height, arm length, object location, and angle of declination. Sinai, Ooi, and He (1998) discovered that eye height was used to determine absolute distance from a target, in addition to finding support for the idea that the ground surface is used as a reference for absolute distance (Gibson, 1950). Longo and Lourenco (2006) found a relationship between arm length and what participants consider near and far space (i.e., within reach corresponds to near space). Further support from Ooi, Wu, and He (2001) shows that manipulating the angular declination of eye height affects both judgements about the distance to an object and judgements of one's own eye height. Although Ooi et al.'s task was not about perceiving affordances, these parameters and the ways in which they interact may form the perceptual invariant used to perceive reachability.

1.1 Virtual Reality and Affordance

VR is a tool that allows us to manipulate environments in ways that would not be possible in real life or with near as much ease. Because of this Virtual Reality environments are becoming commonplace in perceptual research, especially for affordance paradigms (Regia-Corte, Marchal, Cirio, & Lécuyer, 2012; Leyrer, Linkenauger, Bülthoff, Mohler; 2015; Geuss, et al., 2010; Doyon, et al., 2021; Masoner et al., 2020). There is some criticism of VR systems regarding a space compression issue, such that virtual environments appear closer than real world environments (Bakker, et al., 2001; Messing & Durgin, 2005). However, there is also some evidence that the distance compression found in VR perception is not meaningfully different from real-world perception (Interrante, et al., 2006). Nevertheless, the ease of setting up VR experiments makes this tool very attractive for perception and action research.

1.2 Invariant Specifying Reachability Judgements

According to the ecological approach (Gibson, 1979) perception is a function of invariant information that specifies a fact of behavior, for example, whether an object is within reach or not. The goal of perception research is to discover such invariants and to prove that perception is specified by such patterns. For a standing observer who wishes to reach out and grab an object at a distance it is important to detect an optical pattern that specifies the direction of aiming, and the distance to the target location. It is hypothesized that distance is perceived in body-scaled units of arm length. Figure 1 shows the geometric parameters that are relevant in a reaching task for a standing observer. The invariant pattern that specifies object location in body scaled units can be expressed as a dimensionless ratio $R = \frac{H'O}{SA\ X \sin\alpha}$, where R is the reachability of an object. $H'O$ is the vertical distance between shoulder height and ground level on which an object sits (in the example from the figure ground level is the tabletop). *SA* is the arm length of the observer and α is the angle of declination from the horizontal specifying the direction to the object centered around the shoulder. When $R \leq 1$ the object is within reach, when $R > 1$ the object is beyond reach. The individual components of this hypothesized invariant will be tested using a virtual reality environment across three studies in the present contribution. Experiment 1 will test whether the $H'O$ component of the equation can be accurately perceived. Experiment 2 will test whether the angle α specifying the location of the object can be accurately perceived in an aiming task. Experiment 3 will determine whether R (that incorporates perceived eye height, shoulder height and direction of aiming) uniquely maps onto reaching judgments, effectively serving as the invariant information that specifies the affordance of reaching.

1.3 Present Study

Experiment 1 will have participants make judgements about their eye and shoulder height at various distances within and beyond reach. This will allow us to test whether participants are accurate at judging their own height relative to their reaching range. Experiment 2 will test whether participants are able to accurately point in the angular direction of a target at various distances within and beyond reach. This should give us an idea of how accurately participants are able to aim towards an object in the environment. Experiment 3 will investigate both parameters jointly in an affordance reaching task, in which participants are asked to judge the reachability of a target object within the environment.

CHAPTER II – Experiment 1

The goal of Experiment 1 was to determine how humans perceive their shoulder height and their eye height. The present study focused on perception of eye height and shoulder height, as those are hypothesized to be intrinsic units that humans use to guide perception in behavioral tasks such as perceiving affordances. Observers were asked to perceive their own eye height and shoulder height by matching the height of a stimulus mark at various egocentric distances. Sedgwick (1986) has demonstrated that humans use knowledge of their eye height to perceive size and distance of objects in 3D space by equating eye level with the implicit horizon level in visual scenes (Dixon, Wraga, Proffitt, & Williams, 2000; Leyrer, Linkenauger, Bülthoff, Kloos, & Mohler, 2011). Sinai et al. (1998) have demonstrated that humans can perceive their own eye height under various circumstances. We wanted to replicate Sinai's findings in virtual reality.

2.1 Participants

20 (Females= 11, M_{age}= 21.05, SD_{age}= 6.37) participants from the University of Southern Mississippi were tested using the university online psychology pool (SONA). Participants received credit in fulfillment of an extra credit option in their psychology courses for volunteering to participate. Participants were required to have normal or corrected-to-normal vision and have no motor problems. All procedures in this and subsequent experiments were approved by the local Institutional Review Board and all participants provided informed consent.

2.2 Materials

The apparatus consisted of an Oculus Rift virtual reality headset and two wireless hand-held controllers to be used to record participant responses and movement data. The

Oculus Rift Head Mounted Display (HMD) provides a field of view of 110° and can be tracked in an area of 1.52m × 1.52m using two tabletop motion sensors. The virtual environment was created using the Unity game engine software written in the C# programming language. Participants were placed in a well-lit virtual room (4m wide x 7m tall x 7m long). Inside of the room a red target (horizontal bar measuring 2m in length x 0.1 m in width) was presented on each trial. The target was used to indicate responses of perceived eye- and shoulder height.

2.3 Design

Experiment 1 was a one-way repeated measures factorial design. The within-subjects independent variable was target distance (within reach, maximum reach, beyond reach). A target was presented either within reach at a distance corresponding to 50% of arm length, at maximum reach corresponding to 100% of arm length, or out of reach at a distance corresponding to 150% of arm length. The dependent variables were perceived eye height (P_e), perceived shoulder height (P_s), ratio of perceived eye height to actual eye height (π_e), ratio of perceived shoulder height to actual shoulder height (π_s), and response time. The π-ratios were calculated using the formula $\pi = \frac{Perceived\ Height(eye\ or\ shoulder)}{Actual\ Height\ (eye\ or\ shoulder)}$. The results were analyzed using a series of one-sample and paired sample t-tests. Separate analyses were conducted for each dependent variable.

2.4 Procedure

Participants were instructed to stand during the experiment. Head movements were tracked and recorded at 80 fps using the Oculus Rift virtual reality system and its controllers. Before the start of the experiment measurements of participant’s arm length, as well as eye- and shoulder height were taken to scale the VR environment to each participant. Once participants had put on the headset and entered the virtual world, they were presented with a well-lit room. Within the room a red target alternated (in a counterbalanced order) between starting above (150% of eye height) or below (50% of eye height) the participant's eye height. The target also randomly appeared at one of the three distances scaled to the participant's arm length (50%, 100%, or 150% of arm length). Participants were instructed to move the target so that it matches their own eye- or their shoulder height. The horizontal target bar could be moved by pressing buttons on the hand controllers. The task order was counterbalanced between participants such that half of the participants responded to 3 blocks of shoulder height judgements first, while the other half of the participants responded to 3 blocks of eye height judgements first. This was done over a total of 18 trials (3 repetitions × 3 distances × 2 tasks).

2.5 Results

Participants' ratings of P_e were compared to their actual eye height (M=1.62m, SD=.069m for the group) using within-subjects paired samples t-tests. Perceived eye height was overestimated at all three distances. There was a significant difference at a distance of 50% of arm length $t(20)=4.14$, $p<.001$, $d=0.90$, at a distance of 100% of arm length $t(20)=4.06$, $p<.001$, $d=0.89$, and at a distance of 150% of arm length $t(20)=2.67$, $p<.015$, $d=0.58$. Participants' ratings of P_s were compared to their actual shoulder height (M=1.47m, SD=.065m) using within-subjects paired samples t-tests. Perceived shoulder height was overestimated at all three distances. There was a significant difference at a distance of 50% of arm length $t(20)=4.72$, $p<.001$, $d=1.03$, at a distance of 100% of arm length $t(20)=8.25$, $p<.001$, $d=1.80$, and at a distance of 150% of arm length $t(20)=6.97$, $p<.001$, $d=1.52$. The results are shown in Figure 2.

In order to provide results scaled to each individual's actual eye- and shoulder height π ratios were calculated for P_e and P_s at each distance of arm length and were compared to $\pi=1$ (i.e., when perceived height and actual height match) using a series of one sample t-tests. For π_e there was a significant difference at a distance of 50% of arm length, $t(20)=4.04$, $p<.001$, $d=0.88$, at a distance of 100% of arm length, $t(20)=3.99$, $p<.001$, $d=0.87$, and at a distance of 150% of arm length, $t(20)=2.62$, $p=.017$, $d=0.57$, such that eye height was overestimated at all distances. For π_s there was a significant difference at a distance of 50% of arm length, $t(20)=4.52$, $p<.001$, $d=0.99$, at a distance of 100% of arm length, $t(20)=8.23$, $p<.001$, $d=1.80$, and at a distance of 150% of arm length, $t(20)=6.83$, $p<.001$, $d=1.49$, such that shoulder height was overestimated at all distances. The results are shown in Figure 3. Additional analysis compared π_e and π_s and we found a significant main effect for Body Part $F(1,20)=12.64$, $p=.002$, $\eta_p^2=.39$, such that shoulder height was overestimated more compared to eye height.

