Perceived Depth Modulates Perceptual Resolution

Tasfia Ahsan

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL

FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF ARTS

GRADUATE PROGRAM IN PSYCHOLOGY

YORK UNIVERSITY

TORONTO, ONTARIO

July, 2021

ABSTRACT

The goal of this thesis was to investigate whether changes to perceived depth affects the resolution of object perception. In a series of four experiments, I used psychophysical methods to examine how perceived depth, defined by 2D pictorial cues in the Ponzo Illusion, modulated perceptual resolution even when it was independent to the task at hand. For Experiments 1-2, participants completed size and orientation discrimination tasks with a pair of lines, where the stimuli were placed either on the “close” or “far” portion of the Ponzo Illusion, as well as a non-Illusory “flat” portion. Across both experiments, more precise and faster discrimination abilities were found for lines perceived as closer to the observer. To rule out a potential confound of surface size, a follow up control experiment was conducted on the orientation task (Experiment 2b) using two size-matched non-illusory version of the Ponzo illusion. The results continued to show a persistent enhancement of close objects even when surface size was controlled for. Lastly, in agreement with previous findings, results of Experiment 3 showed that this close benefit extends even to high level perceptual processing such as a face identification task. Together these findings support the idea that the human visual system may have dedicated processes for closer things.

ACKNOWLEDGEMENT

I would first like to thank my supervisor and mentor, Dr. Erez Freud for his guidance, continuous feedback, and patience throughout my entire master's thesis. Your dedication inspires me and your kindness and encouragement has made these past two years one of the most productive time for me. I'm excited to continue in this lab as a PhD student!

I also would like to thank Dr. Laurie M. Wilcox for her thoughtful and motivating support for my work. I am very grateful for getting a chance to work with such a brilliant mind and look forward to continuing on with more collaborations. A special thanks to Dr. Shayna Rosenbaum and Dr. James Elder for being part of my committee and dedicating their time to providing feedback and suggestions.

I am also thankful to all the Freud Lab members who have helped me throughout this project. Your friendships have made this road a lot smoother and more enjoyable. Additionally, I am thankful to all the participants who have taken their time to participate in my research. This work wouldn't have been possible without your support.

Lastly, I want to express my absolute gratitude for my family and friends who have provided constant support – both physically and emotionally - to help me continue on with my education.

PREFACE

Chapter 2 is a manuscript accepted for publication in Psychonomic, Bulletin and Review, by Ahsan, T., Bolton. K., Wilcox, L. M., and Freud, E. entitled “Perceived depth modulates perceptual resolution”. The author of the current thesis is the first author of this work whose contributions include the development of the experimental design, data collection and analysis, and drafting and editing of the manuscript. The second author contributed to data collection. The last two authors developed the study concept, contributed to study designs, and edited the manuscript.

Table of Contents

List of Figures

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Depth perception, the ability to see space in 3D, is critical to see and act on the surrounding space. Both humans and animals rely on depth perception to carry out everyday activities. For example: a person walking in the streets will judge how far another person is from them and change course to avoid a collision; or a lion will decide whether to chase a prey based on how far the prey is from them. One of the fundamental challenges of the visual system is reconstructing a three-dimensional (3D) representation of the world from a two-dimensional (2D) image on the retina. Whereas real objects are made up of tangible substance and exist in 3D space, the optical image of those same objects consist only of patterns of light. Let's take the cup from Figure 1 to demonstrate this example. Although the image being projected to the retina is drastically different for each of the three images shown, observers are still able to recognize the cup as being the same object across different viewpoints. The brain uses a variety of depth cues to represent this 3D information that allows us to perceive the object and then plan actions accordingly.

Figure 1: 3D representation of object

The image shows a coffee mug represented from three different angles and viewpoints. The use of 3D perception allows us to recognize this mug as the same object even when it projects completely different images on the retina.
Source: Cox (2018)

Despite the relevancy of depth perception in our day-to-day function, there is still a lack of research on how depth modulates perception when it is not part of the task (van der Stoep et al., 2016). Studies have shown that our brain processes stimuli uniquely in different regions of space relative to our body (Brain, 1941; Rizzolatti et al., 1997). The space close to our body (that is the peri-personal space, PPS) has gained the reputation of being special due to its functional properties. Evidence has shown increased attentional bias (Reed et al., 2006; 2011), better defensive actions (Graziano and Cooke, 2006), and higher sensitivity to emotional valence (Ruggiero et al., 2017), among other things, in PPS. The brain even contains specialized neurons dedicated to representation of this space (Graziano & Gross, 1994). Therefore, it is unsurprising that there is considerable interest in understanding objects and sensory events in peripersonal space (Makin et al., 2008; Holmes et al., 2004; Ladavas, 2002; See di Pellegrino et al., 2015 for a review).

It may be the case that these special properties observed in PPS may be a result of perceived size of the object in PPS. The perceived size of an object is a function of its perceived distance and retinal size (such that closer objects appeared bigger than those farther away) (Gregory, 1963; 2009). A recent study has shown that even when object size was matched across depth, participants were faster at completing a shape discrimination task when the object was closer to them (Blini et al., 2018). This prompts the question whether a superior perceptual resolution would be observed for closer objects that might be more behaviourally relevant. As such, the aim of this thesis was to explore how perceived distance modulated perceptual resolution of stimuli or task. In particular, I was interested in if the enhancement of near space would translate even when the task was independent to depth perception.

The next few sections provide the relevant background pertaining to this work. I started by reviewing some of the depth cues that helps us perceive depth in this world. I then moved through how these different sources of depth information are represented in our brain, particularly focusing on how information in close space (or peripersonal space) is processed. Finally, I describe a set of experiments that explore how perceptual resolution can help to address these issues.

1.2 Depth perception relies on a combination of depth cues

Throughout history, the problem of depth perception has captured the interest of scholars and philosophers. As early as 300 B.C, Euclid wrote his book on Optics, explaining how the difference between our eye positions lead to different images being projected on to each eye. This was further developed by Claudius Ptolemy in 100-175 A.D to bring forth the first geometrical analysis of binocular vision (Howard & Wade, 1996). By the 15th Century, artists of the Italian Renaissance period had begun incorporating monocular depth cues (i.e., perspective and shading) into their paintings. To date, much progress has been made to understand how the visual system integrates these different depth cues to represent 3D space.

Binocular depth cues allow humans to perceive objects in 3D space, and is made possible because of our two eyes, located slightly far apart from each other. Light rays reflected off an object are projected onto the retina of each eye, which receive a slightly different images of the world as a result of the distance between the two eyes. The difference between the images from each eye gives the visual system an important depth cue, called binocular disparity, which allows it to figure out where objects are in 3D space. Binocular disparity is inversely proportional to object distance (Harris, 2004). For instance, if there were three uniformly sized object placed at all distances from an observer, there would be a larger disparity for the object closer to the observer. The human visual system is so sensitive to binocular disparity that this cue alone is sufficient to produce a 3D percept (Julesz, 1964; Blakemore, 1970). However, in order to get a rich representation of our surrounding, depth perception doesn't rely solely on binocular cues, but also on a set of monocular cues.

The human visual system can extract depth information even from a set of monocular cues (also known as pictorial cues), that is, the patterns in the image projected to only a single eye, in order to deduce a 3D layout from a 2D retinal image (Burton, 1945). Gibson (1950) postulated that the visual system achieves this by detecting changes in gradient, or increases and decreases, of visual elements. Since then several psychophysical studies have shown that humans are able to perceive depth from several monocular cues such as, linear perspective (Clark et al., 1955; Stevens, 1983) and texture gradient (Gruber and Clark, 1956). For example, if we return to our earlier example of three uniformly sized objects across depth and only examine the input to a single eye, the object closest to the observer would project to a larger image on the retina than objects farther away (Figure 2B). This monocular cue is known as relative size and occurs alongside another cue called perspective lines. Perspectives lines cause parallel lines to recede in depth as a result of a smaller image being projected on to the retina. Some other examples of monocular cues include blurring, shading, or occlusion (Howard, 2002).

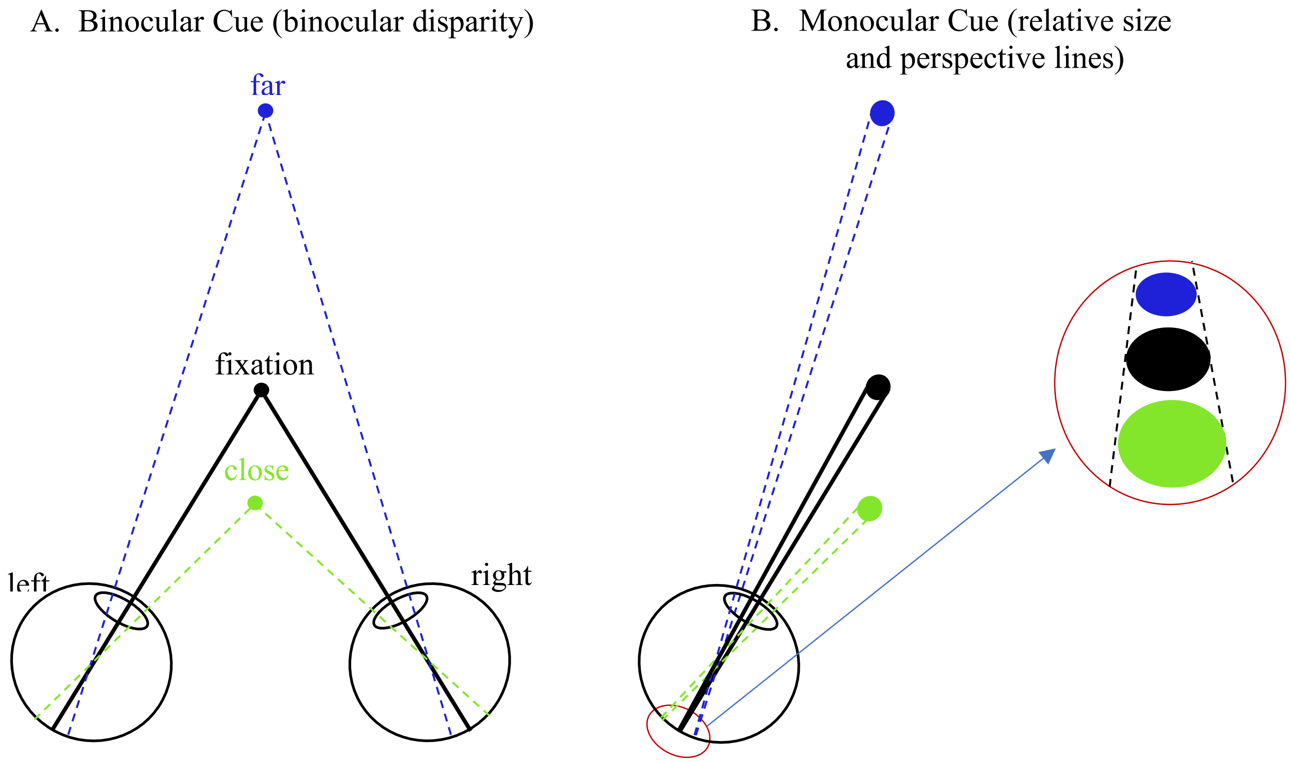


Figure 2: Binocular and monocular depth cues

Figure 2 shows examples of binocular and monocular depth cues. A) binocular disparity, where the black point represents the point in fixation, purple represents a point far away, a green represents a point closer to the observer. B) shows the monocular depth cues perceived by the left eye. The object closest to the observer (green) produces the largest image on the retina, and therefore has the largest relative size. In contrast, the object farthest from the observer (purple) produces the smallest retinal image and has the smallest relative size on the eye.

