Does Tool Use in Virtual Reality Change the Visual Perception of Extrapersonal and Peripersonal Space?

by

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ABSTRACT

When people experience VR for the first time they reach out in an attempt to see their own hands in order to manipulate objects in the virtual environment. In the real world, the space where people are able to physically manipulate objects is referred to as peripersonal space whereas extrapersonal space is any physical area that is beyond the observer's arm's reach. Gamberini, Carlesso, Seraglia, and Craighero (2013) examined how people perform a line bisection task in VR and suggested that a tool's action consequence (i.e., the result of using a tool on an object in a virtual environment) affects how people perceive extrapersonal and peripersonal space. Gamberini et al. reported that when a tool was perceived as a "cutter" because it cut a to-be-bisected virtual line into two segments, the tool effectively extended the boundaries of peripersonal space as it allowed the observer to directly interact with lines that were in extrapersonal space. If, however, the tool was simply a "pointer" (i.e., did not break a virtual line into two segments on a line bisection task), then the separability of peripersonal and extrapersonal space remained intact.

Two experiments are reported that attempted to replicate Gamberini et al.'s (2013) tool (pointer vs. cutter) by distance (peripersonal vs. extrapersonal) interaction. In contrast to Gamberini et al.'s findings, tool and distance had additive effects on response time, accuracy, and directional bias in both experiments. There was, however, a robust interaction between line length (short vs. long) and distance in both experiments. It is concluded that line length and distance have more of an effect than tool type on how observers interact with objects in virtual space.

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INTRODUCTION

There has been a rapid growth in the interest in virtual reality (VR) technologies in recent years. The first head mounted display (HMD) was developed in 1968 (Pausch, 1997) and, at that time, VR struggled to capture the interest of the mainstream consumer technology market. Some of the reasons for the initial difficulties that VR faced in 1968 included a lack of interest from major technology companies to undertake the challenge of developing VR, the high cost that came with purchasing a headset, and the uncertainty regarding the breadth of applicability of VR. Almost 50 years later, there now exists an opposite trend in which major technology companies are releasing their own versions of consumer headsets, the cost of purchasing VR equipment is becoming affordable to the general consumer, and the areas of applicability of VR are rapidly expanding. VR is now being used for entertainment purposes such as viewing images, watching movies, playing games, and exploring different worlds. VR has also been used a rehabilitation tool for people who suffer from psychological disorders such as PTSD or phobias (Parsons & Rizzo, 2008). Another application of VR is the ability to measure someone's level of empathy when viewing a specific scene. The emotional impact that VR has when considering how people view an unpleasant scene or scenario confirms that VR can create the sense of physical and emotional immersion. One very popular VR demo is where the observer is placed inside a cart in a virtual rollercoaster. The realism of this demo is such that people experience the feeling of moving, similar to that experienced in a real rollercoaster. In summary, current VR technology offers the potential user – whether they are military personnel recreating a mission scenario for training purposes or the general consumer that wants immersive gaming capabilities – an affordable and realistic representation of the world like no other technology has before.

Not only does VR allow users to visually recreate experiences that may normally be difficult or dangerous to experience in the real world, but it also provides them with realistic visual representations of the 3-

dimensional world that they are interacting with. When people try VR for their first time, they often try to reach out and grab objects that are in their field of view or at least try to see their hands in the virtual environment. This intuitive response confirms that the interpretation of our physical bodies is also taken into account in virtual environments. However, more research needs to be conducted regardless of which application is being implemented in VR before one can assume that VR is a better alternative to the original form of that application. For example, when computers were developed they were originally used to perform complex calculations because it was a more efficient way than to use a traditional calculator or to do it by hand. The motivation for the development of the computer was to make humans' lives easier and to assist in tasks that would normally be time consuming or strenuous. Computers have progressed to aid humans in several tasks as this technology has evolved. When developing new application of VR the same motivation for doing so should be considered.

Another application of VR is to use it for training and rehabilitation for those who suffer from motor disabilities and cognitive impairments due to the similarities of how space is represented in VR and in comparison to real life (Gamberini, Seraglia, & Priftis, 2008). Spatial neglect is an impairment that has been studied with the use of VR as a training and treatment tool for patients (Ogourtsova, Silva, Archambault, & Lamontagne, 2015). Neglect has been examined traditionally with the use of a pen-and-paper line bisection tasks to measure the severity of a brain-damaged patient's impairment. Neglect can affect the left or right side of a patient's world as well as space near (peripersonal) or far (extrapersonal) from them depending on the location of the brain injury. In the line bisection task, patients are asked to draw a vertical line or point to the centre of a to-be-bisected horizontal line. Neglect patients usually show a pattern whereby performance on a line bisection task is biased rightward if the line is bisected in peripersonal space and leftward if the line is bisected in extrapersonal space. The general population shows an opposite pattern of results on a line-bisection task. That is, there is a leftward bias when the line is in peripersonal space, but shifts rightward as the line moves into extrapersonal space. This pattern of line bisection performance observed in the general population is referred to as pseudoneglect (Bowers & Heilman, 1980; Nicholls, Beckman, & Churches, 2016).

Although the line bisection task has been used as a way to measure visual neglect, it has not necessarily proven to be extremely dependable or reliable. Studies have reported that the traditional method of performing the line bisection task can result in misdiagnosis in patients, especially for those who suffer from mild neglect, which is more difficult to notice (Buxbaum, Dawson, & Linsley, 2012). One explanation for this misdiagnosis is that the task is not carried out in a manner that is representative to how people interact with space in the real world. Consequently, researchers have proposed that VR technology could be a better way to assess and diagnose neglect impairments due to the ability to track eye gaze, introduce more realistic haptic feedback, and track patients overall progress (Baheux, Yoshizawa, Tanaka, Seki & Handa, 2004; Fordell, Bodin, Bucht, & Malm, 2011). Fordell et al. (2011) proposed a VR assessment tool and found that, of the tasks performed in the virtual environment, virtual line bisection still needed to be researched further. They further noted that low sensitivity in the virtual line bisection task might mirror the weakness in test-retest reliability that is also found in traditional pen-and-paper line bisection tasks. More research on the human perceptual system and on VR in general is therefore needed before assuming that VR is a better alternative to the traditional pen-and-paper line bisection task.

Findings from line bisection literature

There are two areas of physical space that can be perceived at any given moment in time: space that allows interaction and space that only allows people to observe. In the psychological literature, these two separate areas have been referred to as peripersonal and extrapersonal space, respectively (Berti & Frassinetti, 2000). Peripersonal space is the space that is easily attended to with the help of arms and hands being able to reach out and manipulate objects. Objects are easily touched, felt, and picked up without any difficulty. In contrast to peripersonal space, extrapersonal space only allows the ability to see, smell, or hear what is around or in front. There are two separate brain regions responsible for coding the environment within these two different spaces, the LIP-FEF and VIP-F4. These brain regions both encode movement and visual stimuli but they do so in different ways. The LIP-FEF area is responsible for movements produced by saccades and the visual field (Barash, Bracewell, Fogassi, Gnadt, & Andersen, 1991). The VIP-F4 fires when there is tactile interaction with objects and people are able to physically and visually observe information while using their head, arm and hand (Barash et al., 1996). The idea that two brain regions are responsible for coding these two different spaces has been confirmed by human research with both normal and brain damaged patients who show neglect within a certain space but not the other (Berti & Frassinetti, 2000; Halligan & Marshall, 1991). Berti and Frassinetti (2000) and Halligan and Marshall (1991) examined patients who suffered a stroke to their right hemisphere and showed neglect for near space but not far space. Cowey, Small, Ellis (1994) and Vuilleumier, Valenza, Mayer, Reverdin and Landis (1998) reported a dissociative effect whereby patients showed neglect in far space rather than near space. Research that has documented neglect in both near and far space independently supports the finding that there are two separate brain regions responsible for processing information that occurs in these two separate spaces. Furthermore, neglect in near and far space seems to also have a directional bias depending on the space that the neglect is taking place. For example, Halligan and Marshall (1991) reported that a patient showed a leftward bias on a line bisection task that occurred in peripersonal (near) space. This leftward bias was reduced when the patient performed the task in extrapersonal space. However, this patient's performance also depended on the length of the to-be-bisected line.