In order to assess whether the distance between eye height and shoulder height was perceived accurately we computed the ratio between perceived eye height and shoulder height (P_e/P_s). We used within-subjects paired samples t-tests to compare perceived shoulder height with respect to perceived eye height at each distance based on the ratios of actual eye height and actual shoulder height of each participant. There was a significant difference at a distance of 50% of arm length $t(20)=-4.15.$, $p<.001$, $d=0.91$, at a distance of 100% of arm length $t(20)=-4.15$, $p<.001$, $d=0.91$, and at a distance of 150% of arm length $t(20)=-2.24$, $p=.036$, $d=0.49$. Participants tended to underestimate the distance between their eyes and their shoulder, meaning they tended to perceive their shoulder to be closer to their eyes than it actually is. The results are shown in Figure 4.

2.6 Discussion

Past research showed that participants are accurate when making judgements about their perceived eye height (Sinai et al., 1998; Ooi et al., 2001). Additionally, there is evidence that participants consider near and far space relative to their perceived arm length, such that near space is the area within arm's reach and far space is the area outside of arm's reach (Longo & Lourenco, 2007). Since manual actions are performed within arm's reach and it is reasonable to assume that the majority of manual tasks require high precision and accuracy, we predicted that participants would be more accurate in perceiving the space within arm's reach than the area that is beyond reach, and thus less relevant to action. In terms of perceived eye height and shoulder height, our results showed significant overestimation that was not consistent with the predictions. However, overestimation of eye and shoulder height was consistent with overestimation in reaching judgments reported in recent investigations (Doyon et al., 2021, Masoner et al., 2020).

Eye height is overestimated to a lesser degree than shoulder height. This is consistent with a theoretical view that the reference point for visual perception of affordances and motor control in reaching judgments should be the eye, even though reaching judgments are performed by the arm that has a reference point in the shoulder joint.

What are the implications of the pattern of overestimation in near space on the perception of reachableness? To the extent that the reference point for reaching judgments is the eye, and perceived eye height is overestimated, it is reasonable to expect that reachability judgments are going to be influenced by this overestimation as well.

Specifically, overestimation of eye height should lead to overestimation of reaching distance as well, perhaps due to the fact that perceiving oneself to be taller might be paired with a perception of having a larger arm span. Another interesting finding was that participants perceived the eyes to be closer to the shoulder than they actually are, indicating an underestimated eye-shoulder distance. This should mean that the difference in angle of declination to a target object with respect to the eye and the shoulder should be perceived as smaller than it actually is. These results raise the question whether the eye or the shoulder is considered the reference point for reachability judgments. In order to accurately reach and grasp an object one has to properly orient the arm with respect to a reference point. Thus, before we can verify that the overestimation of eye height influences reachability judgments, we have to test whether observers can accurately point in the direction of objects within and beyond reach.

CHAPTER III – Experiment 2

The results of Experiment 1 revealed that participants are more accurately attuned to their own eye height than shoulder height. The plausible conclusion was that participants were using eye height as a reference for visual perception. Experiment 2 expanded upon the findings of Experiment 1 by testing whether participants were able to detect the location of an object by accurately pointing their arm in the direction of the object. We predicted that observers would use the shoulder as a reference for pointing judgments. This is contrary to the findings of Experiment 1; however, our prediction was based on the fact that participants would have to use a motor response (pointing with the arm), therefore the reference should be the shoulder joint, not the eye.

3.1 Participants

Twenty (Females= 9, M_{age}= 37, SD_{age}= 17.67) participants from the University of Southern Mississippi were tested from the online psychology participant pool (SONA). This included some members of the local community who were also recruited to participate. Participants received credit in fulfillment of an extra credit option in their psychology courses for volunteering to participate. Participants were required to have normal or corrected-to-normal vision and have no motor problems. All procedures were approved by the university's IRB and all participants provided written consent to participate. One participant was removed from the analysis for having responses greater than two standard deviations from the mean. A sensitivity analysis using G*Power3 (Erdfelder, Faul, & Buchner, 1996) indicated that the sample size had adequate power (.80) to predict medium effect sizes or larger (Cohen's f = .25) for main effects and interactions.

3.2 Materials

In Experiment 2 the same equipment and programing software was used as in Experiment 1. Participants were placed in a well-lit virtual room (4m wide x 7m tall x 7m long). Inside of the room a red target (ball measuring 6.8cm in diameter) was visible. Two seconds after the start of each trial the ball disappeared. Participants responded by pointing to the location of where the ball was located. The perceived direction was computed based on the recording of the coordinates of the controller at the moment when the response button was pressed.

3.3 Design

Experiment 2 was a 5×5 repeated measures factorial design. The within-subjects independent variables for Experiment 2 were Target Angle (0°,15°, 30°, 45°, and 60° below shoulder height) and Target Distance (targets were presented at 5 distances corresponding to a range of 80-120% of maximum arm length, in increments of 10%). The dependent variables were perceived direction (measured as absolute and signed error) and response times. Pointing error was calculated by taking the value of the difference between the pointing direction (calculated using the xyz coordinates from the hand) and the actual angle from the horizontal direction where the target object was placed. Absolute error is the average of the absolute value of the difference between perceived and actual angle of declination, and as such is the indicator of the total magnitude of participants' pointing errors. Signed error is the average of the difference between perceived and actual angle of declination of the target object's location, and as such it takes into account underestimation (when perceived angle is smaller than the actual angle) and overestimation (when perceived angle is larger than the actual angle).

Participants were asked to respond by pointing towards the direction of an object with their arm while holding the VR set controller. Coordinates from the VR controller were used to compute the perceived angle as the measure of direction of pointing. To analyze the results a 5×5 repeated measures ANOVA was used to determine what factors influence accuracy.

3.4 Procedure

Participants were instructed to stand during the experiment. Before the start of the virtual reality experimental session measurements of participant's arm length, as well as, eye- and shoulder height were taken to scale the VR environment to each participant. Once participants had put on the headset and entered the virtual world, they were presented with a darkened room. Within the room a red target ball was presented at one of five angles and distances in the sagittal plane. The target remained visible for 2 seconds, after which it disappeared, and participants were instructed to point using the VR controller to where the target was last seen. When they believed, they were pointing to the right location they were instructed to press a button on the controller recording their response. Participants were presented with 75 trials providing three responses for each combination of target angle and distance.

3.5 Results

A 2 (Body Part: Shoulder, Eye) × 5 (Angle: 0°, 15°, 30°, 45°, 60°) × 5 (Distance: 80%, 90%, 100%, 110%, 120% of arm length) repeated measures ANOVA was used to analyze the absolute error of participants' pointing responses. The perceived angles were calculated from the shoulder and from the eye as a reference point. There was a significant main effect of Angle $F(1.32,25.01)=4.035$, $p<.05$, $\eta_p^2=.18$. Post hoc analysis using the LSD correction showed a significant difference between the 60° angle and all other angles. The main effect of Angle revealed a steady decrease in pointing errors from the 0˚ horizontal shoulder level (*M*=13.71˚, *SD*=11.05˚) to 60˚ below the horizontal level (*M*=9.03˚, *SD*=9.58˚). The results are shown in the graphs in Figure 5.

A 2 (Body Part: Shoulder or Eye) x 5 (Angle: 0°, 15°, 30°, 45°, 60°) x 5 (Distance: 80%, 90%, 100%, 110%, 120% of arm length) repeated measures ANOVA was used to analyze the signed error of participants' pointing responses. There was a significant main effect of Body Part $F(1,19)=14.51$, $p<.01$, $\eta_p^2=.43$. Pointing errors measured from the shoulder (*M*=-0.21˚, *SD*=15.18˚) were significantly smaller than pointing errors with respect to the eye (*M*=5.63˚, *SD*=10.74˚). In addition, the pointing errors with respect to the shoulder were not significantly different from 0˚, $t(19)=-0.06$, $p=0.95$, whereas the pointing errors with respect to the eye as a reference were significantly different from 0˚, $t(19)=2.34$, $p=0.03$, $d=0.52$. The results are shown in the graphs in Figure 6.