Visual artists have long been taking advantages of monocular cues to depict realistic portrayals of depth and visual illusions (Smith & Gruber, 1958). For example, the famous Ponzo Illusion uses a contrasting combination of linear perspective and relative size to trick the visual system (Figure 3). In this illusion, the brain expects the line farther away from the observer (as indicated by the converging perspective lines) to produce a smaller image (smaller relative size). However, since the two lines have identical lengths, we perceive the line on top to be longer in the presence of monocular cues (Figure 3a and b) than when the lines are by themselves (3c).

A) Target lines in naturalistic

B) Target lines with some relevant

C) Target lines without any

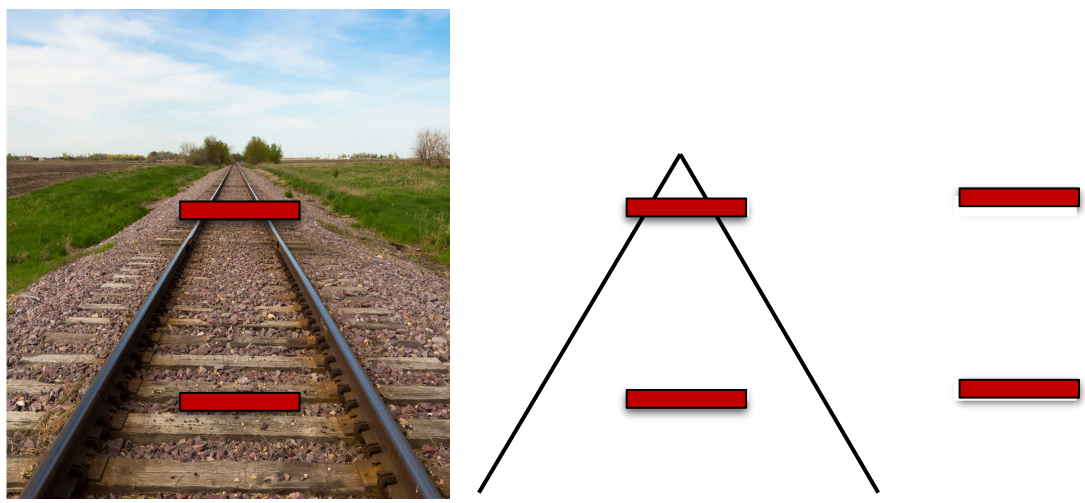


Figure 3: Ponzo Illusion in three different states

Figure 3 depicts a pair of identical red bars in three different scenarios. A shows the red bars on top of a naturally occurring ponzo illusion. The monocular cues of perspective line and relative size makes the top red bar appear longer than the bottom red bar. B strips away all other features except the relevant monocular cue (i.e., perspective lines). The top red bar continues to look longer than the bottom one. C presents the two red bars without any monocular cue, which makes the red bars appear equal in size again. Together these images show how strong the illusion can be even when stripped to its bare minimum.

Susceptibility to these illusions is strong and automatic, and having knowledge of the illusion also doesn't change our perception of it (Pylyshyn, 1999). The illusory effect extends even to observers that are visually naïve. For example, children with extended early-onset blindness were susceptible to the Ponzo Illusion immediately after gaining sight, which is suggestive of a deep-rooted mechanism in humans (Gandhi et al., 2015; Freud et al., 2021) and even some animals (Timney & Keil, 1996; Gunderson et al., 1993). These findings suggest that depth perception is not a learned association, but rather the brain has innate mechanisms to represent close and far spaces.

1.3 Differential processing for near and far space

The idea that the brain constructs various representation of space based on depth information was first suggested by Brain (1940) when he proposed the existence of a grasping distance and walking distance to account for deficits seen in patient with lesions to the right parietal cortex. Rizzolatti and colleagues (1981) elaborated on this idea stating that the brain processes stimuli uniquely in different regions of space relative to our body. According to this view, the space around us can be divided into two major parts: the peripersonal space (PPS) is the region of space that immediately surrounds our body, while the extrapersonal space (EPS) is the region that falls beyond our body's reach. For instance, in Figure 3, the space close to our body in PPS (indicated by blue) are behaviourally relevant because objects in this space (i.e., croissant) are reachable and hence can be manipulated (such as grabbing and eating). In contrast, the objects farther away (i.e., brown jar) fall in the EPS, where the observer must move their body in order to act on the object.

Figure 4: Peripersonal and Extrapersonal space

Figure 4 shows the region of space that can be acted on (in blue) within the PPS.

Over the years, evidence of this pattern of differential processing continued to emerge in neurophysiological studies on nonhuman primates. For instance, in the macaque brain, specialized neurons caudal to the periarcuate cortex have been shown to respond specifically to stimuli presented in proximity to the animal, whereas neurons rostral to the periarcuate cortex are primarily activated by stimuli presented far from the animal (Rizzolatti et al, 1981). In another example, Pettigrew and Dreher (1987) found differential activations in separate visual pathways in response to cats interacting with different parts of the three-dimensional space. In particular, they found the cat Y-cell system (comparable to the primate magnocellular) processed information in peripersonal (near) space, whereas the cat X-cell system (comparable to the primate parvocellular) processed information in the extra personal space. The discovery of the Y-cell/X-cell systems was seminal to understanding the role of two distinct sub-systems (magnocellular/parvocellular) in human depth perception.

A series of studies support the involvement of functionally dissociated sub-systems for PPS (Antonucci, 1992; Ortigue et al., 2006) and EPS (Cowey et al., 1994; Ortigue et al., 2006) in humans. In one notable example, healthy individuals performed a line bisection task, where horizontal lines of different lenths were presented in the personal (300 mm), peri-personal (600 mm), peri-extrapersonal (900 mm), and extra-personal (1200 mm) space (Varnava et al., 2002). They found that participants made more leftward bisection errors in peripersonal space, which was either absent or replaced with a rightward bias in the extrapersonal space. The results of this study provide strong behavioural support towards the existence of two dissociable neural systems responsible for attending and acting in near and far space. This double dissociation was also corroborated by neurophysiological studies (Leinonen & Nyman, 1979; Mountcastle, 1976). More importantly however, several of these studies have found a unique processing benefit to stimuli presented near the observer's body (in the peripersonal space), creating a phenomenon known as the close advantage (Rizzolatti et al., 1983; Kaas & Mier, 2006; Làdavas, 2002).

1.3a Enhanced processing in the peripersonal space

The close advantage refers to an enhanced processing of objects that are in close proximity to the body. In one example, Tseng & Bridgeman (2011) noticed enhanced change detection abilities when they positioned their hands closer to a display. In a similar trend, McCourt and Garlinghouse (2000) used a line bisection task with healthy adults and found more cases of pseudoneglect (defined as the leftward bias in attention) in peripersonal space than in extrapersonal space. Their findings not only provide support for two different systems for processing of space (Varnava et al., 2002) but also highlights better performance in the peripersonal space. Other examples of the close advantage include: a faster rate of image processing (Reed et al., 2006) and increased attentional prioritization and slower attentional disengagement from tasks (Abrams et al., 2008) for objects presented in the peripersonal space (near the hand). Despite the large amounts of multisensory studies that have confirmed the close advantage, very few have been done purely on the visual advantage (de Vignemont, 2018).

One notable exception to this is a recent study done by Blini and colleagues (2018) where the authors show that shape perception, a fundamental attribute of the human visual system, is also enhanced when presented in near space (PPS) compared to far space (EPS). In the study, participants completed a shape discrimination task in a virtual reality environment. The authors matched the retinal sizes of the objects across depth, making the objects farther away appear illusory bigger. Even with closer objects appearing noticeably smaller, their results show a persistent close processing benefit, which cannot be accounted for by upper/lower visual fields, or vergence eye-movements. Notably, Blini at al. (2018) used reaction time as a measure of discrimination abilities which might reflect a more efficient processing of the closer objects but could also reflect other cognitive processes such as response bias. Hence, these findings alone do not allow a clear conclusion about the underlying mechanisms of the close advantage effect.

In another study, Li and colleagues (2011) reported a close advantage for detection of target objects. However, unlike Blini et al (2018) they failed to find any enhanced processing for the identification of target objects. The apparent inconsistencies in the literature may be a result of the task employed by each group. In their study, Blini and colleagues (2018) used a binary decision task which made the task very easy and did not provide insight into psychophysical sensitivity. In comparison, Li and colleagues (2011) used a dual task, which may have made the task too difficult, in addition to the targets being presented in the center and periphery. Due to differences in task type and difficulty, it stands to reason that using a precise psychophysical method will help to determine if there is greater detection and identification of objects in the near space.

1.4 Aims of Present Study

In the above literature review, I have summarized evidence that show differential processing between the close (PPS) and far space (EPS). In particular, I have highlighted behavioural studies that support an altered processing in the near space. However, few studies have investigated depth effects on a fundamental property (such as perceptual resolution). In comparison to previous studies (Blini et al. 2018; Li et al. 2011), my approach allows me to carefully characterize psychophysical sensitivity, while also accounting for individual differences.

My thesis is composed from four different experiments that were designed to elucidate how perceived depth modulates perceptual resolution of different object properties. Across all tasks, participants discriminated between two stimuli presented on surfaces perceived as closer or father away from them, as well as a flat condition with no depth cues. I predicted that enhanced processing would be observed for objects that are perceived as closer to the observer compared with far objects or objects that are perceived on a flat surface. To the extent to which this differential processing reflects a processing enhancement, and not changes in response bias, I predicted that there would be smaller just noticeable difference (JND) values observed for objects perceived as closer to the observer. This should be complimented with shorter reaction times (RT), in line with results of previous studies (Blini et al., 2018; Reed et al., 2006).

CHAPTER 2

Perceived depth modulates perceptual resolution
(Accepted for publication in Psychonomic Bulletin and Review)

Tasfia Ahsan, Kathryn Bolton, Laurie M. Wilcox, and Erez Freud

2.1 Abstract

Humans constantly use depth information to support perceptual decisions about object size and location in space, as well as planning and executing actions. It was recently reported that perceived depth modulates perceptual performance even when depth information is not relevant to the task, with faster shape discrimination for objects perceived as being close to the observer. However, it is yet to be determined if the observed "close advantage" reflects differences in psychophysical sensitivity or response bias. Moreover, it is unclear whether this advantage is generalizable to other viewing situations and tasks. To address these outstanding issues, we evaluated whether visual resolution is modulated by perceived depth defined by 2D pictorial cues. In a series of experiments, we used the method of constant stimuli to measure the precision of perceptual judgements for stimuli positioned at close, far, and flat perceived distances. In Experiment 1, we found that size discrimination was more precise when the object was perceived to be closer to the observers. Experiments 2a and 2b extended this finding to a visual property orthogonal to depth information, by showing superior orientation discrimination for "close" objects. Finally, Experiment 3 demonstrated that the close advantage also occurs when performing high-level perceptual tasks such as face perception. Taken together, our results provide novel evidence that the perceived depth of an object, as defined by pictorial cues, modulates the precision of visual processing for close objects.