The pattern of directional bias shifting from one direction to the other as the space in which lines of different lengths are being bisected is referred to as the *crossover effect*. A crossover effect has been observed in the general population of healthy individuals whereby rightward bisection biases for long lines cross over to leftward bisection bias for very short lines (Halligan & Marshall, 1988). However, Reuckert, Deravanesian, Baboorian, Lacalamita, & Repplinger (2002) reported the opposite finding which found that a leftward bisection bias for longer lines crosses over to a rightward bias for very short lines. Having said that, studies only report a pseudoneglect effect (Bowers & Heilman, 1980) in which there is a consistent leftward bias on the line bisection task.

The pseudoneglect effect is similar to what is found in patients who suffer brain damage and neglect one side of space. This leftward overestimation found in healthy people is commonly noticeable in tasks such as luminance discrimination (Nicholls, Bradshaw, & Mattingley, 1999), visual search (Nicholls, Beckman & Churches, 2914), and left/right mental representations of stimuli (Loftus & Nicholls, 2012). Again, a leftward bias on the line bisection task can be found in both normal and brain damaged patients but is more pronounced in the general healthy population (Bowers & Heilman, 1980).

The leftward bias on the line bisection task observed in healthy individuals occurs when they are asked to manually bisect a line using a pen or pencil and drawing or pointing to the midpoint of the line. Non-visual line bisection tasks also show a leftward bias when participants are asked to manually locate the midpoint of a rod by using their hands to receive tactile and/or kinesthetic feedback. Explanations for this consistent leftward bias in visual and non-visual line bisection tasks include reading direction, hand used to execute the task, and scanning direction post-bisection. Previous research investigating the difference in reading patterns across people who read left-to-right or right-to-left has found a difference in the directional bias during the line bisection task. Chokron and Imbert (1993) found that people who naturally read left-to-right do in fact show a leftward bias whereas those who read right-to-left show a rightward bias.

Hand used to perform a visual line bisection task has also been taken into account as a possible explanation for leftward errors. Halligan and Marshall (1991) found that people who used their left hand to perform the task showed leftward errors and those who used their right hand showed rightward errors. These errors were also affected by the length of the line, which showed increasing errors as line length increased. However, Halligan, Marshall and Manning. (1991) reported that while there were leftward and rightward errors, they did not happen respectively of the hand used. Bradshaw et al. (1983) showed no effect of hand used on directional bias, instead showing a consistent leftward bias regardless of hand used. However, those who used their left hand did err further to the left than those using their right hand. Although a slight increase in the magnitude of directional bias was reported by Bradshaw et al., several other studies have shown no effect of hand used on the task (Dellatolas, Vanluchene & Coutin., 1996; Harvey, Milner & Roberts., 1995). Manning et al. (1990) did, however, report the same interaction as Halligan et al. (1991) in which bias increased with line length. Jewell and McCourt's (2000) meta-analysis on performance factors in line bisection tasks reported that three of eight studies reviewed found no effect of hand used and no significant interactions between hand used and any other factors examined. However, five of the eight studies found a significant effect of hand used and direction of error. Participants who used their right hand to perform the task showed more rightward errors whereas the opposite was found for people who used their left hands. Sampio and Chokron (1992) reported an interaction of hand used and line length in which there was no significant effect of line length when participants used their left hand to bisect a line but, when using their right hand, there was a rightward bias, which continued to worsen with increasing line length.

Reuter-Lorenz and Posner (1990) had participants observe the experimenter tracing a line from either right-to-left or left-to-right and found that the direction of the scanning position had no effect on line bisection performance, with participants always making leftward errors. Additional research examining the effect of scanning and error directionality has found support that initiating a starting point does have an effect on performance whereby when participants scan left-to-right they make leftward errors and when they scan right-to-left they make rightward errors (Chokron et al., 1998; Halligan et al., 1991). Olson (1994) introduced the use of a fixation cross in the centre of the line pre-bisection and also reported a leftward bias in healthy participants. When performing a tactile line bisection task, similar results have been reported. Bowers and Heilman (1980) and Lavender, Tegner, and Caneman's (1993) results showed that when scanning began from the left side of the line, participants made more leftward errors and when scanning started from the right side of the line, they made more rightward errors. Overall, directional scanning seems to have an effect on the outcome of left or rightward errors during a visual and tactile line bisection task.

Research examining tool use on line bisection tasks has found that using a tool to interact with extrapersonal space can affect how people perceive the space they are interacting with and can also effect the direction of their over or underestimation of where the midpoint of the line is (Iriki, Tanaka & Iwamura, 1996). Iriki et al. trained macaques to use a rake to reach for objects outside of their arm's physical reach and recorded brain activation for somatosensory and visual stimulation. After training the monkeys to use the rakes, results from activation of neurons in the VIP-F4 showed that the visual receptive field extended and included the monkey's arms as well as the rake. The authors suggested that the rake became an extension of the monkey's physical arm because the VIP-F4 encodes movement of heads, arms, and hands. In other words, when the tool brought unreachable space into "arm's reach" due to its use, the tool was then encoded as an extension of the monkey's arm. This finding suggested that perhaps extrapersonal space is not defined by physical limits but rather by functional ones. Researchers who studied neglect were intrigued by this finding and tested to if the same was true for human neglect patients and whether or not using a tool to bisect horizontal lines would help the patient and also effect the same brain regions.

Berti and Frassinetti (2000) examined the influence of tool use in a line bisection task with a patient who suffered spatial neglect for objects in near space. Berti and Frassinetti had the participant bisect lines using a laser pointer and a stick. When the patient bisected the line with the laser pointer, they showed a rightward bias when the line was in their peripersonal (near) space, but showed less of a bias when the line was in extrapersonal (far) space. When the patient used a physical stick to point to the midpoint of the line, the stick effectively extended the boundary of peripersonal space, thus the neglect was now observed in both near and far space. Berti and Frassinetti claimed that tool use can extend neglect from peripersonal to extrapersonal space because the tool becomes an extension of the patient's arm.

Longo and Lourenco (2006) found that when healthy participants used a laser pointer as a tool to perform a line bisection task there was a clear leftward to rightward bias as the distance of the line from the observer was increased, which is the common pattern of pseudoneglect. Longo and Lourenco (2006) did not find any difference in performance when healthy participants used a series of different sticks to perform the line bisection task, regardless of the distance of the line from the participant. Instead, participants always showed a leftward bias as though the lines were being bisected in near space. The finding that a stick did not modulate directional bias but a laser pointer did was consistent with Berti and Frassinetti.'s (2000) claim that a physical stick brings extrapersonal space into peripersonal space.

How to implement tool use in virtual reality

The same tool by distance interaction has been found in studies that examined performance on the line bisection task in virtual reality. Gamberini et al. (2008) examined the joint effects of tool use and distance on line bisection tasks performed in both real and virtual environments. The results revealed that there was a significant interaction between of tool and distance when the line was bisected in a real environment. Specifically, when participants used a virtual pointer to bisect a line, their errors were always rightward. When a stick was used to bisect a line, their errors were always leftward. These findings were consistent with those of Berti and Frassinetti (2000), who reported a rightward bias when a laser pointer was used to bisect a line in near space and a leftward bias when a stick was used in both near and far space. These findings suggest that using a stick to bisect a line brought extrapersonal space into peripersonal space because the bisection bias was always leftwards regardless of the distance of the line from the participant, with leftward errors being a hallmark of line bisections that are performed in near space. In addition, Gamberini et al. (2008) and Berti and Frassinetti (2000) both reported that using a laser pointer affected performance more so at distances of 60 cm and 120 cm than at 30 cm or 90 cm. At the distance of 60cm and 120cm there was more of a discrepancy in terms of accuracy between these two distances than 30cm and 90cm. However, when using a physical stick to perform the line bisection, there was no difference between the distances. Similar findings have been reported for line bisection tasks in virtual environments, which show that when participants used a virtual laser pointer to bisect a virtual line, their errors were always rightward, and when they used a virtual stick, errors were always leftward. The consistency of results across real and virtual environments led Gamberini et al. to conclude that tool use and physical space in VR is represented as it is in the real world. Gamberini et al. also reported a main effect of distance in which line bisection performance differed between 60 cm and 90 cm such that performance was better at 90 cm but not between any other combination of distances. Further, a significant tool by distance interaction revealed that participants bisected further leftwards when distance moved from 30 cm to 60 cm but were even more accurate moving from 60 cm to 90 cm showing that as distance increased performance also increased. Gamberini et al.'s (2008) study provided support for the common left to right shift in directional bias on a line bisection task as the distance of the line moved from peripersonal to extrapersonal space in both real and virtual environments.