3.6 Discussion

Being able to locate an object in three-dimensional space requires an observer to know the angle of declination of the object from their shoulder height. The shoulder might be especially salient as a reference point in tasks that involve motor responses such as pointing or reaching. It was predicted that participants would be accurate at completing the pointing task as participants seem to be sensitive to changes in the angular declination (Ooi, Wu, & He, 2001). Absolute error, as a measure of the overall magnitude of pointing error, showed that the average pointing error was a little over 10˚, rendering our prediction not satisfied. There were no differences between an eye-centric and a shoulder-centric reference in terms of absolute error. However, participants were more accurate when responding to targets set to the 60° angle compared to any other angle. Specifically, absolute error decreases as the angle below the horizontal direction increased. This is consistent with Gibson's Ground Theory of space perception (Gibson, 1950). Gibson theorized that an observer perceives objects and events by tuning into an ambient optic array defined by the ground surface. From this optic array an observer perceives a texture gradient that carries invariant information on the possibilities of future actions. This invariant information remains consistent regardless of an observer's position in space; therefore, an active observer is able to make accurate decisions about the possibilities of future action regardless of their orientation in the environment. Based on this, we can conclude that even though the magnitude of the pointing error was substantial, participants perceived the space around them consistent with Ground Theory.

In terms of signed error, a measure of accuracy of pointing, it was found that participants made smaller pointing errors with respect to the shoulder as a reference point compared to using their eye as the reference point. Specifically, the average pointing error was not significantly different from zero when calculated based on the shoulder-centric reference but was substantially larger when computed with respect to the eye. This is inconsistent with the results from Experiment 1, in which participants were more accurate when making responses for eye height compared to shoulder height. One possibility for this is due the fact that in Experiment 1 it was not required of participants to make an action response (other than pressing a button). Therefore, it is possible that in the absence of an action related task, an observer uses their eyes as a reference point. Conversely, when a task requires an action response, participants use their shoulders as the reference point. We set out to test this idea in more detail in the next experiment where participants not only had to use action to respond, but also had to consider a future action: whether an object is reachable by extending the arm.

CHAPTER IV – Experiment 3

In Experiment 2 we demonstrated that pointing based on a shoulder-centric reference point was accurate. In the current experiment we wanted to test whether perception of the affordance of reachableness is also based on a shoulder-centric reference point. We predicted that pointing errors would be smaller and the accuracy of affordance perception would be higher when measured from the shoulder joint than from the eye. We proposed an invariant information that specifies affordance perception composed of 1) the distance of effector (hand) from reference point (eye or shoulder), and 2) the angle calculated from the reference point (eye or shoulder joint). It was hypothesized that the invariant based on the shoulder as a reference would be a better predictor of affordance judgments than an eye centered invariant.

4.1 Participants

17 (Females= 7, M_{age}= 28.82, SD_{age}= 15.61) participants from the University of Southern Mississippi were tested from the university online psychology pool (SONA). Participants received credit in fulfillment of an extra credit option in their psychology courses for volunteering to participate. Participants were required to have normal or corrected-to-normal vision and have no motor problems. All procedures were approved by the IRB and participants provided written consent. A sensitivity analysis using G*Power (Erdfelder, Faul, & Buchner, 1996) indicated that the sample size had adequate power (.80) to predict medium effect sizes or larger (Cohen's f = .27) for main effects and interactions.

4.2 Materials

Experiment 3 used the same equipment and programing software as in Experiments 1 and 2. Participants were placed in a well-lit virtual room (4m wide x 7m tall x 7m long). Inside of the room a red target object (ball measuring 6.8cm in diameter) was visible on a white table. The edge of the table was located .2m in front of the participant, and measured 1m wide x 0.06m tall x 1.75m long). 2 seconds after the start of the trial the ball disappeared. Participants responded by stating whether they could reach the target and then pointed to the location of where the ball was located. The response was collected by pressing a button on the hand-held controller. The coordinates of the response were used to calculate the direction of pointing.

4.3 Design

The design was the same as in Experiment 2, except for the addition of a new dependent measure. The new dependent variable was affordance judgment (i.e., participants would respond verbally by saying “yes” if they perceived the object to be within reach, or “no” if the object was beyond reach). The data was analyzed using factorial ANOVAs (pointing errors) and multiple logistic regression (for affordance judgments).

4.4 Procedure

Participants were instructed to stand during the experiment. Measurements of participant’s eye- and shoulder height were taken to scale the VR environment to each participant. Once participants had put on the headset, they were presented with a large illuminated virtual room. Within the room a red ball was randomly presented at one of five predetermined angles and distances from the observer. This was accomplished by placing the ball on a table surface that varied in height from one trial to the next. The target remained visible for 2 seconds. Participants were instructed to point in the direction of the object and record their pointing judgment by pressing a button on the VR controller. At that point participants were asked to verbally say ‘yes’ or ‘no’ as to whether they would be able to reach the object with an extended arm without leaning forward. Participants were presented with 75 trials providing three repeated responses for each combination of target angle and distance.

4.5 Results

A 2 (Body Part: Shoulder or Eye) × 5 (Angle: 0°, 15°, 30°, 45°, 60°) × 5 (Distance: 80%, 90%, 100%, 110%, 120% of arm length) repeated measures ANOVA was used to analyze the absolute error of participants’ pointing responses. There was a significant main effect of Body Part $F(1,16)=14.80$, $p<.01$, $\eta_p^2=.48$, such that the shoulder-centric pointing error (M=5.6˚, SD=3.5°) was significantly smaller than the eye-centric pointing error (M=11.4°, SD=3.4°). There was a significant main effect of Angle $F(1.48,23.64)=47.72$, $p<.001$, $\eta_p^2=.75$. Absolute error was largest for the 0˚ angle and steadily decreased as the angle of declination increased. There was a significant main effect of Distance $F(1.86,29.80)=14.34$, $p<.001$, $\eta_p^2=.47$. Absolute error was largest for the nearest distance and steadily decreased as the distance increased. There was a significant Body Part × Distance interaction, $F(1.78,28.41)=11.72$, $p<.001$, $\eta_p^2=.42$. The error decreased more dramatically in the eye-centric condition as a function of distance. The error remained low across all distances in the shoulder-centric condition. There was a significant Body Part × Angle interaction, $F(1.68,26.91)=34.77$, $p<.001$, $\eta_p^2=.68$. The error decreased more dramatically in the eye-centric condition as angles increased. The error remained low across all angles in the shoulder-centric condition. There was a significant Angle × Distance interaction, $F(4.21,67.42)=2.66$, $p<.04$, $\eta_p^2=.14$. At the nearest distances the difference in error between the 0˚ and the 60˚ angle was the largest. The results are shown in the graphs in Figure 7.

A 2 (Body Part: Shoulder or Eye) × 5 (Angle: 0°, 15°, 30°, 45°, 60°) × 5 (Distance: 80%, 90%, 100%, 110%, 120% of arm length) repeated measures ANOVA was used to analyze the signed error of participants' pointing responses. There was a significant main effect of Body Part $F(1,16)=225.04$, $p<0.001$, $\eta_p^2=.93$, such that the shoulder-centric pointing error (M=-2.3˚, SD=5.5°) was significantly smaller than the eye-centric pointing error (M=11.7°, SD=3.3°). The pointing errors with respect to the shoulder were not significantly different from 0˚, $t(16)=-1.74$, $p=0.1$, whereas the pointing errors with respect to the eye as a reference were significantly different from 0˚, $t(16)=14.68$, $p<0.001$, $d=3.56$. There was a significant main effect of Angle, $F(1.66,26.57)=16.44$, $p<.001$, $\eta_p^2=.51$, such that the error steadily decreased as the angle increased. There was a significant main effect of Distance, $F(1.85,29.61)=14.61$, $p<.001$, $\eta_p^2=.48$, showing the same trend as the main effect of Angle: a steady decrease of error as a function of distance. There was a significant Body Part × Angle interaction, $F(1.26,20.09)=95.60$, $p<.001$, $\eta_p^2=.86$, such that the error remained consistently low according to the shoulder-centric computation across all angles, whereas it showed a dramatic decrease according to the eye-centric computation as angles increased. There was a significant Body Part × Distance interaction, $F(1.51,24.19)=8.17$, $p<.01$, $\eta_p^2=.34$, showing a similar pattern of results. The three-way Body Part × Angle × Distance interaction was also significant, $F(3.35,53.63)=7.44$, $p<0.001$, $\eta_p^2=.32$. The results are shown in the graphs in Figure 8.