Keywords: Depth perception, JND, close advantage, constant stimuli, object recognition

2.2 Introduction

The ability to see space in three dimensions (3D) is a fundamental achievement of the human visual system. Even though each eye receives a flat two-dimensional (2D) image, the human visual system extracts information from a set of monocular and binocular depth cues to provide us with the 3D layout of the visual environment (Howard, 2012). This information is critical for the perception of relative depth and distance of objects, but also for guidance of actions and interactions with our surroundings.

The importance of depth information to everyday life is also demonstrated by results that show that viewing distance modulates sensory processing. Based on these findings it has been suggested that 3D space can be sub-divided relative to the distance from the observer. Peripersonal space (PPS) is a region of space that immediately surrounds our body, while extrapersonal space (EPS) is a region that falls beyond our body's reach (Previc, 1990, 1998; Rizzolatti et al., 1997). Notably, there is an accumulation of evidence pointing to a privileged processing of objects within PPS (Kaas & Mier, 2006; Làdavas, 2002). For example, participants were found to be more accurate when performing a simple spatial discrimination task for objects in PPS than in EPS (Dufour & Touzalin, 2008). Along similar lines, participants showed enhanced change detection abilities when they positioned their hands closer to a monitor on which the stimuli were displayed (Tseng & Bridgeman, 2011).

Both the above-mentioned studies (Tseng & Bridgeman, 2011; Dufour & Touzalin, 2008) suggest perceptual and attentional performance are affected by the location of the hand in PPS. As such, this privileged processing may reflect top-down processes, such as the relationship between affordance and space. According to this view, the enhanced processing is triggered by specific object features (e.g., handles), particularly when they fall within the reachable space

(Costantini et al., 2010). This link between affordance and PPS is corroborated by other behavioral studies which have shown that participants recognize functional/manipulation verbs more rapidly when objects are placed in PPS (Costantini et al., 2011), a well as neurophysiological studies showing bimodal neurons (that respond to both visual and tactile stimuli) responsible for coding visual PPS (Làdavas, 2002).

While the preceding studies attributed the privileged processing within PPS to action related mechanisms, a recent study by Blini and colleagues (2018) suggests that even shape perception is enhanced when objects are perceived as close to the observer and that this effect holds even when depth is defined by pictorial cues. In their study, response times in a 2-AFC object classification task decreased as the perceived distance of the target decreased. However, since the effect is evident only in the reaction time measure and the task was a binary one (rather than a continuous transformation), it is not clear whether the close advantage reflects changes in response bias or an enhancement of perceptual resolution. Importantly, it was recently reported that humans are less able to inhibit motor actions directed to rewarding cues that are within reach, further demonstrating the potential role of response bias in the close advantage effect (O'Connor et al., 2021). Thus, it is important that we determine if this phenomenon is apparent in measures of psychophysical sensitivity (i.e., Just Noticeable Difference, JND) and not only in terms of reaction time.

To address these gaps, the current study explores whether visual resolution is modulated by perceived depth across a range of tasks and visual attributes, using the method of constant stimuli (Urban, 1910) that allows detailed characterization of perceptual sensitivity. We used 2D pictorial cues of the Ponzo illusion (Fig. 1A) to induce changes in perceived depth. a large number of studies have established that the Ponzo illusion reliably induces significant depth percepts across ages (Freud et al., 2021; Gandhi et al., 2015) and species (Timney & Keil, 1996; Gunderson et al., 1993).

In Experiment 1, we examined the effects of this manipulation on size discrimination. However, given the inherent relationship between size and depth perception, in Experiment 2a, we explored whether sensitivity to orientation, a task orthogonal to depth processing, is similarly affected by perceived depth. In a follow up Experiment 2b, we replicated the orientation task while addressing a potential confound due to the relative sizes of the background surfaces. Finally, in Experiment 3, we examined whether higher-level visual properties were also impacted by perceived depth using a face identification task. Collectively these experiments provide compelling evidence that the visual system prioritizes processing of objects perceived as close to us.

2.3a Experiment 1: Size

Methods

Data Availability

The datasets generated for all experiments are available in the OSF repository: https://osf.io/974du/

Participants

Data was obtained from 18 healthy adults (age: M = 23.8, SD = 9.26; 2 males), none of whom participated in any of the other experiments reported here. The sample size used for this experiment was consistent with the average sample size used in similar studies (Ganel et al., 2008; Blini et al., 2018). The data from two participants were excluded because of near chance level performance for all conditions (indicative of guessing). All participants were recruited from York University's undergraduate research participant pool (URPP) and received course credit for their participation. Participants were screened to be right-handed with normal to corrected vision and were enrolled in the study after obtaining their informed written consent form. All experiments were approved by the York University Human Participants Review Committee (HPRC) prior to data collection.

Materials and Apparatus

Experiment 1 was conducted in a laboratory setting using a PC desktop computer with Windows 10 operating system. The stimuli were displayed on a 24-inch monitor with a viewing distance of 50 cm, the resolution of the monitor was 1900 x 1200 pixels. Experimental stimuli were drawn and displayed using PsychoPy3 (Peirce, 2007). All lines subtended a visual angle of 2.48° x 2.98°. The main experiment consisted of 12 levels, a step size of 0.07 cm (0.05° change in visual angle), with the conditions centred on the reference height of 2.00 cm (See Fig. 1B for sample length continua).

On each trial, two lines[1] of different heights were overlaid on a version of the Ponzo Illusion or non-illusory (Ponzo Flat) background (Fig. 1A). Both versions of the Ponzo background were adopted from previous experiments (Ganel et al., 2008; Freud et al., 2021). Stimuli placed on the larger rectangle of the Ponzo Illusion appeared to the observer, while stimuli placed on the smaller rectangle appeared "far" from the observer. The Ponzo "flat" condition was used as a control and did not contain any depth cues. The size of both

[1] The stimuli in Experiment 1 are better characterized as elongated rectangles than "lines". However, we refer to these stimuli as lines in order to avoid confusion when referring to the rectangles that form the Ponzo background.

backgrounds was 23.85 cm x 11.36 cm (resulting in a visual angle of 28.94° x 14.02°), which were counterbalanced between left and right for the two perceived depths (close and far) and no depth (flat) conditions. All stimuli were presented at the same height relative to a fixation cross to rule out potential confounds due to relative height in the field. Randomized interleaved conditions were used to show all stimuli across the three depth conditions.

Procedure

Each trial consisted of a fixation phase (800 ms) followed by the presentation of a pair of lines randomly chosen to be in the close, flat, or far portion of the Ponzo backgrounds using a method of constant stimuli. On each trial, participants were asked to determine which of the two lines was longer. They indicated their responses by pressing F (for left) and K (for right) keys on the keyboard. Stimuli were presented for up to a maximum of 3000 ms and were replaced by the next stimuli once participants had made a response. If participants failed to respond within the given time, then the stimuli were replaced by a black screen until a response was made. Participants were asked to respond as quickly and accurately as possible. A total of 72 trials (12 sizes x 3 depths x 2 sides (left and right) were repeated 12 times resulting in a total of 864 trials); therefore, each size level was presented a total of 24 times (12 sizes x 2 counterbalanced sides) in a randomized order. The experiment duration was approximately 30 minutes with a break at the mid-point.

Data analysis

Statistical analyses were conducted using JASP (JASP team, 2018), R (R Core Team, 2020), and MATLAB (R2018b, Mathworks). The proportion of 'longer' responses, and reaction times (RT), reported as seconds, were recorded for each participant. Just noticeable difference (JND) values were calculated for each observer by averaging the proportion 'longer' responses for each condition and fitting a cumulative normal psychometric function using the maximum likelihood method. The JND represents the change in sensitivity to one increment change in stimulus magnitude, thus a smaller JND indicates greater precision, and a shorter RT represents more rapid classification.

2.3b Results

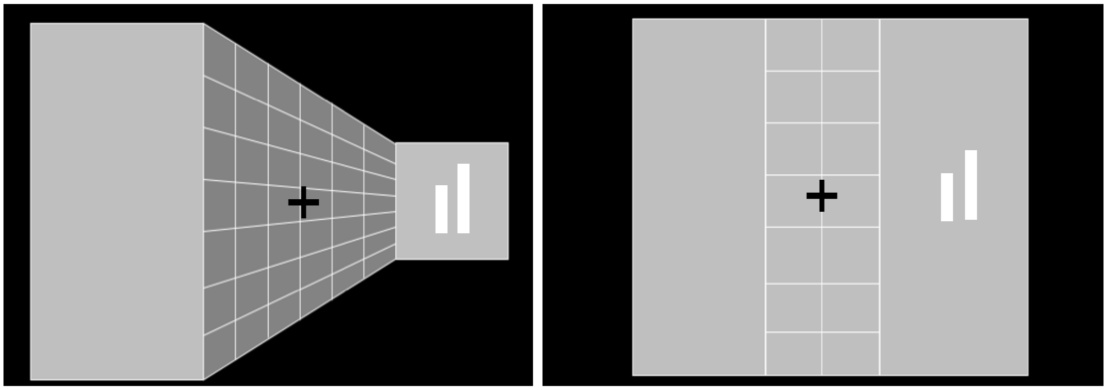
To examine whether perceptual resolution is modulated by the perceived location in depth of the objects, participants discriminated between two lines presented on close vs. far perceived depth planes. The results of Experiment 1 (Fig. 1C) revealed that both JNDs and RTs were lower for objects that were perceived as closer to the observer.

This observation was supported by a repeated measures ANOVA on JND scores with perceived depth as the independent variable. The ANOVA revealed a main effect of perceived depth on size JND [$F_{(2,30)}$=7.451, p<.005, $\eta_p^2 = 0.33$]. Planned comparisons showed that this effect reflected smaller JNDs for the close condition compared with the far condition ($t_{(15)}$ = 3.36, p = 0.004; Mean Difference: 0.100 [CI: 0.036, 0.164]); as well as for the flat condition compared with the far condition ($t_{(15)}$ = 2.54, p=0.02, Mean Difference = 0.062 [CI: 0.010, 0.113]). The close and flat JND scores were not significantly different from each other ($t_{(15)}$ < 1; Mean Difference = 0.039 [CI: 0.09, -0.012]).