A more recent study conducted by Gamberini, Carlesso, Seraglia, and Craighero (2013) examined tool use in virtual reality exclusively and hypothesized that the action consequence of a given tool affects performance on a line bisection task. In Gamberini et al.'s (2013) experiment one tool was represented as a "cutter" and the other as a "pointer". When the cutter was used, an action consequence occurred in which the line would virtually break (i.e. be segmented into two pieces) at the cut-point. Gamberini et al. hypothesized that if physically modifying an object affects how space is interpreted, then line bisection performance should depend on the tool's function. That is, the act of "breaking" a line when using the "cutter" should mimic the act of using a rake Iriki al.'s (1996) study, insofar as the tool (cutter/rake) acts as an extension of one's arm, therefore extending peripersonal space. As such, Gamberini et al. hypothesized that line bisection performance should not be affected by the distance of the line from the participant when using a cutting tool. They further hypothesized that when the tool was a "pointer" it would not act as an extension of the user's arm and thus the distance of the line from the user should affect line bisection performance. Gamberini et al. (2013) therefore predicted an interaction between tool (pointer vs. cutter) and distance (peripersonal vs. extrapersonal) in which the distance of the line from the user should only affect line bisection performance when the tool is used as a pointer. Moreover, they predicted that the effect of distance on line bisection performance should mimic that which is observed in the real world – a leftward bias when bisecting lines in peripersonal space crossing over to a rightward bias when bisecting lines in extrapersonal space.

Gamberini et al.'s (2013) results supported the hypothesis. The authors reported a significant tool by distance interaction in which there was no effect of distance on line bisection performance when the tool was interpreted as a cutter. However, there was a leftward to rightward crossover effect as the distance of the line moved from peripersonal space to extrapersonal space when the tool was interpreted as a pointer. Put another way, tool type (pointer vs. cutter) had no affect on line bisection performance when the line was in peripersonal space, but did affect performance when the line was in extrapersonal space. Gamberini et al. (2013) therefore concluded that using a cutting tool to bisect a horizontal line, it extended the boundary of peripersonal space to include lines that would normally be considered to be in extrapersonal space. The standard pattern of directional bias in a line bisection task was observed when using a pointer, as the pointer did not alter the user's perception of the difference between peripersonal and extrapersonal space.

Present Research

The current research aimed to replicate Gamberini et al.'s (2013) finding that using a "cutter" to perform a line bisection task in VR increases performance relative to a "pointer" when bisection takes place in extrapersonal space. Replication of this finding would confirm that space is represented similarly in VR as it is in the real world. Replication would also ensure that the tool by distance interaction is a robust finding, which would help future developments and applications for VR. If the tool by distance interaction is significant, it would provide further support that using VR to measure a patient's neglect is a reliable alternative to the traditional pen and pencil line bisection task. Furthermore, it would support the view that peripersonal and extrapersonal space is perceived in VR that same way that it is perceived in the real world. Given that a major goal of VR is to make it feel as immersive and realistic as possible, it is important to examine how human perception is represented in VR.

To that end, the results of two experiments are reported here. Both experiments used the same general methodology used by Gamberini et al. (2013). The apparatus was slightly different Gamberini et al.'s, but consisted of a motion-tracking controller to perform the line bisection task, a desktop computer, and a VR headset. The current research measured line bisection performance using three measures; response time, accuracy (root mean squared error [RMSE]), and directional bias (percentage error).

Experiment 1

The goal of Experiment 1 was to replicate Gamberini et al.'s (2013) finding that when people use a tool to bisect a line (i.e., pointing to a line versus cutting a line) in VR, the "cutter" tool changes the perception of the space being interacted with. Specifically, Gamberini et al. reported a tool by distance interaction in which tool type (pointer vs. cutter) had no effect on line bisection performance when the line was within the observer's peripersonal space (60 cm), but showed higher line bisection accuracy (i.e., closer to the line's true midpoint) for the cutter when the line was in the observer's extrapersonal space (120 cm).

Methods

Participants. Forty-two Carleton University undergraduate students (17 females) participated. Ages ranged from 17 to 49 years (M = 21.5, SD = 5.98). All participants had normal or corrected-to-normal vision and were given course credit for participating.

Design. A 2 (Tool Type: Pointer vs. Cutter) x 2 (Distance: 60 cm vs. 120 cm) x 2 (Line Length: Short vs. Long) repeated measures design was used. Distance and line length were mixed factors and were randomly presented with the constraints that there were an equal number of 60 cm/120 cm trials and short/long trials within each block. Tool type was a blocked factor and counterbalanced across participants such that the two block orders were represented an equal number of times. Participants completed 64 pointer trials and 64 cutter trials for a total of 128 experimental trials.

Materials. The line bisection task was viewed in a virtual environment and displayed on an Oculus Rift DK2 head mounted display. The virtual environment was developed using the Unreal gaming engine and was presented on a Windows 10 64-bit computer. The orientation of the pointer/cutter tools and responses to the line bisection task were made using a Razor Hydra controller. The wired Hydra controller has 6 degrees of freedom with 1 mm (1°) precision and uses a weak magnetic field in order to detect absolute position and orientation.

Tasks. Participants were required perform a line bisection task in a virtual environment by using a Razer Hydra controller to control the position of a laser beam such that it intersected the midpoint of a horizontal line. Participants were instructed to bisect the line as quickly and as accurately as possible by positioning the laser on the line's midpoint and pressing a button on the controller.

Procedure. Participants were tested individually in a quiet room. Participants completed an informed consent form and general task instructions were verbally reiterated by the experimenter to ensure comprehension. Participants were explicitly reminded to respond as quickly and as accurately as possible. Participants were then asked to position their chair such that it was a set distance from the front edge of a standard desk. The Oculus Rift head-mounted display (Gamberini et al. (2013) used a 3DStudio Max 8 headset) was then placed on the participant's head and comfortably secured. A white 50 x 50 cm panel appeared on a virtual desk that served as a background for presenting the to-be-bisected black horizontal lines. The lines were presented such that they appeared near (60 cm) or far (120 cm) from the participant (see Figures 1 & 2 respectively).

In the 60 cm condition the viewing panel subtended a horizontal visual angle of 45.2°. When the lines were 120 cm away the horizontal visual angle of the visual panel was 23.5°. In the 60 cm condition, the lines appeared to be either short (8 cm, 7.63°) or long (16 cm, 15.19°). In the 120 cm condition, the lines appeared to be either short (16 cm, 7.63°) or long (32 cm, 15.19°). The thickness of the line was 2 mm in the 60 cm condition and 4 mm in the 120 cm condition, thus keeping the vertical visual angle constant at 0.19°. Participants used an external controller to perform the line bisection task: Gamberini et al. (2013) used a Nintendo Wii remote whereas a Razer Hydra controller was used in the present experiment. In the present experiment, a green laser beam extending from the tip of the controller to the surface of the white panel/black horizontal line appeared in the virtual environment to represent the movement of the controller and the point at which the line would be bisected. Participants were instructed to press the bottom left button on the controller to confirm the bisection point.