A linear mixed-effects logistic regression model was used to predict participants' responses to the affordance task. The model was built using arm length, angle, and reference point (eye or shoulder) to compute the R invariant ratio and is expressed with the following formula:

AFFORDANCE RESPONSE ~ (TRIAL|PARTICIPANT) + TRIAL + R_S + R_E,

where R_S is the invariant ratio based on the shoulder as the reference (vertex of the angle of declination is in the shoulder joint), and R_E is the invariant ratio based on the eye as the reference (vertex of the angle of declination is at the eye). Trial and Participant are random effects with Trials nested within participants. Table A shows the output from the logistic regression analysis. We found a significant negative main effect of the invariant based on the shoulder (β=-5.66, *SE*= 1.44, p<.001), such that as the invariant increased from a low value to a high value, the likelihood of saying "yes" steadily decreased. The invariant based on the eye was not significant (p=0.5). This indicated that participants' affordance responses were best predicted by the invariant based on the shoulder, not the eye.

We computed the accuracy of each affordance judgments by comparing them to the correct answer based on the eye- and should-centric R ratio invariant, respectively. The accuracy of participants' affordance judgements was analyzed using the McNemar Chi-Square test. We found a significant difference (McNemar's $\chi^2(1, N = 17)=110.04$, $p<0.001$, Odds Ratio= 5.79, Cohen's g=0.35) such that participants were more accurate when using the invariant based on their shoulder (71.17% accurate) compared to the invariant based on their eye as a reference point (61.85% accurate).

4.6. Discussion

Experiment 3 added a behaviorally meaningful task in which participants had to make reachability judgements in addition to pointing responses. Based on pointing errors (in terms of absolute and signed errors) we found that participants were more accurate when steering towards an object as the object moved further away from their body, and closer to the ground. Again, this is in line with Gibson’s Ground Theory of Space Perception (Gibson, 1950) suggesting that the ground surface provides a necessary context for affordance perception.

Participant’s affordance judgements were affected by both angle and distance, such that participants were aware of how changes to the target’s location affected their ability to reach the object. Additionally, the accuracy of responses to the reaching task show that participants were more accurate when their response was based on the invariant with respect to their shoulder height compared to the invariant based on their eye height.

To the extent that the R ratio is used as an invariant, we predicted that participants would accurately perceive their reaching capabilities both in terms of accuracy of aiming direction and perceived distance if they used the shoulder joint as the reference point. Experiment 3 tested how participants used the parameters investigated in Experiment 1 and 2 jointly in a realistic, well-lit environment to perceive whether an object is within reach. We expected there to be a relationship between the R ratio parameter and reaching judgments. Specifically, we expected that the R ratio would be a significant predictor of affordance judgments. Results show that the R ratio calculated using the shoulder as a reference point is the best predictor for participants' affordance responses and leads to higher accuracy.

CHAPTER V – General Discussion

The current study investigated the invariant that specifies reaching behavior. Potential sources of information include eye- and shoulder height, arm length, object location, and angle of declination (Sinai, et al., 1998; Longo & Lourenco, 2006; Ooi, et al., 2001). In Experiment 1, we investigated whether eye height and shoulder height are perceived accurately. Perceived eye height was shown to be more accurate than perceived shoulder height, although both were overestimated. This suggests that the eye might be the reference point for visual perception. One possible source of this overestimate could stem from the reliance on postural cues to determine eye height in virtual reality (Leyrer et al., 2015). Specifically, eye and shoulder height to the ground changes as a function of an observer's body movements. As an observer moves throughout space their effective eye- and shoulder height will change, depending on how their body is positioned in spaced. This could have caused fluctuations in participants' responses to both eye- and shoulder height, which, due to the reliance on postural cues, could have presented as overestimation of perceived eye and shoulder height in the present experiment.

Alternatively, participants' tendency to overestimate eye/shoulder height could stem from the richness of our virtual environment. Leyrer et al (2015) found that participants underestimated eye height in a visually sparse virtual environment (i.e., a virtual environment composed of a floor and a horizon), while participants overestimated eye height in a visually rich virtual environment (i.e., a replica of an office). The virtual environments employed in the present study were composed of a floor, four walls, and a roof. For this reason, the virtual environments in the present study could be considered visually rich, and this could have caused participants to overestimate their judgements.

Future planned experiments will manipulate the visual richness of the virtual environment.

In Experiment 2 we investigated an observer's ability to point in the direction of a potentially graspable object at various distances relative to their maximal reaching distance. We discovered that pointing errors were significantly smaller with respect to the shoulder than with respect to the eye. This is seemingly in contradiction with the conclusions of Experiment 1 where perceived eye height was more accurate. However, in Experiment 1 there was no behavioral response, and thus no use of the arm to respond in a specific way (apart from pressing buttons on a controller). This absence of a specific motor response in Experiment 1 may have underspecified the task. So, visual perception in the absence of action-oriented response requirements appears to be based on the eye as a reference. However, when the motor system is involved (like in a pointing task), the more useful reference point appears to be the shoulder joint. The act of pointing (and perhaps reaching) is centered around the shoulder joint. Interestingly, we did not find distance effects for pointing judgements as we predicted. One possible reason for this may have to do with the information required for accurate pointing. Specifically, pointing should not require the same distance information that a functional action such as reaching would require; therefore, participants can accurately point without requiring information that specifies distance.

In Experiment 3 we employed a more meaningful behavioral task: affordance perception. Not only do we have to consider the reference point, but also use the motor system to point and perceive whether something is within reach or not. The results showed that pointing errors decreased as a function of angle and distance. Participants were more accurate at pointing at targets that appeared further away from their body than the targets that appeared close to them. One possible reason for this could be the observed utility for pointing movements towards the natural grasping distance (i.e., pointing gestures that require the participant to extend their arm to maximum arm length) as opposed to movements away from the natural grasping distance (Wiesing, Kartashova, & Zimmermann, 2021). This would mean that pointing judgements would be more accurate for targets that appeared at or beyond reach and biased within reach. Participants would have to bend their arm at the elbow, which may be an additional source of error, as pointing may be more complicated when forced to bend at the elbow. In general, pointing errors were smaller according to the shoulder-centric reference. The pointing errors were also larger for larger angles when using the eye as a reference point. We calculated a new invariant that contains arm length, angle, and reference point (eye or shoulder) called the R ratio. A mixed effects logistic regression (Bates, et al., 2014) showed that affordance responses depended on the shoulder-based invariant and were more accurate than based on the eye-invariant.

Even though the design of Experiment 2 and 3 were identical, the pattern of significant effects and interactions differed. This apparent discrepancy may have been due to one of the following factors (or both): 1) low experimental power due to small sample sizes; or 2) the difference in tasks (pointing versus affordance perception) between the two experiments. As noted earlier, a sensitivity analysis indicated that both experiments were sufficiently powered to detect the effects we have found with medium effect sizes. In fact, the achieved effect sizes for significant effects and interactions across the two experiments were the same, or larger than predicted by the sensitivity analysis.

Therefore, we believe that the differences in the pattern of results between Experiment 2 and 3 were due to the difference in tasks (pointing versus affordance perception) between the two experiments. Based on the large effect sizes found in these experiments we are confident that we achieved appropriate power to find the significant effects that were hypothesized.

The use of virtual environments in the present study might fall under scrutiny due to some evidence that virtual environments are compressed or appear closer than they would in the real-world equivalent (Bakker, et al., 2001; Messing & Durgin, 2005). However, the use of affordance paradigms in virtual reality have shown consistent results for both real world and virtual environments. In a study by Geuss et al (2010), participants were asked to give a size estimate of an aperture and judge whether they could pass through it (passability). The aperture was located in either a real or virtual classroom. They found that there was no difference in estimates or perceived passability when comparing the responses from the real and virtual classroom. However, virtual environments might require more dynamic information to obtain the same accuracy as a real environment (Bhargava et al, 2020). While participants were accurate in both the real world and VR, participants in the virtual environment required more exploration to reach the same accuracy rates. In a recent study on reachability, participants were asked to make reaching judgements in real world or virtual environments (Doyon et al., 2020). They found that participants overestimated their reaching capabilities in both the virtual and real environment. Given the results of these experiments, we are confident that similar results would be found if this study were replicated in a real-world environment.

One potential confounding variable that could have influenced our results is the retinal size of the target object. The size of the retinal image of an object provides cues to distance (Baird, 1963). The size of the retinal image of the target stimuli was not controlled for in the present set of experiments. The information gained from the size of the retinal image could have specified the distance of the object. However, we believe that the size of the retinal image would affect both eye and shoulder responses equally and would not change our main results. This will be controlled for in future experiments that are planned.