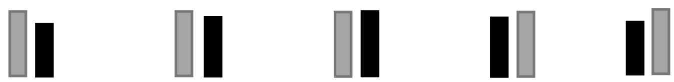
The RT results were also consistent with our hypothesis. That is, a main effect of perceived depth was found for size RT [$F_{(2,30)}$=5.84, p<.01, $\eta_p^2 = 0.28$]. Results of planned comparisons showed faster RTs for the close condition compared with the far condition ($t_{(15)}$ =3.80, p = 0.001; Mean Difference = 99 [CI: 43, 154]); as well as for the flat condition compared with the far condition ($t_{(15)}$ = 2.54, p=0.02 Mean Difference = 102 [CI: 16.7, 187]). Similar to the JND scores, RT were similar between the close and flat conditions ($t_{(15)}$ <1; Mean Difference = 3 [CI: -70, 76.4]).

Together, the results of Experiment 1 revealed a clear effect of perceived depth; both perceptual resolution and speed of judgment improved when objects were positioned on the perceptually closer surface, even though their retinal size remained constant across depth conditions.

A



B



Target length (cm):	1.86	1.93	2.00	2.07	2.14
Reference (cm):	2.00	2.00	2.00	2.00	2.00

C

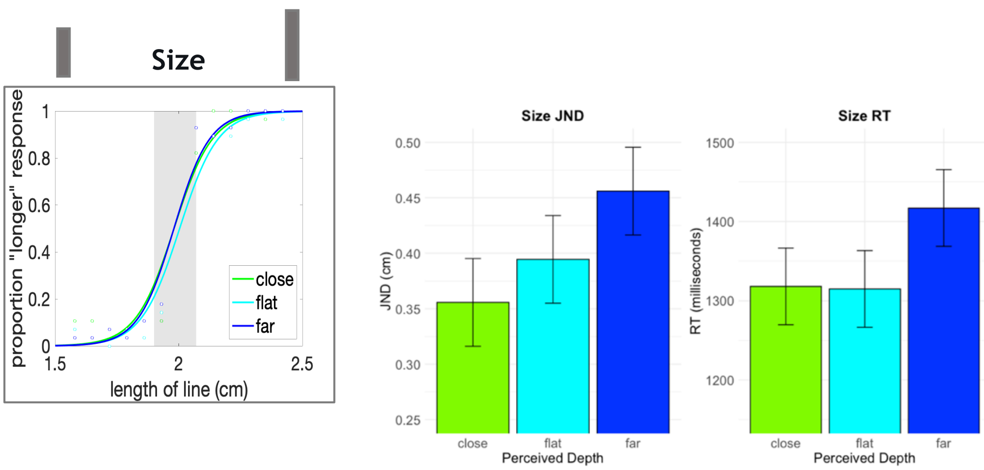


Fig. 1 Experimental backgrounds (A) , and Experiment 1 Stimuli (B), and Results (C)

A) Experimental backgrounds - Ponzo illusion (left) and control "flat" background (right) were used as the background across the different experiments. The Ponzo illusion is based on 2D perspective cues which make stimuli appear "close" or "far" from participant. The Ponzo Flat has all perspective lines removed to provide a non-illusory control background. Sample white lines are used to show how stimuli would be presented on top of the background (example is presented on "far" right side and "flat" right side. **B)** Experimental stimuli for Experiment 1 – the length of the target lines was manipulated with a step size of 0.07cm, while the length of the reference line was set at 2.00 cm. **C)** Results of Experiment 1 – changes in perceptual resolution as a function of perceived depth. Left panel shows the fit for one representative participant, middle panel shows the average JNDs and right panel shows average RTs. Error bars across all figures are 95% Confidence Intervals (Jarmasz & Hollands, 2009).

2.4a Experiment 2a: Orientation

The results of Experiment 1 demonstrated improved size discrimination with more precision and faster processing time for closer objects compared with those that were perceived as far. However, it is important to note that the even though the retinal sizes of the stimuli were equal across the depth conditions, the perceived sizes of the stimuli could have been modulated by their perceived depth, such that “closer” objects were perceived as smaller. Importantly, in accordance with Weber’s law (Baird & Noma, 1978), better perceptual resolution is predicted for smaller objects within the limits of visual acuity. Thus, it could be argued that the results of Experiment 1 simply reflected an adherence to Weber’s law based on the perceived object size. To address this concern, in Experiment 2a, we evaluated whether a similar “close advantage” is observed in a task involving orientation classification, a visual feature that should not be modulated by perceived depth and should not be affected by Weber’s law.

Method

Participants

Data was obtained from 18 adults (age: M=23.4, SD = 4.03; 4 males), none of whom participated in any of the other experiments. The data from 3 participants were excluded because of near chance level performance in all conditions. All other aspects of the recruiting process followed the same guidelines as Experiment 1.

Material and Apparatus

The apparatus and stimuli were same as Experiment 1, with the exception of the following changes. Both lines were 2 cm in length and 0.2 cm in width, separated by a distance of 2 cm. The main experiment consisted of 11 levels, step size varying from 0.5º to 2.5º rotated clockwise from a vertical position, with the conditions centred on the reference orientation of 15º (See Fig. 1A for background and Fig. 2A for sample orientation continua).

Procedure

The procedure was the same as that described in Experiment 1 except that observers were asked to judge line orientation. Participants performed an orientation task involving two lines of different orientations, and determine which line is more rotated clockwise. Each participant underwent a brief pretest consisting of 24 trials repeated four times (total 96 trials). The pretest was used to calculate the step size for each individual and was not included in the final analysis. For the main experiment, a total of 66 trials (11 orientations x 3 depths x 2 counterbalanced sides) were repeated 12 times (total 792 trials); therefore, each level was presented 22 times (11 orientations x 2 counterbalanced sides) in a randomized order.

2.4b Results

In Experiment 2a, participants judged line orientation while their perceived depth was manipulated. As presented in Fig. 2B, in agreement with Experiment 1, more precise orientation classification was found for objects positioned on the surface that appeared to be closer to the observer.

Results of a repeated measures ANOVA on the JND data revealed a main effect of perceived depth [$F_{(2,28)} = 3.95$, $p<.05$, $\eta_p^2 = 0.22$]. Planned comparisons showed significantly smaller JND scores for the close condition compared to the far condition ($t_{(14)}= 2.19$, $p=0.004$; Mean Difference = 0.180, [CI: 0.004, 0.355]) and significantly smaller JNDs for the close condition compared to the flat condition ($t_{(14)}$ = 2.36, p= 0.02. Mean Difference = 0.205, [CI: 0.018, 0.390]). No significant differences were found between far and flat condition JND values ($t_{(14)} < 1$; Mean Difference = -0.025, [CI: -0.171, 0.121]).

Similarly, a main effect of perceived depth on RT was found [$F_{(2,28)} = 5.65$, $p<.01$, $\eta_p^2 = .28$]. Planned pairwise comparisons supported the pattern of results seen in the JND scores such that participants performed significantly faster for objects on the close surface compared to both the far ($t_{(14)}$=2.92, p = 0.01, Mean Difference = 69, [CI: 18, 118]) and the flat condition ($t_{(14)}$ = 2.69, p = 0.01, Mean Difference = 49, [CI: 10, 88]). No difference was found between far and flat RT ($t_{(14)} < 1$; Mean Difference = -19, [CI: -25, 64]).

Taken together, the results of Experiment 2a support the conclusion of Experiment 1 and provide additional evidence for superior perceptual resolution for objects that appeared to be closer to the observer even for a task which is considered to be independent of depth processing.

A

Target orientation (°):	7.0	11.0	15.0	19.0	23.0
Reference (°):	15.0	15.0	15.0	15.0	15.0

B

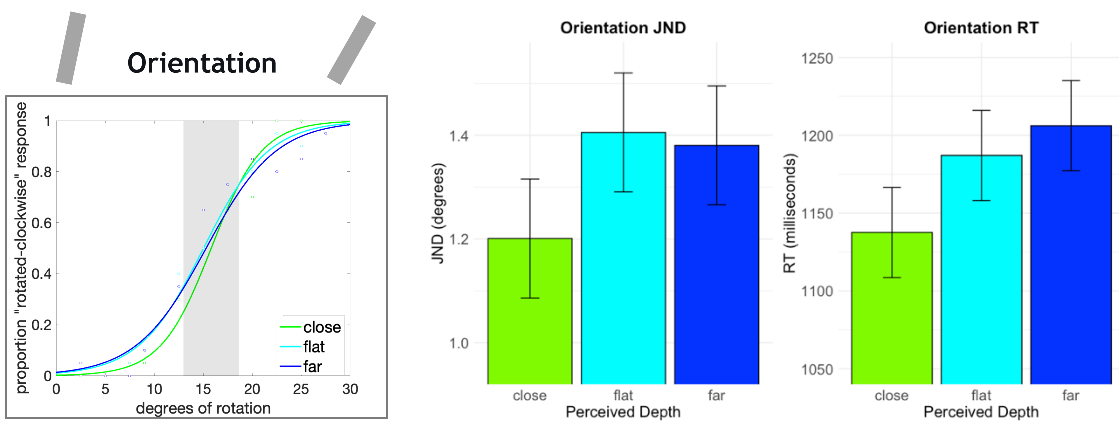


Fig. 2 Experimental stimuli (A) and Results (C) of Experiment 2a

Experiment 2a – Stimuli and Results **A)** Experimental stimuli – the orientation of the target line was manipulated with a step sizes varying from 0.5º to 2.5º, rotated clockwise from a vertical position. The orientation of the reference line was set at 15 º. During the experiment the color of the two lines was identical. **B)** Results– changes in perceptual resolution as a function of perceived depth. Left panel shows the psychometric fit for one representative participant, middle panel shows the average JNDs and the right panel shows average RTs .

2.5a Experiment 2b: Orientation – controlling for changes in surface size

The results of Experiment 2a showed that the "close advantage" holds for a visual task unrelated to depth processing. However, an alternative explanation for the observed results relates to the size of the stimuli relative to the sizes of the close and far surfaces. Particularly, the far surface is smaller than the close surface (see Fig. 1A). Since the physical size of the target stimuli was constant, the target lines were always closer to the edges of the surface in the far condition compared with the close condition. While unlikely, the proximity of the stimuli to the surface edges may have made it more difficult for the observer to judge the relative orientation of the two test stimuli. Since the surfaces' size manipulation was integral to the 2D depth manipulation, we cannot remove this aspect of the stimuli. However, to evaluate whether the proximity to the surface edges had any impact on performance in this study, we systematically manipulated the surface size in the *flat* condition. That is, we created two flat conditions: one with large surfaces and the other with small surfaces (Fig. 3A) and examined whether orientation sensitivity differed as a function of surface size (and therefore proximity of the test lines to the surface edges). We also used this experiment as an opportunity to replicate and generalize the results of Experiment 2a.

Method

Participants:

Due to restrictions on in person data collection, this experiment was conducted using an online platform. This testing approach also allowed us to access a very broad sample of the population. Notably, we implemented several changes to adapt to this online testing environment. Based on previous studies on efficient online study designs (Mason & Suri, 2012;

Reips, 2000), a larger sample size and shorter experiment time was used. In particular, we generated three shorter versions of the experiment and recruited a total 77 participants for each version. Sixteen participants were excluded from the results because they failed to follow experimental instructions properly (i.e., guessing) and one participant was excluded because his JND scores deviated from the mean JNDs by more than four standard deviations. Thus, the final analysis was based on a total of 60 participants (20 for each version) (age: M = 27.8, SD=6.03; 21 males).