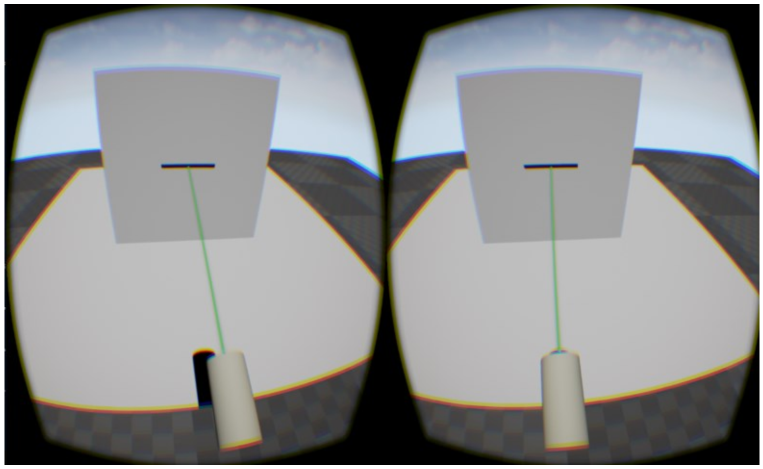

Figure 1.Screen shot of participant's perspective of viewing a line at a near (60 cm) distance through the Oculus Rift.

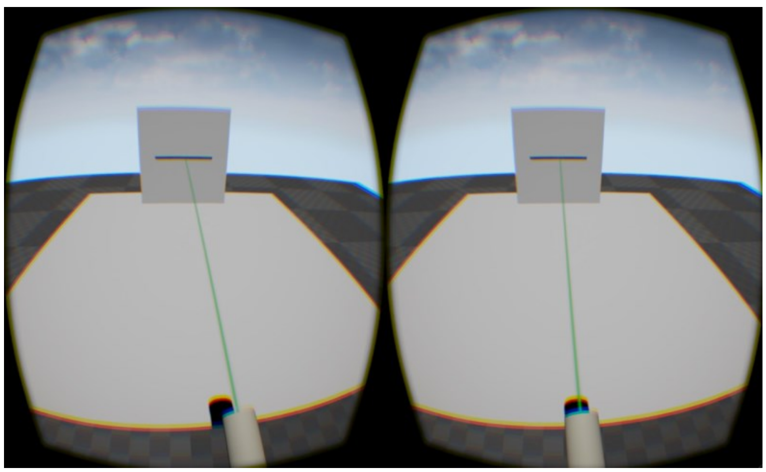

Figure 2. Screen shot of participant's perspective of viewing a line at a far (120 cm) distance through the Oculus Rift.

Participants were given a verbal description of what the virtual environment would look like, what their task would be and what their goal of the task was. Depending on the experimental counterbalance, participants completed a practice block of eight pointer or eight cutter trials. Participants were told that the goal of each trial was to try to bisect the horizontal line as quickly and as accurately as possible. Once participants confirmed the bisection point by pressing a button on the controller, the line would either break (See Figure 3) at the selected bisection point in the cut condition or stay solid (See Figure 4) in the point condition. Thus, there was no visual feedback with respect to line bisection accuracy in the point condition.

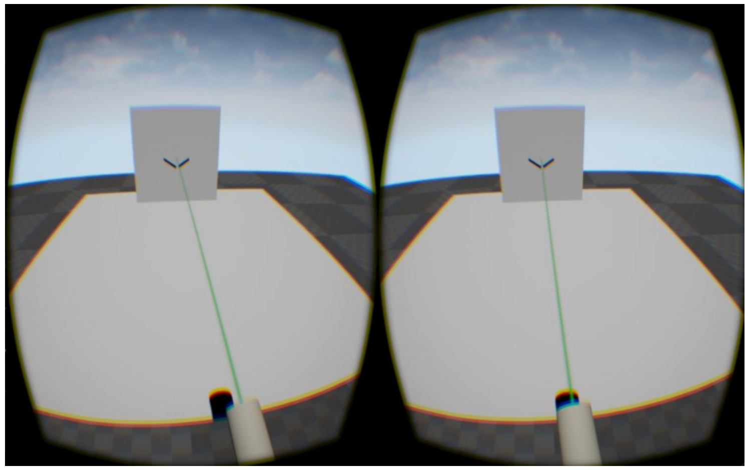

Figure 3. Example of a cutter trial for a line in the far (120 cm) condition. Here the line breaks after the participant's response.

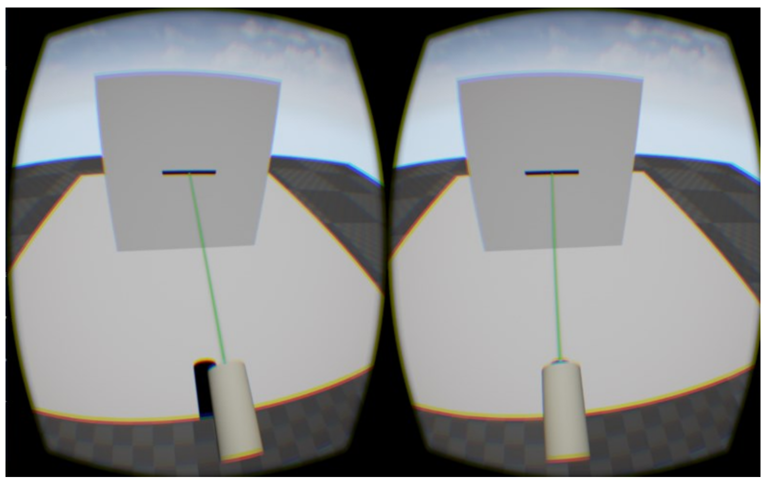

Figure 4. Example of a pointer trial for a line in the near (60 cm) condition. Here the line stays solid after the participant's response.

If necessary, the experimenter provided feedback during the practice trials to assist participants with the functionality of the Hydra. Participants then began the first block of 64 pointer/cutter experimental trials depending on the counterbalance. Participants were given a break following completion of the experimental trials. A second block of 64 experimental cutter/pointer (depending on the experimental counterbalance) was then presented. Following the second block of trials, participants were debriefed and the experimenter answered any remaining questions. They were instructed that a small square would appear on the left or right side of the white panel at the beginning of each trial and that they were to "click on it" by positioning the laser beam on the square and pressing a button on the Hydra. The purpose of the square was to calibrate the starting position of the Hydra controller to account for any left or right biases. Once the calibration task was complete, a uniform visual mask appeared for 10 ms, followed by the to-be-bisected line, which appeared at the centre of the white panel (See Figure 5). The line remained on the screen until the participant pressed the bottom left button on the Hydra controller to confirm the location of the bisection response. In the cutter condition, the line split into two pieces at the bisection point and both pieces "fell" downwards as if hinged at their outer endpoints. There was no visual feedback in the pointer condition. The inter-trial interval was 1000 ms.

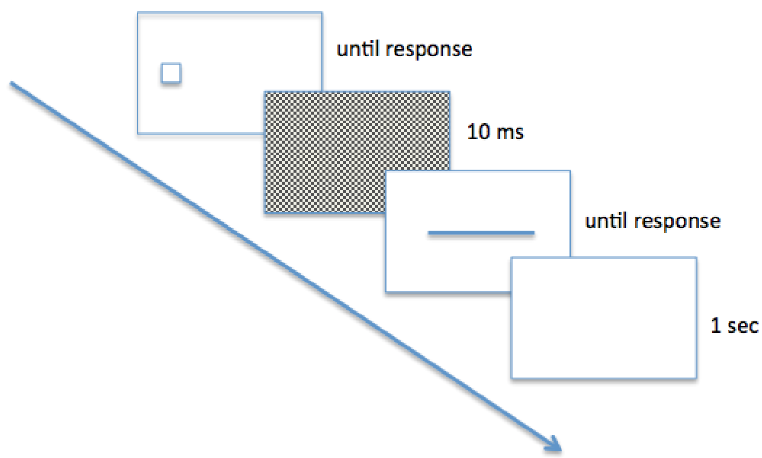

Figure 5. Example of a trial sequence.