Why would visual perception of the affordance of reachableness be centered around the shoulder joint and not the eye? To use a metaphor: why should the shoulders “have” eyes? One explanation for this would be that visual perception of affordances is by definition action-oriented, and as such it is necessarily embodied. It makes sense then to have a reference point in the relevant limb that performs the action. The choice of reference points is important in building and controlling artificial agents such as robots, because engineers have to build into the robot some knowledge of its bodily proportions. Based on our results it is more important to know where the shoulder is with respect to the rest of the body than to know where the eye is with respect to the rest of the body. This is an example of proprioception at work, i.e., the ability to know where different parts of the body are in relation to the rest of the body (Sherrington, 1952). In relation to the affordance task, exproprioception, the ability to know where the limbs are with respect to an external object, is centered around the shoulder joint for a reaching task (Pagano, Carello, & Turvey, 1996). Our results also revealed that the invariant information works best when the object of interest is not at shoulder- or eye- level. Since the puzzle of Molyneux’s premise (Atherton, 1990; Gibson, 1950; Pastore, 1971), it is commonplace knowledge in vision science that the distance to objects placed at different distances at eye level are difficult (if not impossible) to perceive due to the fact that they project a single point on the same location on the retina. The angle of declination seems to be a crucial component of the invariant R ratio. When this angle is zero (at eye level), the formula is uninterpretable since the denominator becomes zero, rendering the quotient indeterminate. Apart from this mathematical fact, vision scientists do not have a plausible behavioral explanation for why perceiving distances at eye- (or shoulder-) level is difficult. Our study is a step in the direction of trying to address this important gap in the literature.

APPENDIX A - Tables

Mixed effects logistic regression model of affordance judgments in Experiment 3.

Predictor	*β*	*SE*	*p*	*odds ratio*	*lower 95% CI*	*upper 95% CI*	
Intercept	6.52	0.4	<.001	0.9947	0.9870	1.0023	*
Trial	-0.01	0.01	0.17	0.0035	0.0002	0.0586	
R_S	-5.66	1.44	<.001	2.2564	0.2109	24.1371	*
R_E	0.81	1.21	0.5	0.9947	0.9870	1.0023	

Table A.1 Mixed Effects Model of Affordance Judgements

APPENDIX B – Figures

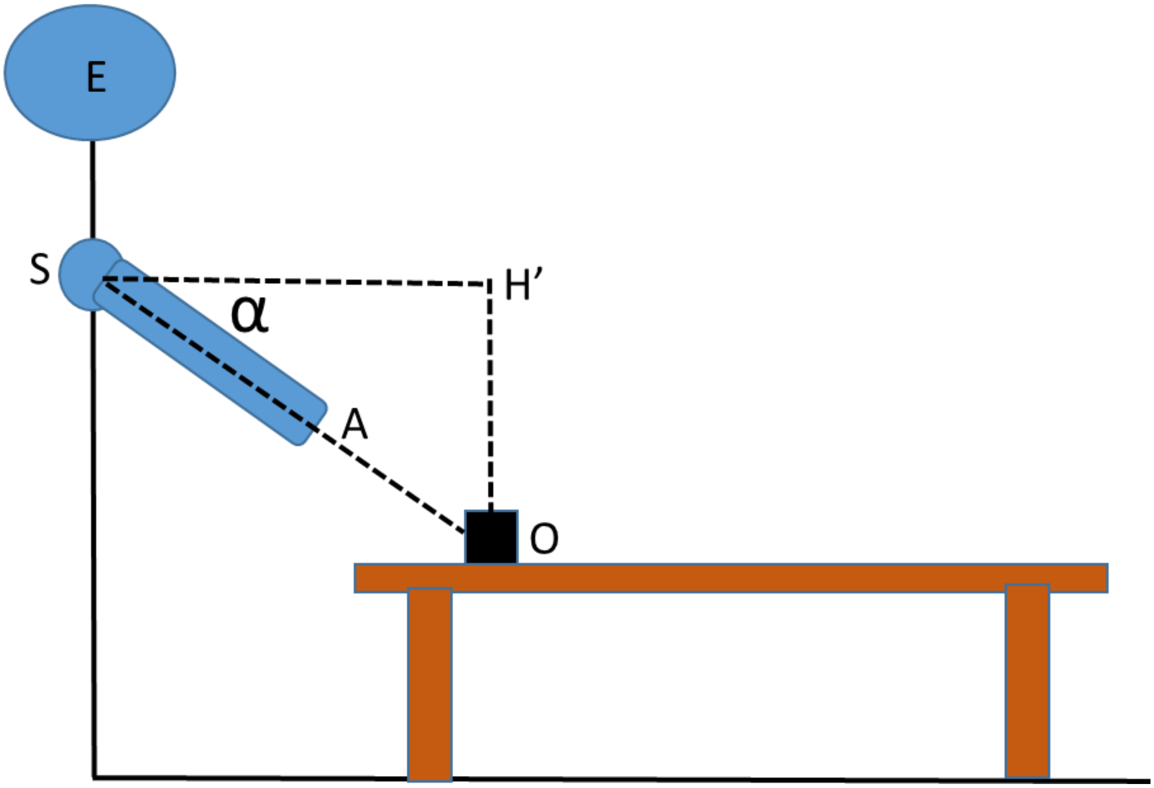


Figure B.1 *Invariant that Specifies Reaching*

An observer standing in front of an object that is placed on a tabletop. *E*: observer's head; *S*: shoulder; *H'O* is the vertical distance between shoulder height and ground surface (tabletop); *SA*: arm length; *SO*: distance from shoulder to object; *α*: angle of declination with the horizontal that specifies the location of the object measured from the shoulder.

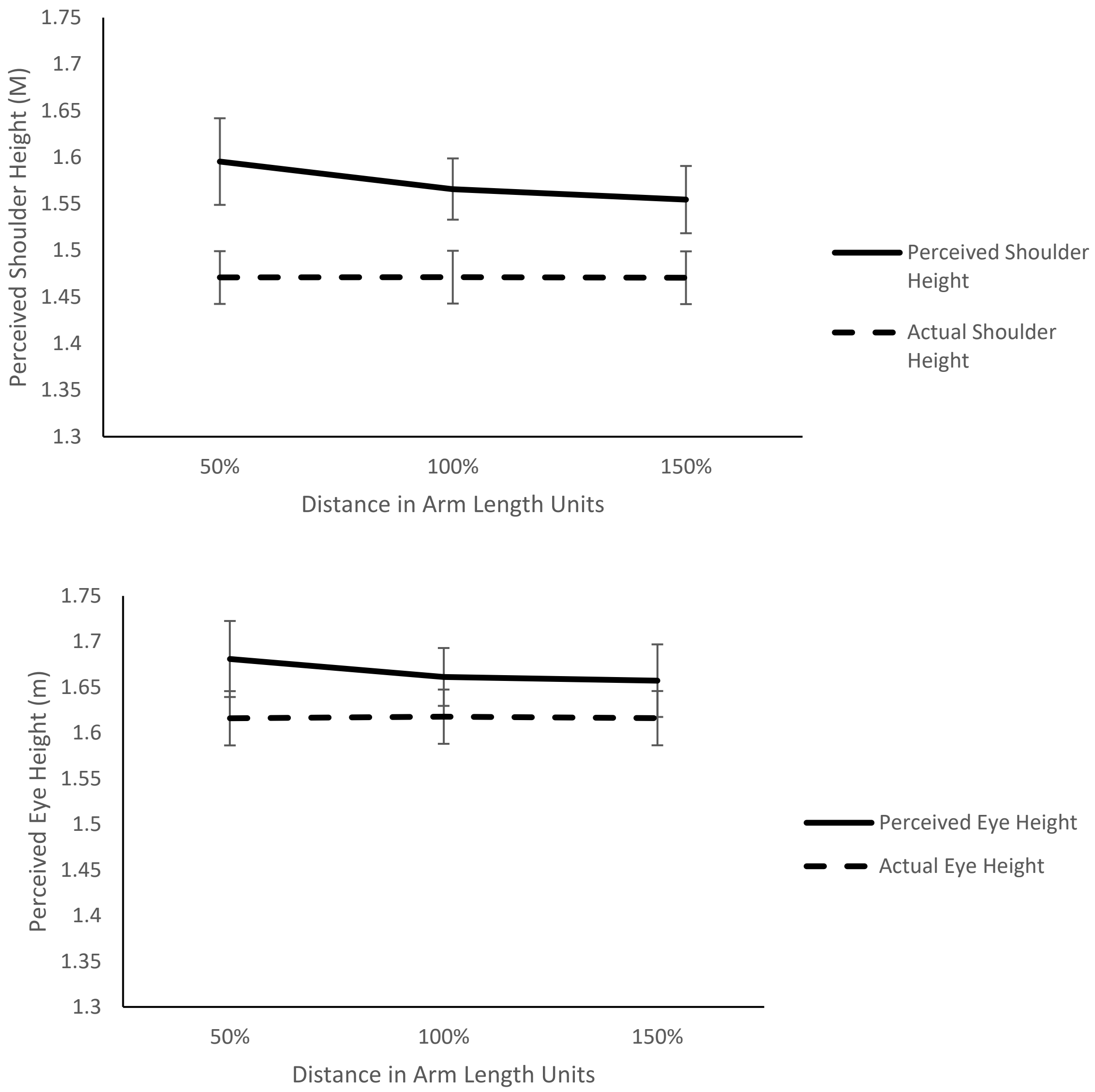


Figure B.2 *Perceived Height by Distance*

Perceived Height by distance for Eye and Shoulder responses in Experiment 1. Responses for eye height were compared to an average value of 1.62m, and responses for shoulder height were compared to an average of 1.47m Error bars represent 95% confidence intervals.