Material and Apparatus

Participants were recruited from https://www.prolific.co/ participant pool (Palan & Schitter, 2018) and received monetary compensation for their participation. Participants were screened to be right-handed with normal to corrected vision and were enrolled in the study after obtaining their informed written consent form through the Qualtrics survey platform (https://www.qualtrics.com/). The orientation task was hosted on the Pavlovia server (https://pavlovia.org/), which offers an online implementation of PsychoPy (Peirce et. al, 2019).

Experimental stimuli and settings were the same as Experiment 2a with the following exceptions. The Ponzo Flat background (Fig. 1A) was replaced with two relative size matched flat conditions (small-flat and big-flat) (see Fig. 3A). Therefore, participants were presented with 4 conditions (far, close, flat-small, flat-big) where all stimuli presentations were counterbalanced for presentation side (left vs. right). Participants performed one of three shorter versions of the experiment, each composed of 9 levels, step size of 3º, centred on the reference orientation of 15º (See Fig. 3B for sample orientation continua). Version 1 of the experiment contained orientations ranging from 2º to 26º, Version 2 ranged from 3º to 27º, and Version 3 from 4º to 28º.

Recruitment for each version was independent; participants completing one version did not take part in any other versions of the experiment. Together, the three experiments covered the full experimental range used in Experiment 2a.

Procedure

Participants began the experiment by performing a set of practice trials with feedback. The practice trials consisted of 8 trials, ranging from orientations 5º to 25º with a step size of 2.5º. Six consecutive correct answers were required to move on to the main experiment. Once participants successfully passed the practice trials, the main experiment consisted of 72 trials (9 orientations x 4 conditions x 2 counterbalanced sides) repeated 5 times (total 360), so each level was presented a total of 18 times (9 orientations x 2 counterbalanced sides). The experiment duration was approximately 10 minutes without any breaks.

2.5b Results

To rule out relative size as a potential confound, we replicated the orientation task of Experiment 2a with two additional relative size matched flat conditions (Fig. 3A). Results were consistent with our previous findings with smaller JND scores for apparent closer objects compared to all other depth conditions. Furthermore, no significant difference was found between the two flat conditions, allowing us to rule out surface edge proximity due to relative size differences as an alternative explanation (Fig. 3C).

The repeated measures ANOVA on the JND scores revealed a main effect of perceived depth [$F_{(3,177)}$= 3.227, p<.05, $\eta_p^2 = 0.052$]. Notably, planned comparisons replicated previous results indicating smaller JND score for the close conditions (in accordance with the "close advantage” effect) compared to the far [$t_{(59)}$= 2.133, $p < 0.05$; Mean Difference = 0.176, CI: 0.010, 0.341], the flat-small [$t_{(59)}$= 2.029, $p < 0.05$; Mean Difference = 0.192, CI: 0.002, 0.381] and the flat-big condition [$t_{(59)}$=-3.368, $p < 0.05$; Mean Difference = 0.240, CI: 0.097, 0.382]. There was no significant difference between the far condition and the two flat conditions: far and flat-small [$t_{(59)} < 1$; Mean Difference = -0.016, CI: -0.195, 0.163;] and far and flat-big [$t_{(59)} < 1$ Mean Difference = -0.064, CI: -0.202, 0.075].

To examine whether edge proximity modulated JNDs, we employed a Bayesian paired samples t-test on the two flat conditions. In contrast to the Null Hypothesis Significance Testing, a Bayesian t-test can also provide evidence in favor of the null hypothesis (that is – no difference between the two flat conditions) (Van den Bergh et al., 2019; Wagenmakers et al., 2018). The Bayesian t-test supported the null hypothesis (i.e., no difference between the two flat conditions) [BF_{10} = 0.164] such that the null hypothesis was 6.25 more likely than the H1 hypothesis. This result suggested that the surface edge proximity did not mediate the close advantage effect found in our previous studies.

The analysis of the RT did not produce significant results, [$F_{(3,177)} < 1$]. The lack of RT effect is consistent with previous literature that suggests that online behavioural studies may add noise to reaction times due to differences in hardware (de Leeuw & Motz, 2015; Reimers & Stewart, 2015). To conclude, the results of Experiment 2b complemented those found in Experiment 2a (Fig. 2B), and further confirmed that the close advantage cannot be accounted by the relative sizes of the surfaces.

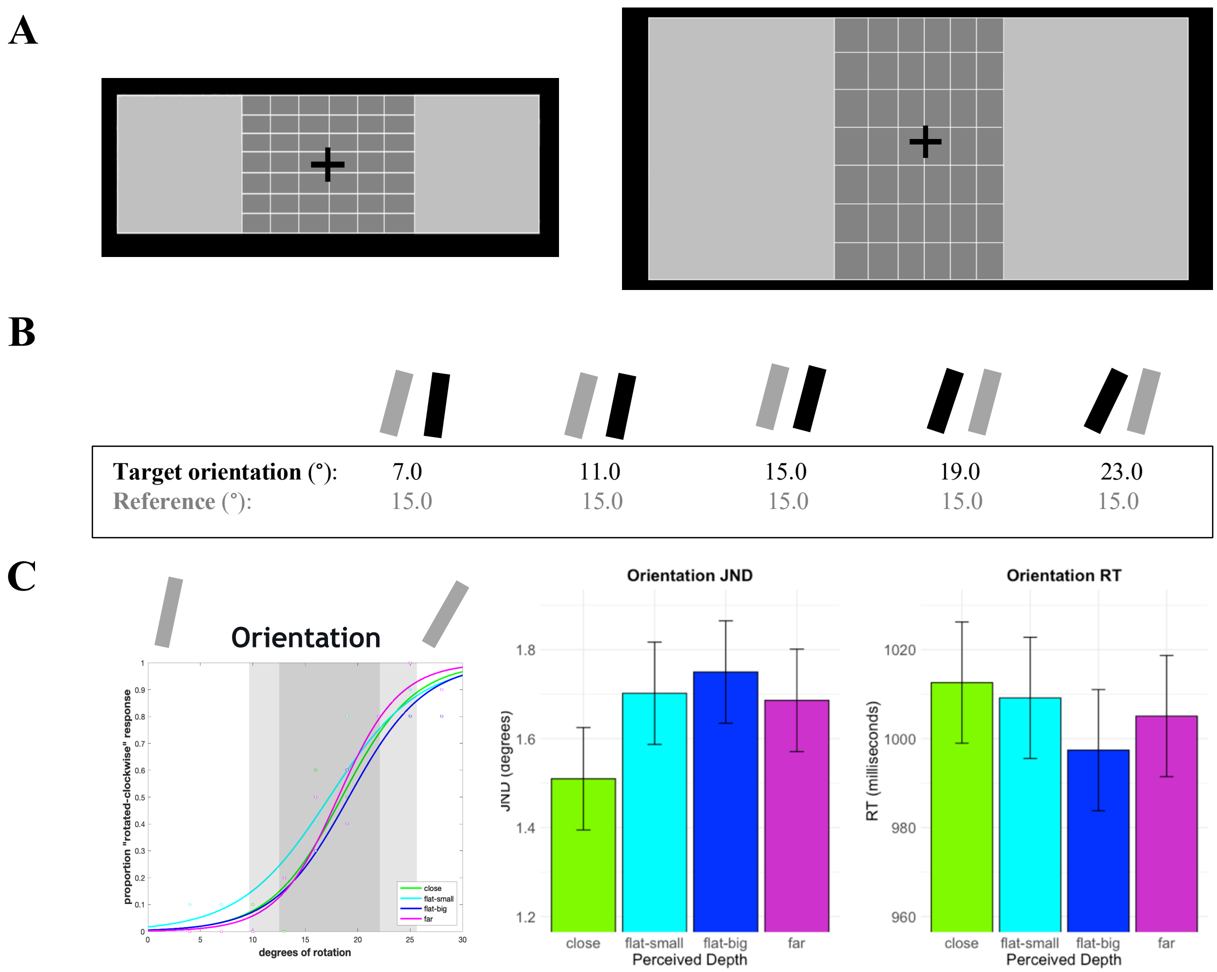


Fig. 3 Experimental stimuli (A) and Results (C) of Experiment 2b

Experiment 2b Stimuli and results **A)** Ponzo size matched Flat conditions. The left image (flat-small) is matched with the smaller rectangle (far condition) and the right image (flat-big) is matched with the bigger rectangle (close condition) of the Ponzo Illusion **B)** Experimental stimuli - lines of different orientations with target line changing with a step size of 4 degrees, reference line at constant orientation of 15 degrees. **C)** Results. Left graph shows the psychometric fit for one participant, middle graph shows the average JNDs and right graph shows average RTs.

2.6a Experiment 3: Face Identification

The experiments described above examined the effects of perceived depth on the processing of low-level visual features. An outstanding question is whether the observed close advantage extends to higher level visual tasks, such as object recognition (Blini et al., 2018) and target identification (Li et al., 2011). Here, we focus on face perception, a high-level ability of the human visual system. A previous study already showed that participant's PPS was altered by the emotional status of a face; participants stopped angry avatars earlier (farther away from them) compared with happy avatars (Ruggiaro et al. 2017). The goal of Experiment 3 was to examine whether such subjective judgments also translate to psychophysical sensitivity. To this end, we examined whether face perception abilities are modulated by their perceived position in depth relative to an observer.

Methods

Participant

Data was collected from 32 participants (age: M = 20.93, SD=5.48; 5 males). Sample size was based on that used in previous face perception studies (e.g., Hadad et al., 2019). A-priori we decided to recruit more participants compared with previous experiments given the known variability in face perception abilities (Bobak et al., 2016; Freud et al., 2020). One participant was excluded as their JNDs deviated from the average of the sample by more than four standard deviations. All other aspects of the recruiting process was the same as that described in Experiments 1 and 2a.

Materials and apparatus

The size of the backgrounds (Ponzo Illusion and Ponzo Flat – See Fig. 1A) were doubled to subtend a visual angle of 54.61° x 27.63° in order to accommodate the larger stimuli size. The stimulus set for Experiment 3 was obtained from a previous study (Hadad et al., 2019). The stimuli consisted of two base faces (unmorphed) that were morphed to form a continuum of faces (See Fig. 4A for sample). Faces were always presented at a visual angle of 6.81° x 8.05°. Face stimuli were controlled for luminance and contrast using the SHINE Toolbox in MATLAB (Willenbockel et al., 2010).

Procedure

Participants were given an opportunity at the beginning of the experiment to study the two unmorphed faces, labelled "Kyle" or "Fred". Then participants underwent eight supervised practice trials where they viewed morphed faces, presented one at a time, in the close, flat, or far portion of the Ponzo Illusion. They were asked to identify which face they saw by pressing the keys K (for Kyle) or F (for Fred). After ensuring participants understood the task correctly, they performed a brief pretest consisting of 24 trials repeated 4 times (total 96 trials) which was used to determine appropriate step size for the main experiment (but was not used in the final analysis). In the main experiment, they completed 11 levels, with step sizes ranging from 3% to 9% level of morphing, centered on the midpoint (50% morphing). The main experiment consisted of a total of 66 trials (11 faces x 3 depths x 2 counterbalanced sides), repeated 12 times (total 792 trials), hence, each level was presented 22 times (11 faces x 2 counterbalanced sides) in a randomized order.