Results

The data were analyzed using a 2 (Tool Type: Pointer vs. Cutter) x 2 (Distance 60 cm vs. 120 cm) x 2 (Line Length: Short vs. Long) repeated measures analysis of variance (ANOVA). All figures reported show Jarmasz and Hollands (2009) 95% confidence intervals.

Three variables were measured: response time, accuracy (RMSE) and directional bias (percentage error). As per convention in the line bisection task literature, the leftmost point of the line was assigned a value of 0 and the rightmost point of the line was assigned a value of 1, with the midpoint being 0.5. Any error to the left of the midpoint was calculated by subtracting 0.5 from the bisection point (e.g., 0.4 – 0.5 = -0.1), which always yields a negative value. Any error to the right of the midpoint is calculated by subtracting 0.5 from the bisection point (e.g., 0.6 – 0.5 = +0.1), which, in contrast, always yields a positive value. Traditionally, these errors are averaged across trials to indicate an overall directional bias (leftward if the average error is negative and rightward if the average error is positive). This is what was done here (and multiplied by 100) for the percentage error measure of directional bias. However, directional bias does not provide a good measure of overall accuracy. Imagine data where half of a normally distributed set of responses is leftward biased and centered around a value of 0.4 and the other half of a set of normally distributed responses is rightward biased and centered around 0.6. Simply averaging these responses (as would be done for determining directional bias) would yield an average error of zero. This is clearly not the case. In order to provide a more appropriate measure of accuracy, root mean squared error (RMSE) was calculated. RMSE removes the directionality of the response (by squaring the difference between each observed and optimal (0.5) responses) and then computing the square root of the means of the difference scores. In so doing, the negative scores associated with leftward biases and the positive scores associated with rightward biases no longer cancel each other out. RMSE therefore provides a measure of absolute error.

Response Time

Response time (RT) was measured in milliseconds, with the RT clock starting as soon as the horizontal line appeared and stopping once the participant pressed the button on the controller to bisect the line. One participant was removed from the analysis because their mean RT (collapsed across all eight conditions) was an outlier according to the procedure described below. Data from trials on which participants "misfired" (i.e., clicked above or below the horizontal line at least once prior to clicking on the line) were removed from the analysis. This resulted in an elimination of 0.2% of the data. The remaining data were submitted to a recursive outlier analysis in which scores falling three or more standard deviations above or below the mean score for that condition were eliminated from further analyses (VanSelst & Jolicoeur, 1994). This resulted in a further elimination of 0.89% of the data.

A marginal main effect of distance F(1, 40) = 3.25, MSE = .065, p = .08, η^2 = .127) showed that participants took longer to bisect lines in the far (M = 1550 ms, SE = .063) condition than in the near (M = 1499 ms, SE = .079) condition. No main effects of line length or tool type were found.

As seen in Figure 6, a significant interaction of distance by line length F(1, 40) = 5.82, MSE = .009, p = < .05, η^2 = .127) showed that participants took longest to bisect lines that were far and long (M = 1.576, SE = .083). There was no difference in performance when the line was long or short in the near condition (M = 1.499, SE = .064). There was also no interaction found for tool type by distance F(1, 40) = 1.173, MSE = .019 p = < .285, η^2 = .028) as seen in Figure 7.

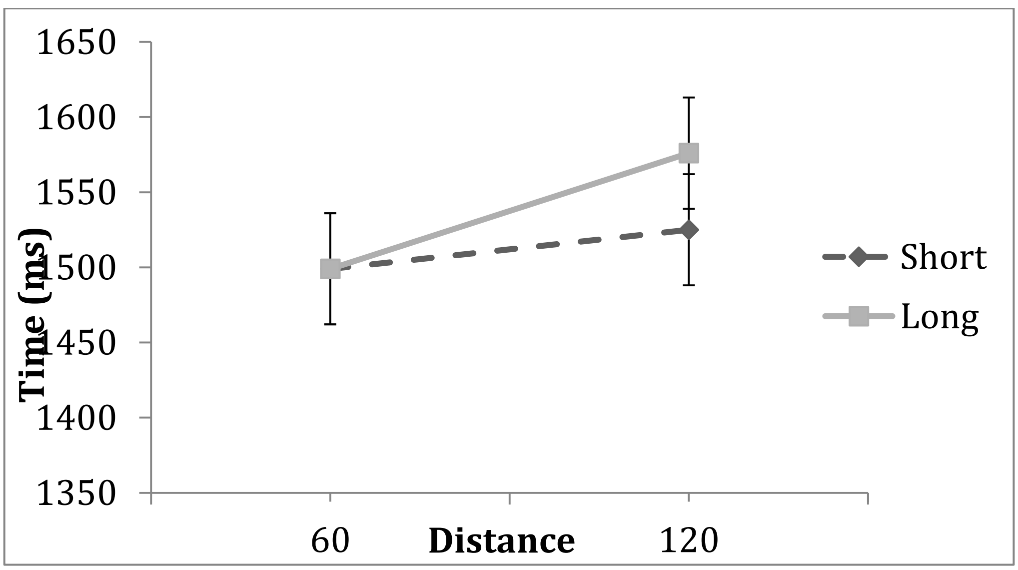

Figure 6. Mean Response Time as a Function of Distance and Line Length.

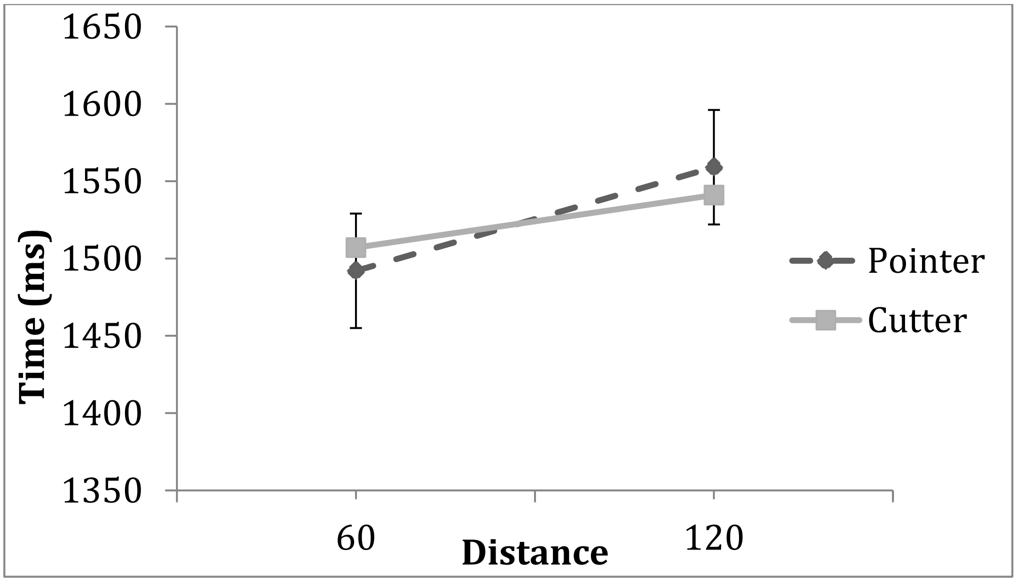

Figure 7. Mean Response Time as a Function of Tool Type and Distance.

Accuracy (Root Mean Squared Error)

The RMSE data were submitted to the same recursive outlier analysis procedure used for the RT data, which resulted in an elimination of 0.61% of the data. No participants were eliminated as outliers. The results of the ANOVA indicated that there no main effect of tool type $F(1, 41) = 1.62$, MSE = .00008, $p = .21$, $\eta^2 = .038$). There was a significant main effect of distance $F(1, 41) = 10.38$, MSE = .001, $p < .01$, $\eta^2 = .202$), with line bisection performance being more accurate when the line was far (M = .028, SE = .002) than when it was near (M = .031, SE = .002). There was also a significant main effect of line length $F(1, 41) = 58.07$, MSE = .001, $p < .01$, $\eta^2 = .586$), with line bisection performance being more accurate when the line was long (M = .025, SE = .001) than when it was short (M = .034, SE = .002).