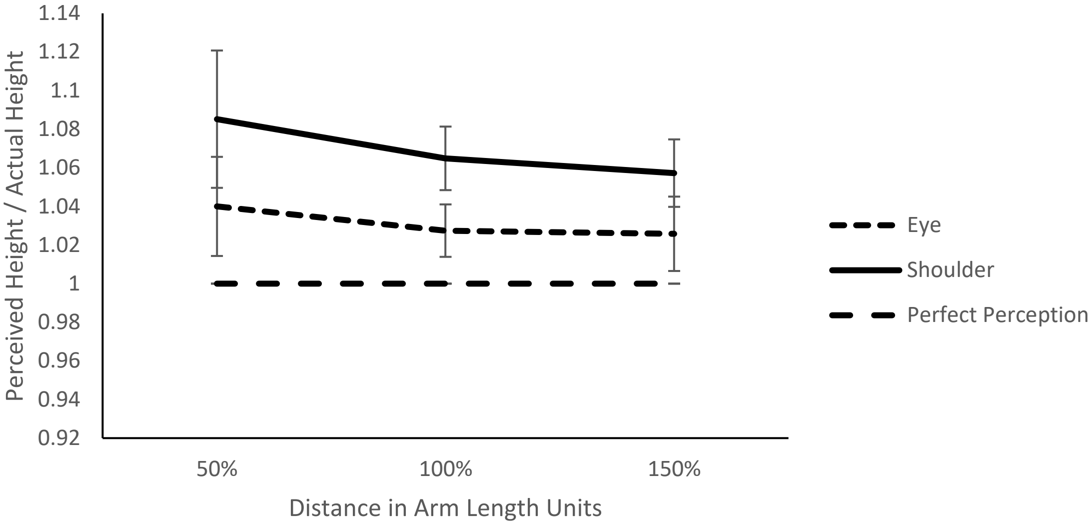


Figure B.3 *Perceived Height over Actual Height (π) as a Function of Distance*

π numbers by distance for Eye and Shoulder Responses in Experiment 1. π numbers are compared to a value of 1 that indicates accurate perception. Error bars represent 95% confidence intervals.

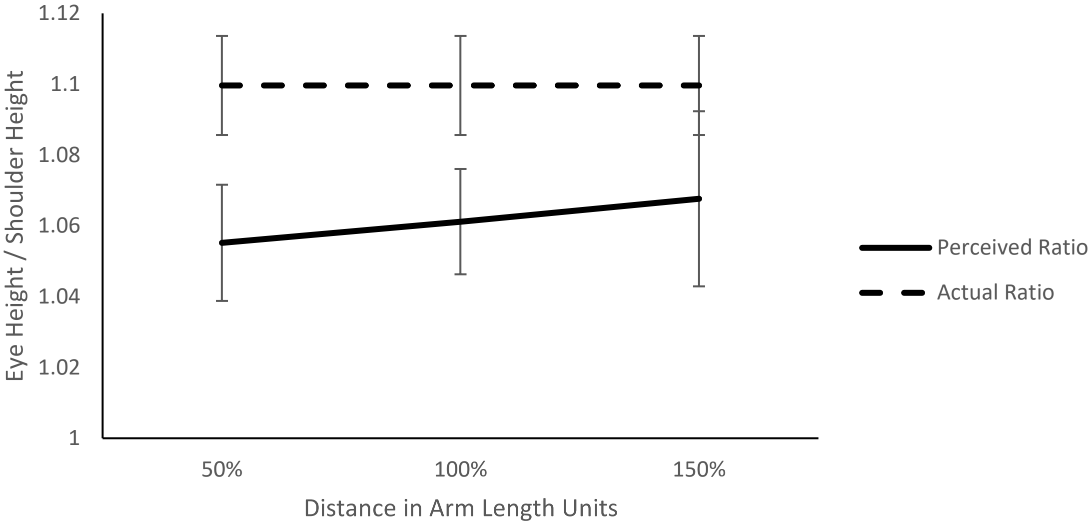
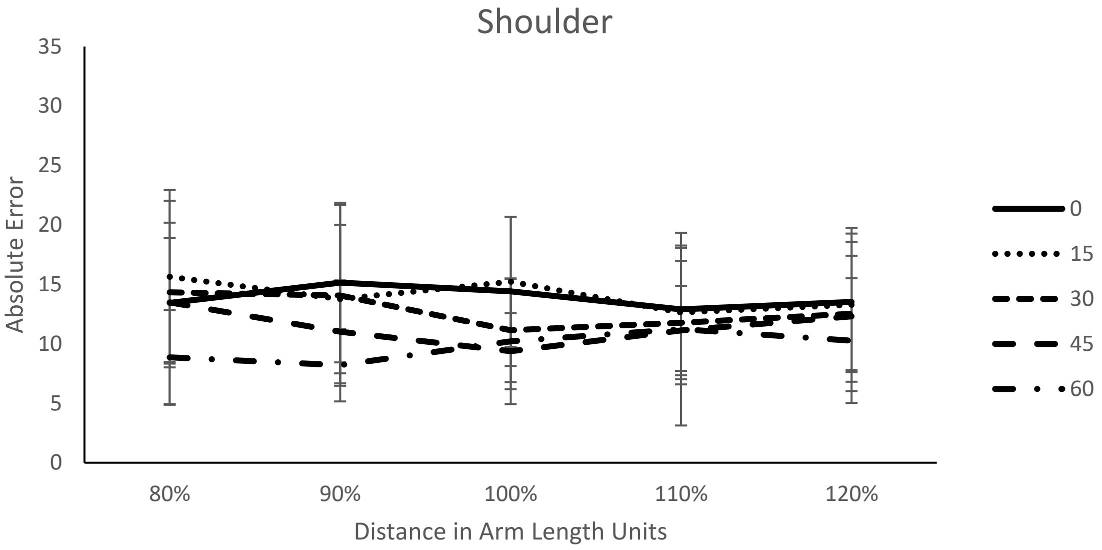


Figure B.4 *Perceived Eye Height/Perceived Shoulder Height as a Function of Distance*

Ratio of perceived eye height to perceived shoulder height as a function of distance in arm length units in Experiment 1. Error bars represent 95% confidence intervals.



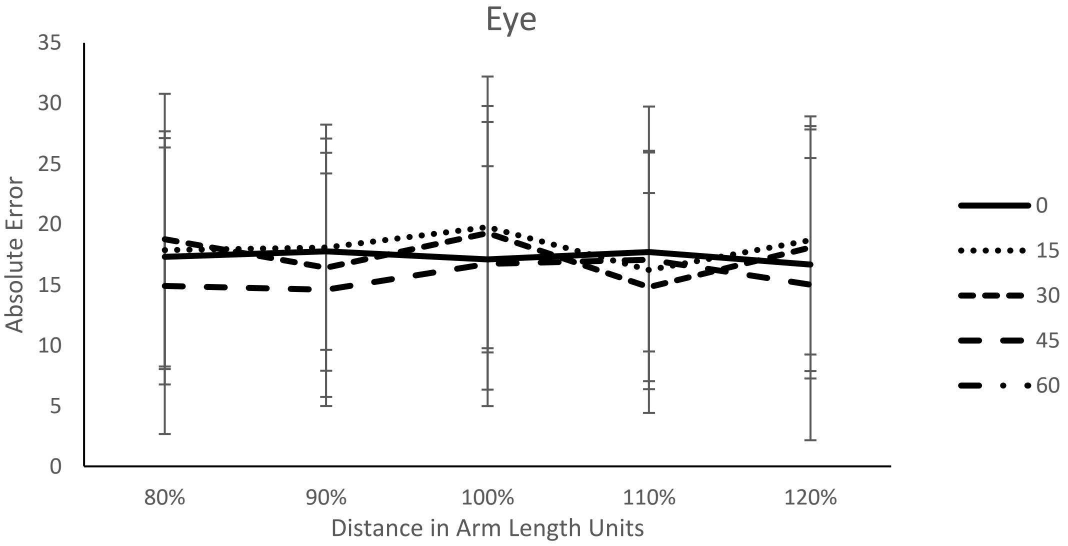


Figure B.5 *Absolute Error Experiment 2*

Absolute Error of pointing as a function of angle of declination and distance in arm length units in Experiment 2. Error bars represent 95% confidence intervals.