2.6b Results

In this study, participants performed a face identification task to determine whether the "close advantage" is generalizable to higher-level visual tasks. Consistent with Experiments 1-2, faces placed on the close surface yielded smaller JNDs (more accurate classification) relative to the other conditions (Fig. 4B depicts the mean JND scores and RT values).

Repeated measures ANOVA of the JND scores found a main effect of perceived depth [$F_{(2,60)} = 3.683$, $p<.05$, $\eta_p^2 = .109$]. Planned comparisons revealed a significantly lower JND score for faces perceived as closer in comparisons to the far condition: ($t(30)= 2.485$, $p = 0.01$, Mean Difference = 0.349, [CI: 0.062, 0.635]), as well as the close and flat condition: ($t_{(30)} = 2.060$, $p=0.048$, Mean Difference = 0.326, [CI: 0.002, 0.648]). The far and flat condition did not show significant differences ($t_{(30)} = 0.174$, $p=0.86$; Mean Difference = 0.023, [CI: -0.245, 0.291]). Together, the JND results supported the "close advantage" account and provided evidence of better perceptual resolution for faces that were perceived as closer.

Statistical analysis of the RT data did not reveal a significant main effect of perceived depth [$F_{(2,60)} = 2.632$, $p=0.109$ $\eta_p^2 = 0.081$[2]]. Importantly, however, there was no evidence for speed-accuracy trade-off as the trend observed for RT was consistent with that observed for the JND results.

[2] Analysis was corrected for sphericity using the Greenhouse-Geisser method (to account for violation of the sphericity assumption)

A

Face (% Kyle):	0%	25%	50%	75%	100%
Face (% Fred):	100%	75%	50%	25%	0%

B

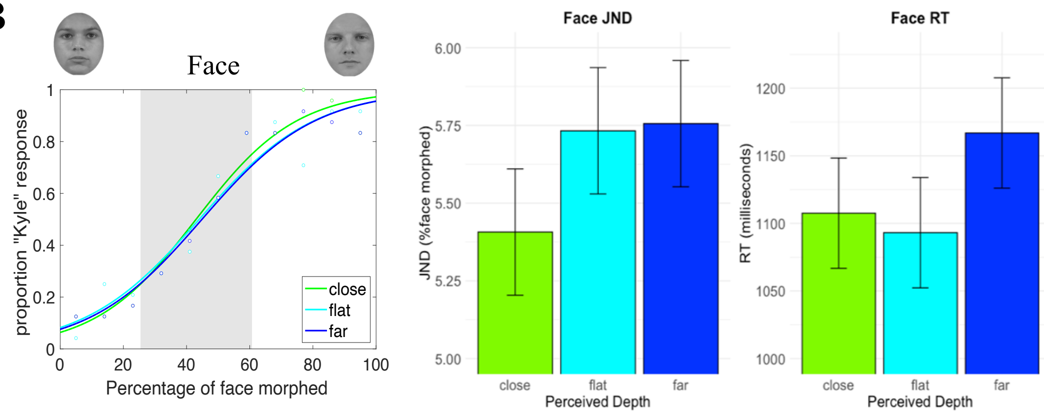


Fig. 4 Experimental stimuli (A) and Results (C) of Experiment 3

Experiment 3 Stimuli and Results **A)** Experimental stimuli - sample faces presented in morphed in reference to the face "Kyle" and "Fred". Standard face is 50%, halfway morphing between the two faces. **B)** Results: Left panel shows the psychometric fit curve for one participant, middle graph shows average JNDs and the right graph shows average RTs.

2.7 Discussion

The goal of the current study was to determine whether perceptual resolution is modulated by perceived depth. We assessed this across a variety of tasks and visual attributes by presenting stimuli on the 'close', 'flat', and 'far' version of Ponzo Illusion backgrounds. Our results reveal a consistent effect of depth, where more precise (lower JND) and faster processing was observed for objects positioned on the surface that appeared closer. This was evident for lower-level visual attributes such as size and orientation (Experiment 1, 2a, 2b) as well as a high-level visual task, such as face perception (Experiment 3).

While we do not always find an effect of perceived distance on reaction times in our experiments, our findings are aligned with that of Blini et al. (2018), as both studies found a consistent advantage for objects that are perceived to be closer to the observer. Importantly, the current study extended those previous results along two critical dimensions. First, we generalized the close advantage effect from low-level to high-level visual tasks. Second, we demonstrated that the "close advantage" can be attributed to an enhancement in psychophysical sensitivity. While we cannot rule out that response bias contributes to the differences between the far and close condition, it is still the case that JND scores are more likely to reflect perceptual resolution rather than response bias.

Notably, previous research suggests that the close advantage effect is not evident across all tasks and conditions. In particular, a study by Li and colleagues (2011) reported a consistent advantage for detection of targets that were presented on a closer surface. However, in contrast to the current findings and to Blini et al.'s (2018) results, this early study did not find any advantage for *identification* of these close targets. The apparent inconsistencies between these studies might be explained by the nature of the task employed by Li et al. (2011), where participants were required to complete a dual task for two targets presented in the center and the periphery of the visual field. Additional research may be needed to characterize how the close advantage phenomenon is modulated by location across the visual field and by task demands.

2.7a What are the mechanisms that mediate the close advantage?

It is well established that depth perception modulates visual perception. This is best illustrated by Emmert's Law (Emmert, 1881); Emmert showed that an afterimage, which has a fixed retinal size, changes apparent size depending on the distance of a surface on which it is seen. If the observer looks at the afterimage on a near surface it appears smaller than if it is seen on a far surface. This relationship between perceived size and perceived distance was found to influence the activity of early visual cortex, such that objects that are perceived as bigger result in more neural activation in the early visual cortex (Murray et al., 2006). Interestingly, these findings were used to predict a reverse pattern to that observed here. Specifically, according to this view, if objects on the far surface recruit more EVC processing, they should be seen with higher resolution than those perceived to be closer (and smaller). However, there is limited psychophysical support for this idea (Schindel & Arnold, 2010; Lages et al., 2017), instead, there is more consistent evidence in favor of enhanced processing of close objects. Thus, the question regarding the neural mechanisms underlying the close advantage remains an open one.

One account attributes the close advantage to differential processing between the PPS and EPS (di Pellegrino & Ladavas, 2015). For example, di Pellegrino & Frassinetti (2000) provided evidence for privileged visual processing in the PPS compared with the EPS in patients with lesions to the parietal cortex. In particular, the authors found that visual extinction, a pathological bias of favouring recognition of objects presented to the ipsilesional visual field, was less evident for stimuli presented in the PPS. This finding is complemented by behavioural studies that show a faster rate of image processing (Reed et al., 2006), increased attentional prioritization and slower attentional disengagement from tasks (Abrams et al., 2008) when objects were presented closer to the hand than farther away.

Importantly, in contrast to previous findings, our results show that the close advantage is evident even for perceived, rather than real, depth, and even when hand location was not manipulated. Our results suggest that the close advantage occurs even when depth is solely defined by pictorial cues and therefore cannot be fully explained by the classic PPS/EPS account. Instead, the close advantage phenomenon might be better accounted for by affordance, the mere potential for action offered by objects (Bamford et al., 2020). For instance, a recent study by O'Connor et al., 2021 shows that spatial proximity to reward increases impulsive behaviour since objects of greater value (such as a food reward) can afford a more valuable outcome in closer proximity. Notably, and consistent with the current findings, previous studies have also demonstrated that affordance could influence behavior even when pictures, and not real objects, are used as experimental stimuli (e.g., Creem et al., 2001).

As such, objects that are strongly associated with actions (i.e., affordance), such as man-made tools that are behaviourally relevant may elicit a greater close advantage. Indeed, previous work has shown that even perceiving objects that potentiates action can alter behaviour. For instance, participants viewing pictures of objects with handles oriented towards their ipsilateral hand (i.e., easier to grasp) were faster to respond than when handles were orientated to the contralateral hand (Tucker & Ellis, 1998; 2001; 2004). A recent study by Pilacinski et al. (2021) has shown that even eye saccades are primed for tool heads (the functional part of the tool), rather than tool handles. An enhanced resolution of the feature-rich tool heads may help facilitate recognition of tool's unique identity and functionality.

Moreover, affordance was not only modulated by object features that evoked actions, but also whether the object was within reachable space to act on. In one notable study by Witts et al. (2005), participants were asked to estimate distances to the target while holding or not holding a tool, with the intention of reaching the target or not. Although targets were always presented at the same distance away, participants perceived target to be closer when holding a tool, with the intention of using them. Linkenauger et al. (2009) corroborated these findings by showing that tools that are more difficult to pick up were perceived as farther than those closer to the observer.

Finally, another possible contributing factor to the close advantage phenomena could be attentional biases. Although we did not explicitly test this in our current study, it is well established that spatial attention is not uniformly distributed along the dimension of depth (Shelton et al., 1990, Gawryszewski et al. 1987; See Goodhew et al., 2015 for a review). Therefore, it is possible that closer object may receive a more dedicated attentional processing (Makin et al. 2009), which in turn facilitated the processing of these objects. This is in line with Li et al.'s (2011) findings that show differential processing at near and far distances as a result of attentional load, as well as other previous studies that support an attentional enhancement in the near space (Reed et al., 2006; Reed et al., 2013). Future studies should disentangle between perceptual and attentional processes that might contribute to the observed close advantage effect.

2.7b "Close advantage" or "Far disadvantage"?

An outstanding question is whether the difference observed between the close and far conditions in our study reflected facilitation of the close space processing ("close advantage"), interference in the processing of the far space ("far disadvantage") or a combination of those two processes. To disentangle these options, we included the flat condition, for comparison, across the four experiments. We expected that performance in the flat condition would consistently fall midway between the close and far conditions, however this was not the case. Instead, in 3 of our 4 experiments (Experiments 2a, 2b, and 3) we found that performance in the flat condition was equivalent to that seen in the far condition with JNDs significantly larger than those obtained in the close condition. This supports the interpretation that the results we see here are not due to a reduction in sensitivity as a function of distance, but instead reflect an enhancement within PPS. The results of Experiment 1 differ from the other experiments in that JNDs for the flat condition and are statistically smaller than those found in the far condition. As outlined previously, it is possible that the relative performance across conditions in Experiment 1 was influenced by the interrelationship between size and perceived distance.

2.7c Conclusion

To conclude, the present series of experiments provides supportive evidence of higher perceptual resolution for objects that are perceived as closer to the observer. This benefit is seen consistently, across visual properties such as length and orientation, and even higher-level properties such as face identification. Together, our results point towards the existence of a dedicated processing mechanisms for closer things.