There was also a significant distance by line length interaction $F(1, 41) = 13.65$, MSE = .00004, $p < .01$, $\eta^2 = .25$). Figure 8, shows that the effect of line length was significantly greater when the line was near (60 cm) than when it was far (120 cm). None of the other interactions reached significance. This included the tool by distance interaction ($F < 1$) as seen in Figure 9.

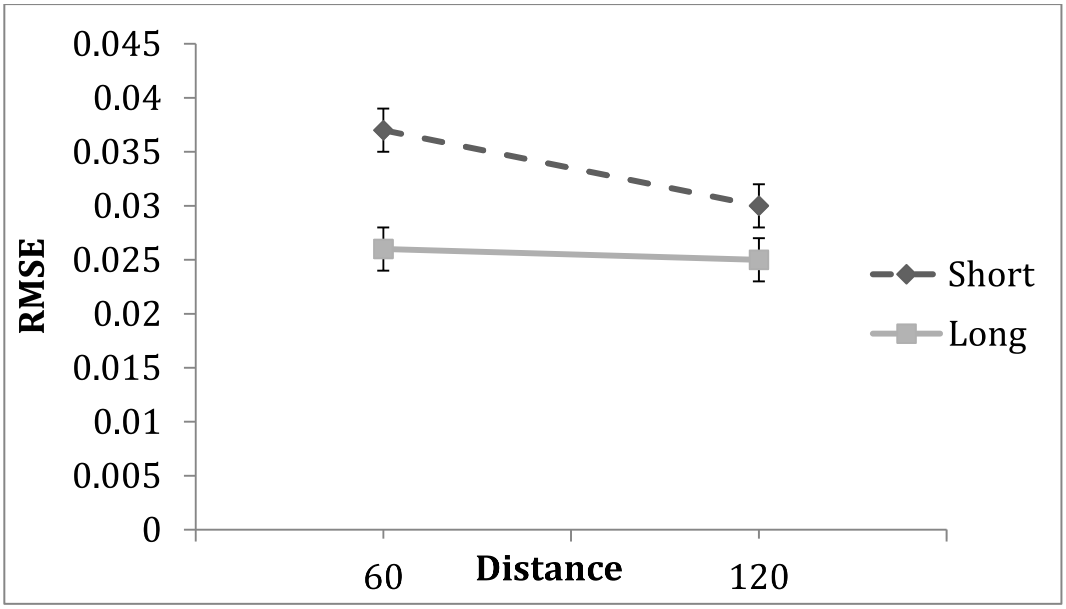

Figure 8. Mean RMSE as a Function of Distance and Line Length.

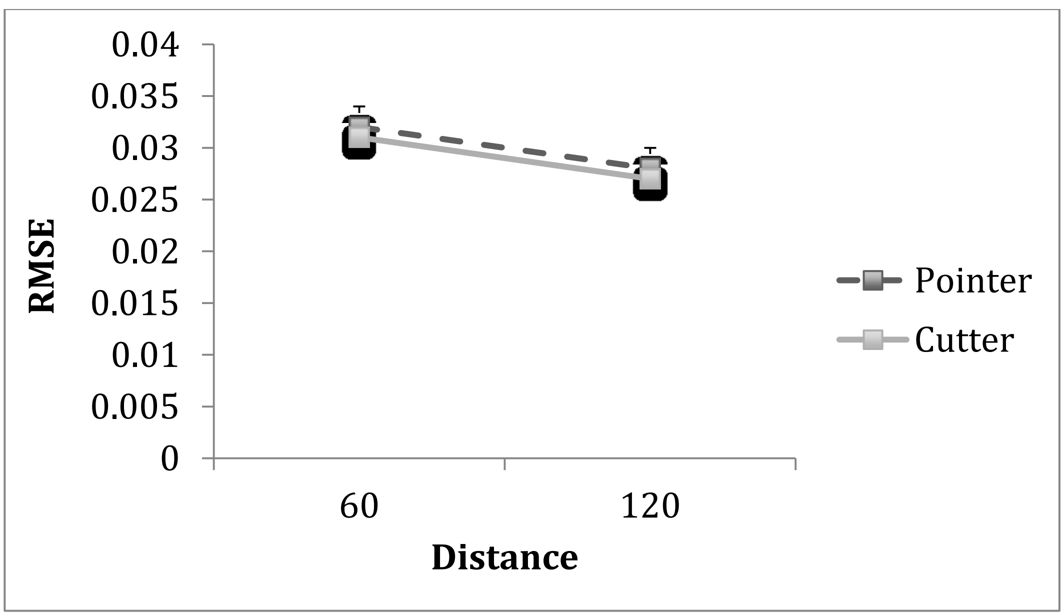

Figure 9. Mean RMSE as a Function of Tool Type and Distance.

Directional Bias (Percentage Error)

The same trials that were identified as outliers in the accuracy analysis were eliminated here. There was no main effect of tool ($F < 1$) or line length $F(1, 41) = 1.242$, $MSE = 1.122$, $p = .27$, $\eta^2 = .03$) There was, however, a significant main effect of distance $F(1, 41) = 5.93$, $MSE = 1.613$, $p < .05$, $\eta^2 = .126$ with greater leftward biases when the line was near (M = -.446, SE = .183) than when it was far (M = -.108, SE = .186). It should be noted that there was always a leftwards bias, regardless of distance or line length given that negative means represent a leftward bias and positive means represent rightward biases.

There was a marginal distance by line length interaction F(1, 41) = 2.94, MSE = .816, $p < .07$, $\eta^2 = .081$). As can be seen in Figure 10, there was no effect of line length when participants bisected the line at 60 cm, but there was significantly less of a leftward bias (there was a slight *rightward* bias) when bisecting long lines at 120 cm. None of the other two way interactions were significant, including the tool by distance interaction (F < 1) as seen in Figure 11.

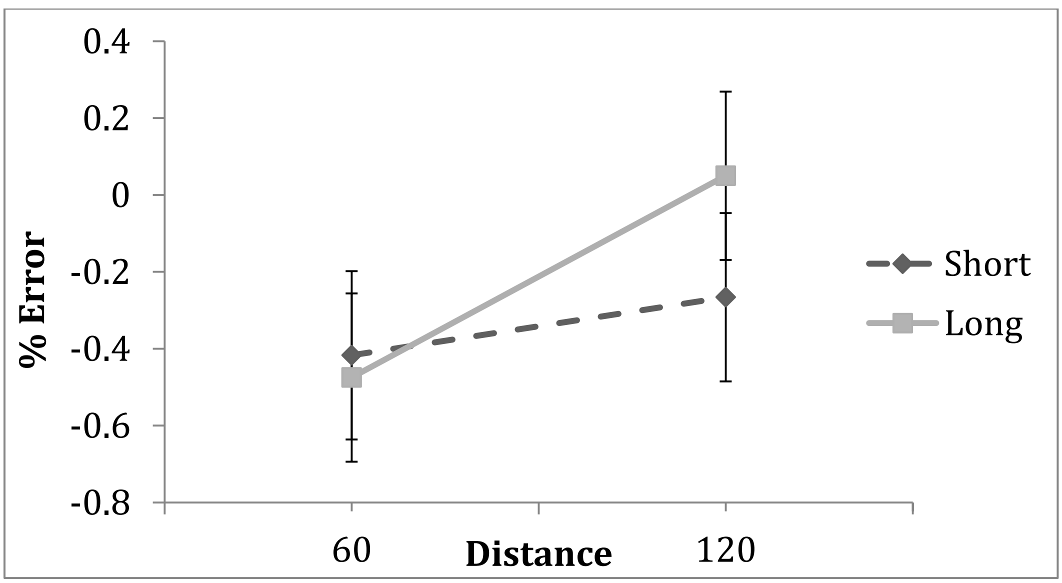

Figure 10. Mean Percentage Error as a Function of Distance and Line Length.