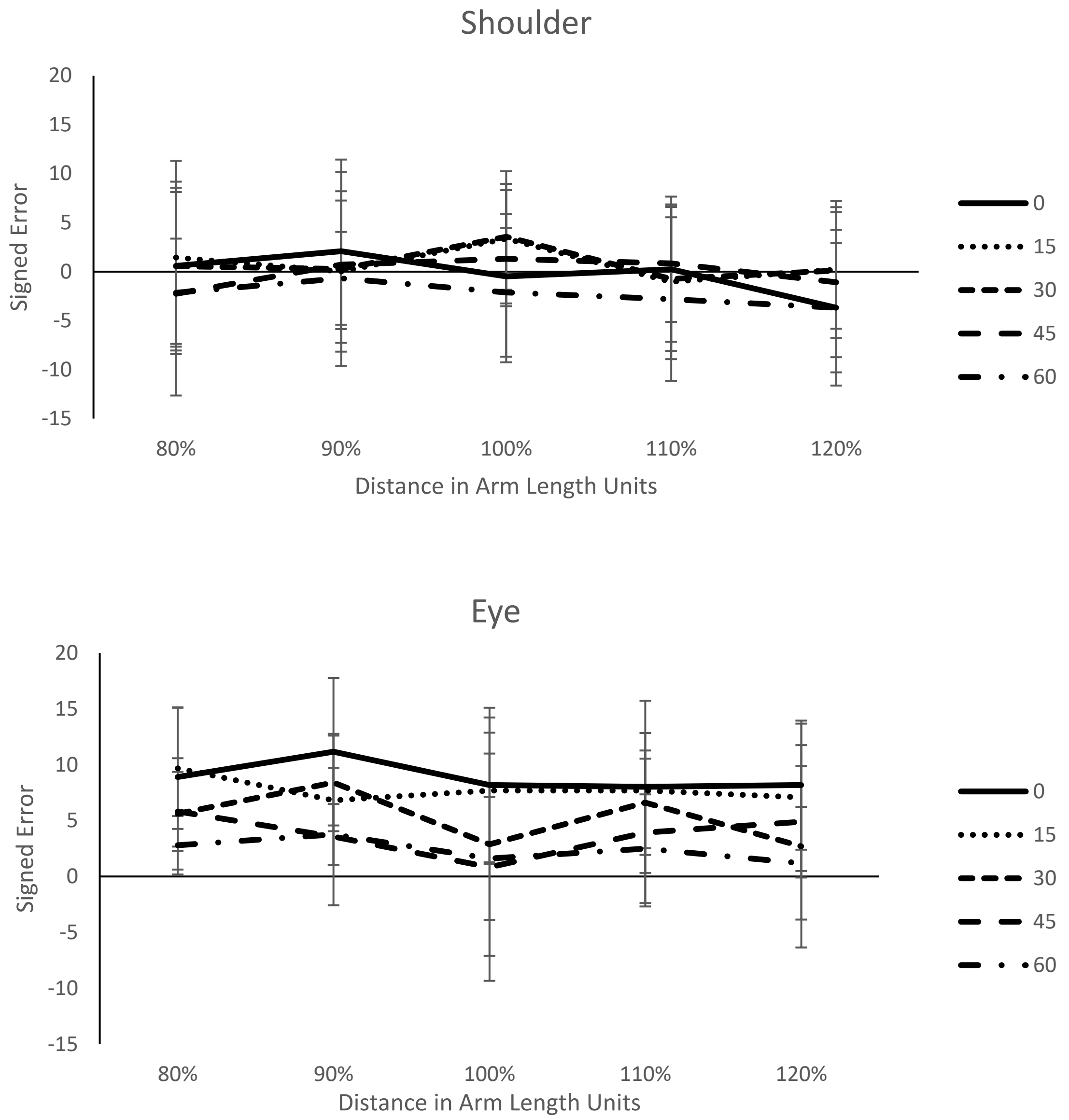


Figure B.6 *Signed Error Experiment 2*

Signed Error of pointing as a function of angle of declination and distance in arm length units in Experiment 2. Error bars represent 95% confidence intervals.

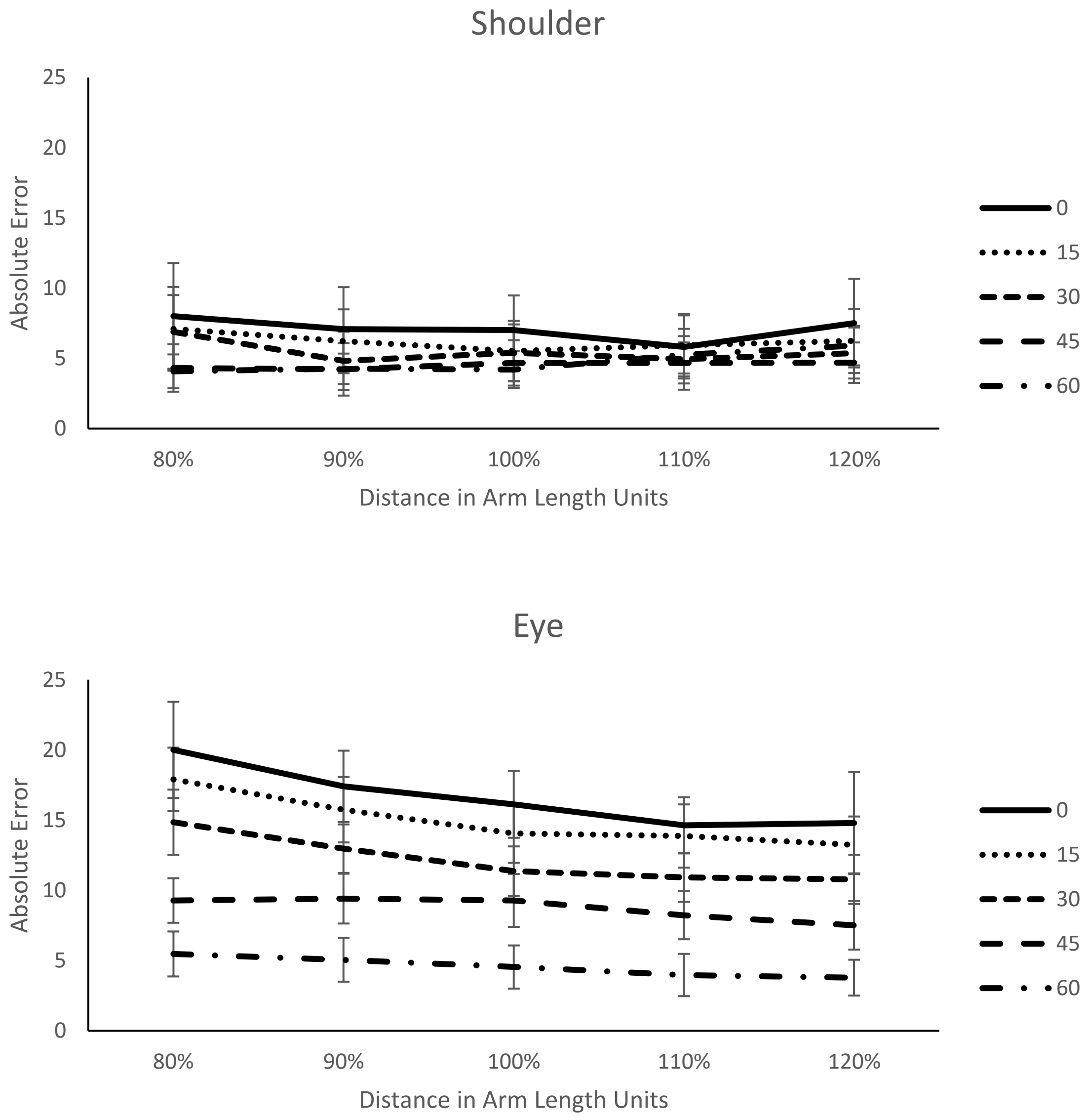
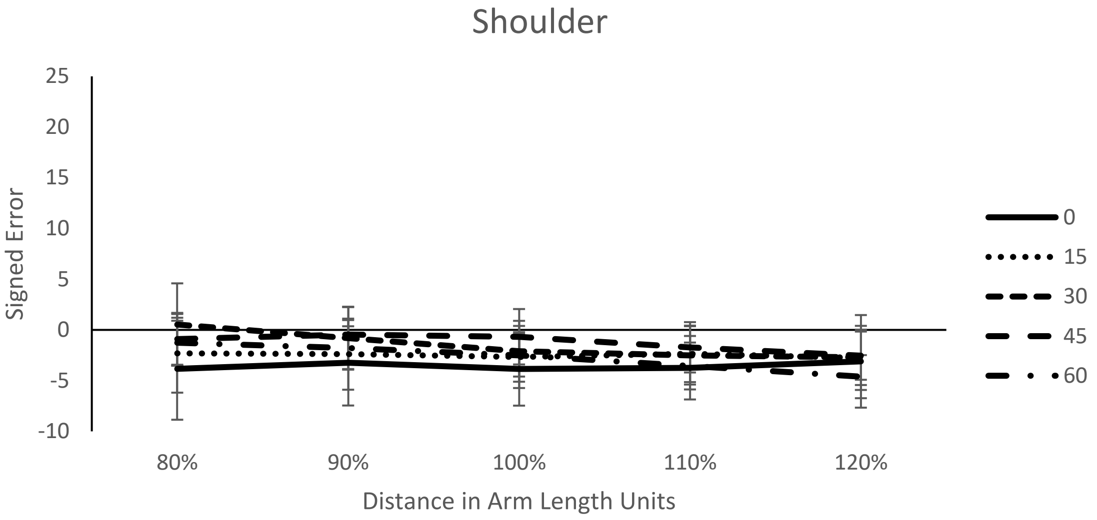


Figure B.7 *Absolute Error Experiment 3*

Absolute Error of pointing as a function of angle of declination and distance in arm length units in Experiment 3. Error bars represent 95% confidence intervals.