CHAPTER 3

GENERAL DISCUSSION

3.1 Summary

In this thesis, I investigated whether visual resolution is modulated by perceived depth defined by 2D pictorial cues (perspective and size). In a series of experiments, I tested this across a variety of tasks and visual attributes by placing them on the ‘close’, ‘flat’, and ‘far’ portion of the Ponzo Illusion. Across all experiments, despite the fact that all stimuli were physically at the same distance from the observers and with an identical retinal size, I found enhanced discrimination (more precise and faster) for objects *perceived* as closer in depth. An additional control experiment (Experiment 2b) provided further validation that the observed depth effect cannot be accounted for by relative size of the background surfaces.

3.2 What are the cognitive mechanisms that give rise to the close advantage?

A large body of research has established changes to visual perception in the near-hand space (di Pellegrino & Ladavas, 2015). However, in contrast to previous findings, the observed effect in my experiment was seen in the absence of manipulation of the hand position, and for perceived depth (not real depth). Since depth perception modulates visual perception, objects that project the same retinal image would be perceived as bigger when placed on the “far” surface compared to the “close” surface. Objects perceived as bigger are shown to recruit more neural activations in the early visual cortex (Murray et al., 2006), and therefore a greater resolution for “far” objects would be expected. However, the present study in addition to previous other studies has shown more evidence for an enhanced near processing benefit, which raises the important question: what mechanisms mediate the observed close advantage?

In the next section, I discuss some of the popular accounts that have been put forward to explain the near processing benefit. It's important to note that the focus of this next section is not to tease apart which depth-specifics mechanisms are at play at any instance since it may be the case that they are all inextricably linked, and we may not know for certain which mechanism is responsible without having tested for it in our study. Instead, the goal is to gain a better understanding of the close advantage as a whole.

3.2a Enhanced affordance processing in the close space

Objects in the close space may be more behaviourally relevant thus, one possible explanation for the close advantage can be affordance, which is the potential for action offered by objects (Bamford et al., 2020). A recent study by O'Connor et al., 2021 showed that impulsive behaviour to objects increases as their value increases. An item with a greater value affords a more valuable outcome which strongly influences behaviour in the close space. This is in line with other studies that show that even pictures of objects that afford action can influence behaviour (Creem et al., 2001). Accordingly, a series of experiments by Tucker & Ellis (1998; 2001; 2004) showed that pictures of objects with handles that were oriented towards the ipsilateral hand were processed faster than when handles were oriented towards the contralateral hand. In another example, Witts and colleagues (2005) asked participants to estimate target distances while holding or not holding a tool, with the intention of reaching the target or not. They found that despite targets being the same distance away, participants perceived target to be closer when holding a tool and having the intention to use it. In support of these findings, Linkenauger et al. (2009) showed that tools were more difficult to pick up if they were perceived to be farther away from the observer. Together these results show that affordance processing is not only evoked by object features (i.e., handles that insight action) but more importantly, object location, the reachable space where objects can be acted on. Relating this back to the results found by my study, objects in the near space are great candidates of manipulation (moving a block, hugging a person), so it may be the case that the higher perceptual resolution of near objects may be indicative of an affordance benefit. In my future experiments, I plan to test this by investigating how perception of objects that strongly afford actions (i.e., tools) are modulated by perceived distances.

3.2b Enhanced attentional processing in the close space

Attentional biases could be another possible contributing factor to the observed close advantage effect. Previous studies have reached general consensus that spatial attention is not uniformly distributed along the dimension of depth (Shelton et al, 1990, Gawryszewksi et al. 1987; See Goodhew et al., 2015 for a review). Therefore, it is possible that closer object may receive more dedicated attentional processing (Makin et al. 2009). For instance, Reed et al., 2006 used a cued visual detection task where they changed the participants hand position either close or far away from the targets. Notably, they found faster detection of stimuli when hands were perceived to be near the target. In a subsequent experiment using event related potentials, Reed et al. (2013) concluded that hand position was sufficient to modulate early and late attention-sensitive component of the brain.

Plewan & Rinkenauer (2017) used a purely visual task where they presented targets in stereoscopic depth in either far or near position. Distractor stimuli were presented in the same plane (i.e. near-near or far-far) or opposing depth plane (i.e., near-far). Their results showed that visual selection was consistently slower when target and distractor were in the same depth plane.

Even more interestingly, near target selection was affected more by distractors in the near plane, while selection of the far target was much slower with increased information in the near plane. The results of this study are suggestive of a gradient-like organization of attention through space, that is affected by the information of the surrounding visual environment. Consistent with these findings, it may be possible that in our present study, closer objects enjoy a great attentional prioritization that is slowly diminished as perceived depth increases (flat or far). Although we did not specifically test for attention, it’s possible that what we see for Experiment 1 and 2a RT values follow a similar gradient pattern where the close condition has the lowest RT value, followed by the flat condition, and far condition has the largest. We did not find a significant effect of RT in the other two experiments, which can be attributed to using an online platform (Experiment 2b) or performing a higher-level task (Experiment 3).

3.2c Automatic defensive mechanisms in the close space

Defensive actions may particularly benefit from a specialized processing of the close space (Graziano & Cooke, 2006). Evolutionary, we possess a strong motivation to escape from potentially threatening stimuli (i.e., swatting bee away from face). However, in order to activate defensive mechanisms, the approaching stimuli must appear as a threat and violate some personal boundary (Hediger, 1950). The PPS is known to have specialized neurons coding for this boundary, where the boundary can be flexible (Bufacchi & Iannetti, 2018). For example, a study conducted Ruggiaro et al. (2017) presented participants with avatars showing different emotional reactions approaching them in a virtual reality setup. Participants were asked to stop the avatar at a distance they began feeling uncomfortable. For example, if the avatar started coming from 30m away, a participant may press a button to stop the avatar 10m away if they felt it was too close in their space. The results indicated that the more threatening the avatar appeared (i.e., angry), the larger the personal boundary was established. In accordance with this, the results of Experiment 3 from my study suggests that the sensitivity to emotional valence in the peripersonal space may be explained by a higher resolution, extending our findings to social-interaction spaces. Our paradigm could be used to examine this topic further by comparing the close advantage effect for threating and neutral stimuli (e.g., snakes vs. sticks), as well as test microaggressions in facial expressions that may be more application in a social context.

3.3 What is the neural basis for the close advantage?

Inspired by the first influential study in the role of cat Y cell and X cell systems in division of space (Pettigrew and Dreher, 1987), it was proposed that the human analogous systems may carry out the same role in the human visual system (Rizollati et al., 1981; Previc, 1990). The human visual system can be divided into two major pathways that are anatomically and functionally distinct (Ungerleider & Mishkin, 1982; Goodale & Milner,1992). The ventral (predominantly parvocellular) pathway is pertinent to object recognition and identification. In contrast, the dorsal pathway (predominantly magnocellular) is involved with visuomotor controls such as grasping. Objects that are close may be more manipulable (i.e., affordance) and thus recruit regions of the dorsal pathway (Chao & Martin, 2000). This is evident through studies that show a faster reaction time for objects near the hand (Reed et al., 2006), and fits well within the general magnocellular enhancement for PPS account (Goodhew et al., 2015; Bush & Vecera, 2014).

It is well known that the human dorsal visual cortex is sensitive to depth information (Ban et al., 2012; Orban, 2011) which may be mediating the close effect, even in the absence of action affordance. For instance, in one study, Weiss et al. (2000) measured participant’s regional cerebral blood flow with positron emission tomography (PET) while they performed either a line bisection judgment (perception) or manual line bisection task (action) in far or near space. Their results showed that irrespective of task type, far space presentation enhanced activation in the ventral visuoperceptual stream, while near space presentation enhanced dorsal visuomotor processing stream activity. Their results support a differential neural mechanism for processing of stimuli presentation (far, near), but not task demands (perception, action). In fact, recent research has shown that the dorsal pathway is capable of processing shape information, somewhat independently of the ventral pathway (Freud et al., 2016). Together, the above studies may help explain the role of the dorsal pathway in mediating the enhanced processing of shape information observed in our study. In my future research program, I plan to investigate this topic further using behavioral and neuroimaging approaches.

3.4 Conclusion

To conclude, this thesis provides novel evidence that depth information modulates visuoperceptual resolution. In particular, I have found that observers had a better perceptual resolution for objects that were perceived as closer to them, even when depth information was solely induced by pictorial cues. This benefit was seen consistently, across both lower-level visual attributes (e.g., orientation judgments) and higher-level tasks (e.g., face perception). This effect, defined as the “close advantage”, is an exciting development in perceptual research suggesting that depth information, even if orthogonal to the task in-hand, can modulate the neural processing and the perception of objects.

REFERENCES

Abrams, R. A., Davoli, C. C., Du, F., Knapp III, W. H., & Paull, D. (2008). Altered vision near the hands. *Cognition*, *107*(3), 1035-1047. https://doi.org/10.1016/j.cognition.2007.09.006

Ahsan, T., Bolton, K., Wilcox, L. M., & Freud, E. (under review; resubmitted with minor revisions to Psychonomic Bulletin and Review). Perceived depth modulates perceptual resolution. https://psyarxiv.com/xkqcv/

Appleby, T. R., & Manookin, M. B. (2020). Selectivity to approaching motion in retinal inputs to the dorsal visual pathway. *Elife*, *9*, e51144. https://doi.org/10.1016/j.cognition.2007.09.006

Baird, J. C., & Noma, E. J. (1978). *Fundamentals of scaling and psychophysics*. John Wiley & Sons.

Bamford, L. E., Klassen, N. R., & Karl, J. M. (2020). Faster recognition of graspable targets defined by orientation in a visual search task. *Experimental brain research*, *238*(4), 905–916. https://doi.org/10.1007/s00221-020-05769-z

Bobak, A. K., Pampoulov, P., & Bate, S. (2016). Detecting superior face recognition skills in a large sample of young British adults. *Frontiers in psychology*, *7*, 1378. https://doi.org/10.3389/fpsyg.2016.01378

Blini, E., Desoche, C., Salemme, R., Kabil, A., Hadj-Bouziane, F., & Farnè, A. (2018). Mind the depth: Visual perception of shapes is better in peripersonal space. *Psychological science*, *29*(11), 1868-1877. https://doi.org/10.1177/0956797618795679

Brain, W. R. (1941). Visual orientation with special reference to lesions of the right cerebral hemisphere. *Brain: A Journal of Neurology*. 244-272

Canzoneri, E., Ubaldi, S., Rastelli, V., Finisguerra, A., Bassolino, M., & Serino, A. (2013). Tool-use reshapes the boundaries of body and peripersonal space representations. *Experimental brain research*, *228*(1), 25-42.

Costantini, M., Ambrosini, E., Tieri, G., Sinigaglia, C., & Committeri, G. (2010). Where does an object trigger an action? An investigation about affordances in space. *Experimental brain research*, *207*(1-2), 95-103. https://doi.org/10.1007/s00221-010-2435-8

Costantini, M., Ambrosini, E., Scorolli, C., & Borghi, A. M. (2011). When objects are close to me: affordances in the peripersonal space. *Psychonomic bulletin & review*, *18*(2), 302-308.

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage*, *12*(4), 478-484. https://doi.org/10.1006/nimg.2000.0635

Clark, W. C., Smith, A. H., & Rabe, A. (1955). Retinal gradient of outline as a stimulus for slant. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *9*(4), 247.

Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: a necessary interaction between cognition and action. *Journal of experimental psychology: Human Perception and Performance*, *27*(1), 218. https://doi.org/10.1037/0096-1523.27.1.218

Culham, J. C., Danckert, S. L., De Souza, J. F., Gati, J. S., Menon, R. S., & Goodale, M. A. (2003). Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. *Experimental brain research*, *153*(2), 180-189. https://doi.org/10.1167/1.3.194

De Leeuw, J., & Motz, B. (2015). Data & experiment code for" Psychophysics in a web browser?".

Di Pellegrino, G., & Frassinetti, F. (2000). Direct evidence from parietal extinction of enhancement of visual attention near a visible hand. *Current Biology*, *10*(22), 1475-1477. https://doi.org/10.1016/S0960-9822(00)00809-5

Di Pellegrino, G., & Làdavas, E. (2015). Peripersonal space in the brain. *Neuropsychologia*, *66*, 126-133. https://doi.org/10.1016/j.neuropsychologia.2014.11.011

Dufour, A., & Touzalin, P. (2008). Improved visual sensitivity in the perihand space. *Experimental Brain Research*, *190*(1), 91-98. https://doi.org/10.1007/s00221-008-1453-2

Freud, E., Stajduhar, A., Rosenbaum, R. S., Avidan, G., & Ganel, T. (2020). The COVID-19 pandemic masks the way people perceive faces. *Scientific reports*, *10*(1), 1-8. https://doi.org/10.1038/s41598-020-78986-9

Freud, E., Binur, N., Srikanth, A., Davidson, E., Ganel, T., & Hadad, B. S. (2021). Double dissociation between perception and action in children. *Journal of experimental child psychology*, *201*, 104986. https://doi.org/10.1016/j.jecp.2020.104986

Gallivan, J. P., & Goodale, M. A. (2018). The dorsal "action" pathway. *Handbook of clinical neurology*, *151*, 449-466. https://doi.org/10.1016/B978-0-444-63622-5.00023-1

Gandhi, T., Kalia, A., Ganesh, S., & Sinha, P. (2015). Immediate susceptibility to visual illusions after sight onset. *Current Biology*, *25*(9), R358-R359. https://doi.org/10.1016/j.cub.2015.03.005

Ganel, T., Tanzer, M., & Goodale, M. A. (2008). A double dissociation between action and perception in the context of visual illusions: opposite effects of real and illusory size. *Psychological Science*, *19*(3), 221-225. https://doi.org/10.1111/j.1467-9280.2008.02071.x

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in neurosciences*, *15*(1), 20-25. https://doi.org/10.1016/0166-2236(92)90344-8 de Gonzaga Gawryszewski, L., Riggio, L., Rizzolatti, G., & Umiltá, C. (1987). Movements of attention in the three spatial dimensions and the meaning of "neutral" cues. *Neuropsychologia*, *25*(1), 19-29.

Goodhew, S. C., Edwards, M., Ferber, S., & Pratt, J. (2015). Altered visual perception near the hands: A critical review of attentional and neurophysiological models. *Neuroscience & Biobehavioral Reviews*, *55*, 223-233.

Graziano, M. S., & Cooke, D. F. (2006). Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia*, *44*(6), 845-859. https://doi.org/10.1016/j.neuropsychologia.2005.09.009

Gruber, H. E., & Clark, W. C. (1956). Perception of slanted surfaces. *Perceptual and Motor Skills*, *6*(3), 97-106.

Gunderson, V. M., Yonas, A., Sargent, P. L., & Grant-Webster, K. S. (1993). Infant macaque monkeys respond to pictorial depth. *Psychological Science*, *4*(2), 93-98. https://doi.org/10.1111/j.1467-9280.1993.tb00467.x

Hadad, B. S., Schwartz, S., & Binur, N. (2019). Reduced perceptual specialization in autism: Evidence from the other-race face effect. *Journal of Experimental Psychology: General*, *148*(3), 588. http://dx.doi.org/10.1037/xge0000550

Howard, I. P. (2012). *Perceiving in depth, volume 1: basic mechanisms*. Oxford University Press.

Kaas, A. L., & Van Mier, H. I. (2006). Haptic spatial matching in near peripersonal space. *Experimental Brain Research*, *170*(3), 403-413. https://doi.org/ 10.1007/s00221-005-0223-7

Làdavas, E., Zeloni, G., & Farnè, A. (1998). Visual peripersonal space centred on the face in humans. *Brain: a journal of neurology*, *121*(12), 2317-2326. https://doi.org/10.1093/brain/121.12.2317

Làdavas, E. (2002). Functional and dynamic properties of visual peripersonal space. *Trends in cognitive sciences*, *6*(1), 17-22. https://doi.org/10.1016/S1364-6613(00)01814-3

Li, T., Watter, S., & Sun, H. J. (2011). Differential visual processing for equivalent retinal information from near versus far space. *Neuropsychologia*, *49*(14), 3863-3869. https://doi.org/10.1016/j.neuropsychologia.2011.10.002

Linkenauger, S. A., Witt, J. K., Stefanucci, J. K., Bakdash, J. Z., & Proffitt, D. R. (2009). The effects of handedness and reachability on perceived distance. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(6), 1649.

Makin, T. R., Holmes, N. P., Brozzoli, C., Rossetti, Y., & Farne, A. (2009). Coding of visual space during motor preparation: approaching objects rapidly modulate corticospinal excitability in hand-centered coordinates. *Journal of Neuroscience*, *29*(38), 11841-11851.

Mason, W., & Suri, S. (2012). Conducting behavioral research on Amazon's Mechanical Turk. *Behavior research methods*, *44*(1), 1-23. https://doi.org/10.3758/s13428-011-0124-6

O'Connor, D. A., Janet, R., Guigon, V., Belle, A., Vincent, B. T., Bromberg, U., ... & Dreher, J. C. (2021). Rewards that are near increase impulsive action. *Iscience*, *24*(4), 102292.

Orban, G. A. (2011). The extraction of 3D shape in the visual system of human and nonhuman primates. *Annual review of neuroscience*, *34*, 361-388.

Palan, S., & Schitter, C. (2018). Prolific. ac—A subject pool for online experiments. *Journal of Behavioral and Experimental Finance*, *17*, 22-27. https://doi.org/10.1016/j.jbef.2017.12.004

Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of neuroscience methods*, *162*(1-2), 8-13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., ... & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior research methods*, *51*(1), 195-203. https://doi.org/10.3758/s13428-018-01193-y

Pilacinski, A., De Haan, S., Donato, R., & Almeida, J. (2021). Tool heads prime saccades. *Scientific reports*, *11*(1), 1-8.

Previc, F. H. (1990). Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications.

Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological bulletin*, *124*(2), 123. https://doi.org/10.1037/0033-2909.124.2.123

JASP Team (2018). *JASP (Version 0.8.5) [Computer software]*. JASP Team.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reed, C. L., Grubb, J. D., & Steele, C. (2006). Hands up: attentional prioritization of space near the hand. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(1), 166-177. https://doi.org/10.1037/0096-1523.32.1.166

Reed, C. L., Leland, D. S., Brekke, B., & Hartley, A. A. (2013). Attention's grasp: Early and late hand proximity effects on visual evoked potentials. *Frontiers in Psychology*, *4*, 420.

Reimers, S., & Stewart, N. (2015). Presentation and response timing accuracy in Adobe Flash and HTML5/JavaScript Web experiments. *Behavior research methods*, *47*(2), 309-327. https://doi.org/10.3758/s13428-014-0471-1

Reips, U. D. (2000). The Web experiment method: Advantages, disadvantages, and solutions. *Psychological experiments on the Internet,* 89-117. https://doi.org/10.1016/B978-012099980-4/50005-8

Rizzolatti, G., Fadiga, L., Fogassi, L., & Gallese, V. (1997). The space around us. *Science*, *277*(5323), 190-191. https://doi.org/10.1126/science.277.5323.190

Ruggiero, G., Frassinetti, F., Coello, Y., Rapuano, M., Di Cola, A. S., & Iachini, T. (2017). The effect of facial expressions on peripersonal and interpersonal spaces. *Psychological research*, *81*(6), 1232-1240.

Schindel, R., & Arnold, D. H. (2010). Visual sensitivity can scale with illusory size changes. *Current Biology*, *20*(9), 841-844.

Shelton, P. A., Bowers, D., & Heilman, K. M. (1990). Peripersonal and vertical neglect. *Brain*, *113*(1), 191-205.

Stevens, K. A. (1983). Surface tilt (the direction of slant): A neglected psychophysical variable. *Perception & Psychophysics*, *33*(3), 241-250.

Timney, B., & Keil, K. (1996). Horses are sensitive to pictorial depth cues. *Perception*, *25*(9), 1121-1128. https://doi.org/10.1068/p251121

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human perception and performance*, *24*(3), 830.

Tucker, M., & Ellis, R. (2001). The potentiation of grasp types during visual object categorization. *Visual cognition*, *8*(6), 769-800.

Tucker, M., & Ellis, R. (2004). Action priming by briefly presented objects. *Acta psychologica*, *116*(2), 185-203.

Tseng, P., & Bridgeman, B. (2011). Improved change detection with nearby hands. *Experimental brain research*, *209*(2), 257-269.

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., ... & Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic bulletin & review*, *25*(1), 58-76. https://doi.org/10.3758/s13423-017-1323-7

Weiss, P. H., Marshall, J. C., Wunderlich, G., Tellmann, L., Halligan, P. W., Freund, H. J., ... & Fink, G. R. (2000). Neural consequences of acting in near versus far space: a physiological basis for clinical dissociations. *Brain*, *123*(12), 2531-2541. https://doi.org/10.1093/brain/123.12.2531

Weiss, P. H., Marshall, J. C., Zilles, K., & Fink, G. R. (2003). Are action and perception in near and far space additive or interactive factors? *Neuroimage*, *18*(4), 837-846. https://doi.org/10.1016/S1053-8119(03)00018-1

Willenbockel, V., Sadr, J., Fiset, D., Horne, G. O., Gosselin, F., & Tanaka, J. W. (2010). Controlling low-level image properties: the SHINE toolbox. *Behavior research methods*, *42*(3), 671-684. https://doi.org/10.3758/BRM.42.3.671

Witt, J. K., Proffitt, D. R., & Epstein, W. (2005). Tool use affects perceived distance, but only when you intend to use it. *Journal of experimental psychology: Human perception and performance*, *31*(5), 880.

Valyear, K. F., Culham, J. C., Sharif, N., Westwood, D., & Goodale, M. A. (2006). A double dissociation between sensitivity to changes in object identity and object orientation in the ventral and dorsal visual streams: a human fMRI study. *Neuropsychologia*, *44*(2), 218-228. https://doi.org/10.1016/j.neuropsychologia.2005.05.004

Van den Bergh, D., van Doorn, J., Draws, T., van Kesteren, E. J., Derks, K., Dablander, F., ... & Wagenmakers, E. J. (2019). A Tutorial on Conducting and Interpreting a Bayesian ANOVA in JASP. https://doi.org/10.31234/osf.io/spreb