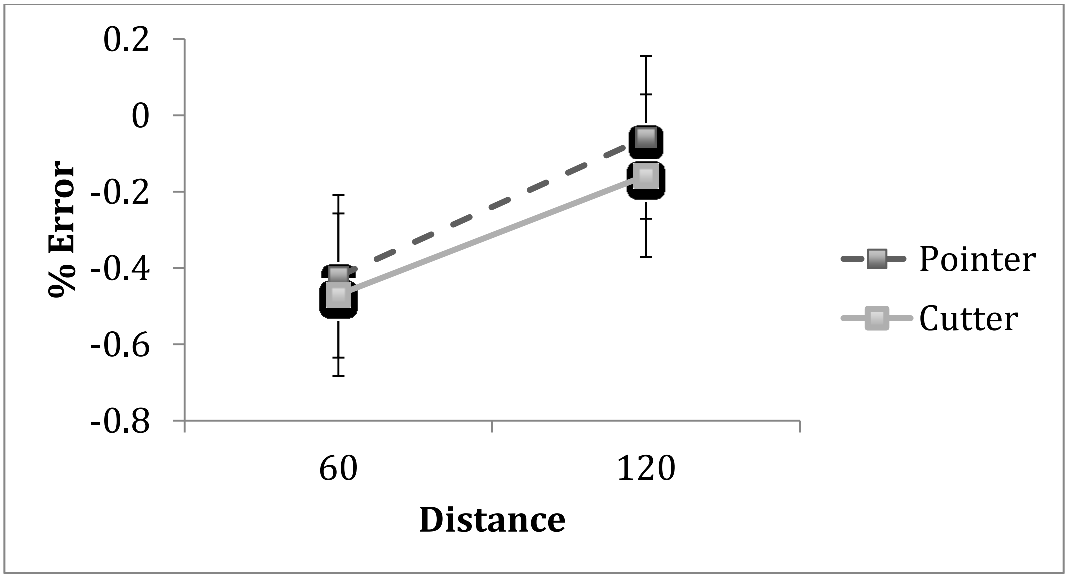

Figure 11. Mean Percentage Error as a Function of Tool Type and Distance.

There was a marginal three-way Tool x Distance x Line Length interaction $F(2, 41) = 3.75$, $MSE = .492$, $p < .06$, $\eta^2 = .084$). As shown in Figures 12 and 13, there was a crossover interaction between distance and line length when the tool was a cutter. In contrast, distance and line length had additive effects on directional bias when the tool was a pointer.

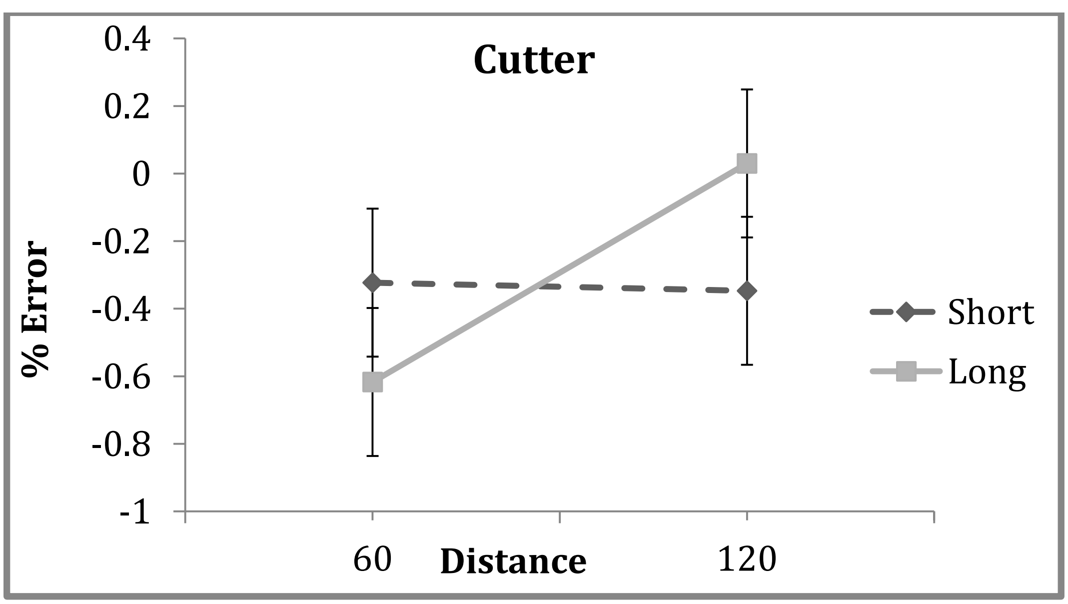

Figure 12. Mean Percent Error as a Function of Distance and Line Length in the Cutter Condition.

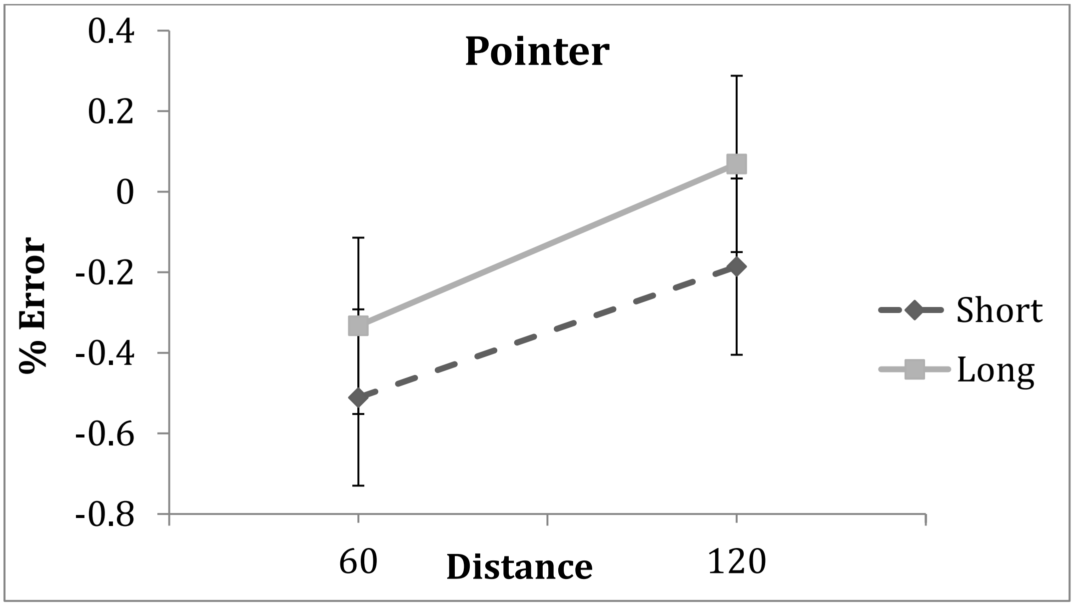

Figure 13. Mean Percent Error as a Function of Distance and Line Length in the Pointer Condition.

Discussion

The present research partially replicated Gamberini et al.'s (2013) findings insofar as there was no main effect of tool type (pointer vs. cutter) on line bisection performance. As in Gamberini et al., there was a significant main effect of distance (60 cm vs. 120 cm) on line bisection performance, however, the main effect of distance observed here in the opposite direction as the main effect of distance reported by Gamberini et al.

More specifically, Gamberini et al. found that participants bisected the lines to the left of the midpoint when the lines were in peripersonal space and bisected the lines to the right of the midpoint when the lines were in extrapersonal space. In the present experiment participants showed a consistent leftward bias and this bias was more pronounced when the lines were in peripersonal space than when they were in extrapersonal space. Further, Gamberini et al. reported that participants required more time to bisect a line when it was in peripersonal space than when it was in extrapersonal space. In the present experiment the opposite trend ($p < .08$) was found where longer bisection response times occurred when the line was in extrapersonal space than when it was in peripersonal space. The current experiment also found a significant main effect of line length with longer lines being bisected more accurately and with less directional bias than short lines. It is unclear whether Gamberini et al. found this same line length effect because, even though it was a manipulation in their experiment, they did not report it in their analysis.