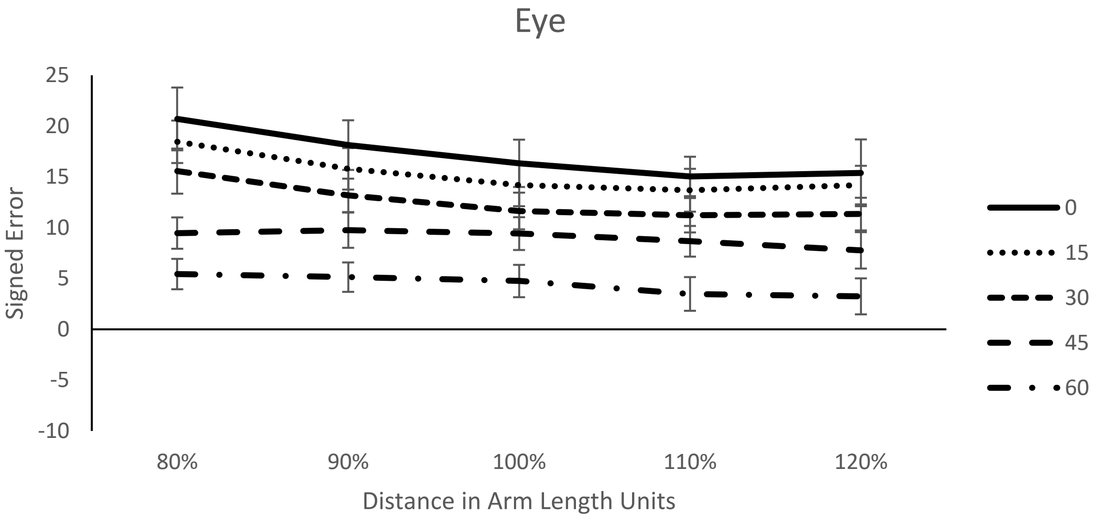
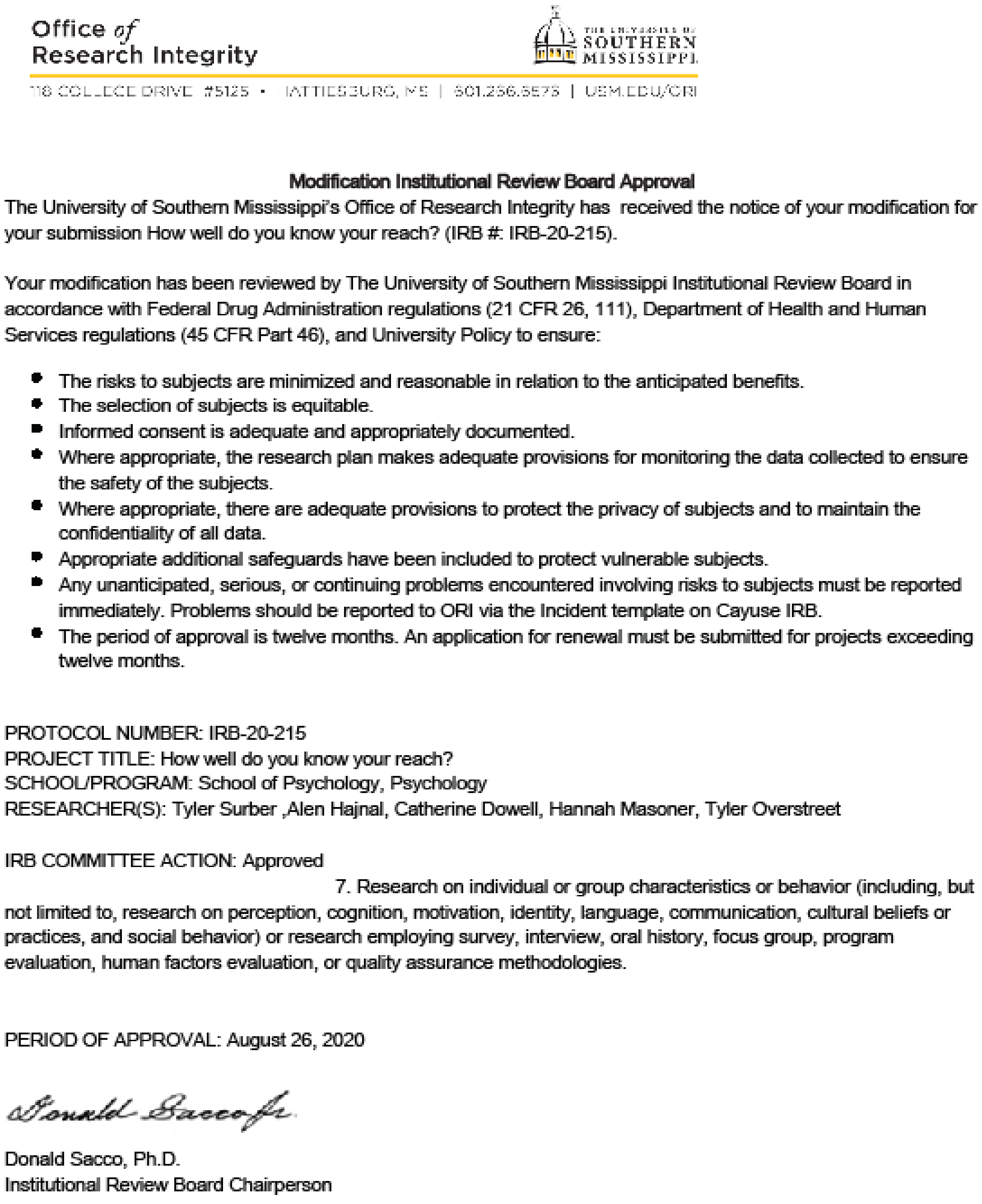


Figure B.8 *Signed Error Experiment 3*

Signed Error of pointing as a function of angle of declination and distance in arm length units in Experiment 3. Error bars represent 95% confidence intervals.

APPENDIX C – IRB Approval Letter



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Modification Institutional Review Board Approval

The University of Southern Mississippi's Office of Research Integrity has received the notice of your modification for your submission How well do you know your reach? (IRB #: IRB-20-215).

Your modification has been reviewed by The University of Southern Mississippi Institutional Review Board in accordance with Federal Drug Administration regulations (21 CFR 26, 111), Department of Health and Human Services regulations (45 CFR Part 46), and University Policy to ensure:

- The risks to subjects are minimized and reasonable in relation to the anticipated benefits.
- The selection of subjects is equitable.
- Informed consent is adequate and appropriately documented.
- Where appropriate, the research plan makes adequate provisions for monitoring the data collected to ensure the safety of the subjects.
- Where appropriate, there are adequate provisions to protect the privacy of subjects and to maintain the confidentiality of all data.
- Appropriate additional safeguards have been included to protect vulnerable subjects.
- Any unanticipated, serious, or continuing problems encountered involving risks to subjects must be reported immediately. Problems should be reported to ORI via the Incident template on Cayuse IRB.
- The period of approval is twelve months. An application for renewal must be submitted for projects exceeding twelve months.

PROTOCOL NUMBER: IRB-20-215
PROJECT TITLE: How well do you know your reach?
SCHOOL/PROGRAM: School of Psychology, Psychology
RESEARCHER(S): Tyler Surber ,Alen Hajnal, Catherine Dowell, Hannah Masoner, Tyler Overstreet

IRB COMMITTEE ACTION: Approved

7. Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

PERIOD OF APPROVAL: August 26, 2020

Donald Sacco Jr.

Donald Sacco, Ph.D.
Institutional Review Board Chairperson

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