Perhaps the most theoretically important finding from Experiment 1 is that it failed to replicate Gamberini et al.'s (2013) tool type by Distance interaction. Gamberini et al. found that tool type had no impact on line bisection performance when the line was in peripersonal space but using a cutting tool reduced line bisection errors relative to a pointer when the line was in extrapersonal space. Here, tool and distance had additive effects on response time ($F = 1.17$, $p > .25$) and on RMSE and percentage error ($F < 1$). Gamberini et al. interpreted the tool type by distance interaction as evidence that peripersonal space is determined by an action's consequence and not necessarily by a person's physical affordances. That is, the action consequence of breaking the line resulted in users interpreting their tool as a cutter, which resulted in better performance on the line bisection task relative to when the line remained solid and the tool was interpreted as a pointer. Gamberini et al. (2013) hypothesized that if a tool physically changes a stimulus that is being interacted with (in this case a horizontal line), then the space that is being interacted with will be interpreted as peripersonal space. On this view, using a tool that acts as a cutter extends peripersonal space when actually interacting with it at an unreachable distance but has no effect when interacting in reachable distance. The present research does not support this idea as tool and distance had additive effects on RT, accuracy, and directional bias.

In the present experiment, there were significant interactions between line length and distance for all performance measures (RT, RMSE and percentage error). It is important to note, however, that the pattern of the line length by distance interaction was different for each performance measure. The response time and directional bias measures showed similar patterns in that there was a greater effect of line length when the lines were in extrapersonal space than when they were in peripersonal space, but revealed a speed-directional bias trade-off in which response time was sacrificed for reduced directional bias for long lines. That is, long lines were bisected significantly more slowly but with significantly less directional bias than short lines when they were in extrapersonal space. In contrast, the distance by line length interaction for RMSE revealed that the effect of line length was greater when the lines were in peripersonal space than when they were in extrapersonal space. The finding that long lines showed less of a directional bias when being bisected in extrapersonal space is consistent with the results reported in Nicholls et al.'s (2016) study. That is, Nicholls et al. reported a line length by distance interaction whereby there was a strong leftward bias for bisecting long lines in peripersonal space that was absent when the lines were in extrapersonal space. This finding in the current experiment and Nicholls et al. (2016) are consistent with the pseudoneglect effect (McCourt, 2001; McCourt & Jewell, 1999; Thomas et al., 2015).

There was also a moderately significant ($p < .07$) three-way tool by distance by line length interaction in terms of directional bias. The three-way interaction showed that when the tool being used was a cutter, performance for bisecting long lines increased from near to far space but when bisecting short lines, there was no difference in performance across distances. Figure 9 shows a crossover effect whereby performance bisecting short and long lines both increases with distance. Figure 10 shows an additive effect where long lines show the same pattern as in Figure 9 but performance for cutting short lines does not improve with distance. This finding suggests that a cutter improves performance only when bisecting long lines rather than short lines.

The present work makes a distinction between line bisection accuracy (RMSE) and directional bias (percent error). The line bisection literature often conflates these two measures of performance, with directional bias often being considered as an index of accuracy. The finding that the distance by line length interaction was qualitatively different for RMSE than is was for percentage error, coupled with the finding that percentage error yielded a significant ($p < .07$) tool x distance x line length interaction whereas RMSE did not ($p > .25$) indicates that these measures are indexing different aspects of performance on the line bisection task.

The lack of replication of the tool type by distance interaction could possibly be because of the difference in the design of the laser pointer in the virtual environment. The virtual laser pointer used in the present experiment was designed as a green beam whereas in Gamberini et al. (2013) the laser was represented as a red dot or reticle. One possible explanation for the difference in performance from a laser dot and a laser beam is that the presence of the laser beam could mimic similar effects of using a stick or one's arm in the real world. Gamberini et al. explained that using a physical stick in the real world brings extrapersonal space into peripersonal space, which results in a leftward bias. This effect could explain the present experiments results whereby participants make constant leftward biases.

Experiment 2

The goal of Experiment 2 was to determine whether the failure to replicate Gamberini et al.'s (2013) tool by distance interaction was caused by the presence of the laser "beam" that extended from the controller to the surface of the white panel. It was hypothesized that the laser beam may have been perceived by the user as an extension of their arm or a stick, resulting in extrapersonal space being treated peripersonal space, regardless of whether they were using the tool as a cutter or as a pointer. In order to address this possibility, the laser "beam" was removed such that only the end point of the beam was visible where it made contact with the surface of the white panel or to-be-bisected line. This manipulation had the visual effect of having the user control a laser "dot" (see Figure 14) instead of a laser "beam" and therefore removed the visual extension of their arm. In order to avoid experimental confounds, no other changes were made to Experiment 2. Thus, Experiments 1 and 2 were identical in terms of methodology and design except that the laser beam used in Experiment 1 was replaced with a laser dot.

Given that Experiment 2 eliminated the possibility that the presence of the laser beam effectively extended the user's reach into peripersonal space for both the pointer and the cutter, it was hypothesized that tool type and distance would now interact, thus replicating Gamberini et al.'s (2013) findings.

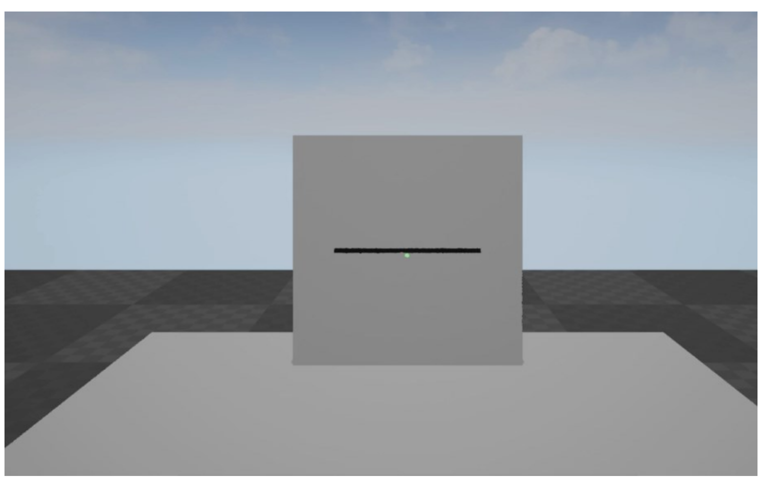

Figure 14. Screen shot of the pointer/cutter being represented as a laser "dot" rather than a laser "beam".

Methods

Participants. Forty-four Carleton University undergraduate students (20 females) participated. Ages ranged from 17 to 30 years (M = 20, SD = 2.87). All participants were assumed to have normal or corrected-to-normal vision and were given course credit for participating.

Design. Identical to Experiment 1.

Materials. Identical to Experiment 1 except that the laser "beam" extending from the participant's controller was replaced with a laser "dot" that appeared on the surface of the white panel or to-be-bisected line.

Tasks. Identical to Experiment 1.

Procedure. Identical to Experiment 1.

Results

The data were analyzed using a 2 (Tool Type: Pointer vs. Cutter) x 2 (Distance 60 cm vs. 120 cm) x 2 (Line Length: Short vs. Long) repeated measures analysis of variance (ANOVA). The same line bisection measures of performance used in Experiment 1 were used here and were calculated using the same methodologies.

Response Time

Three participants were removed from the RT analysis because their mean RT (collapsed across all eight conditions) was an outlier according to VanSelst and Jolicoeur's (1994) recursive outlier procedure. Data from trials on which participants "misfired" (i.e., clicked above or below the horizontal line at least once prior to clicking on the line) were removed from the analysis. This resulted in an elimination of 0.12% of the data. The remaining data were submitted to a recursive outlier analysis, which resulted in a further elimination of 2.01% of the data.

A significant main effect of distance F(1, 40) = 10.19, MSE = .02, $p < .01$, $\eta^2 = .2$) showed that participants took longer to bisect the line when it was far (M = 1403 SE = .055) than when it was near (M = 1355, SE = .048). There was no main effect of line length or tool.

As can be seen in Figure 15, there was a significant interaction between distance and line length F(1, 40) = 6.267, MSE = .009, $p = .02$, $\eta^2 = .135$), in which the effect of line length was greater when the line was bisected in near space than in far space. No other interactions were significant, most notably the Tool x Distance interaction (F < 1) seen in Figure 16.

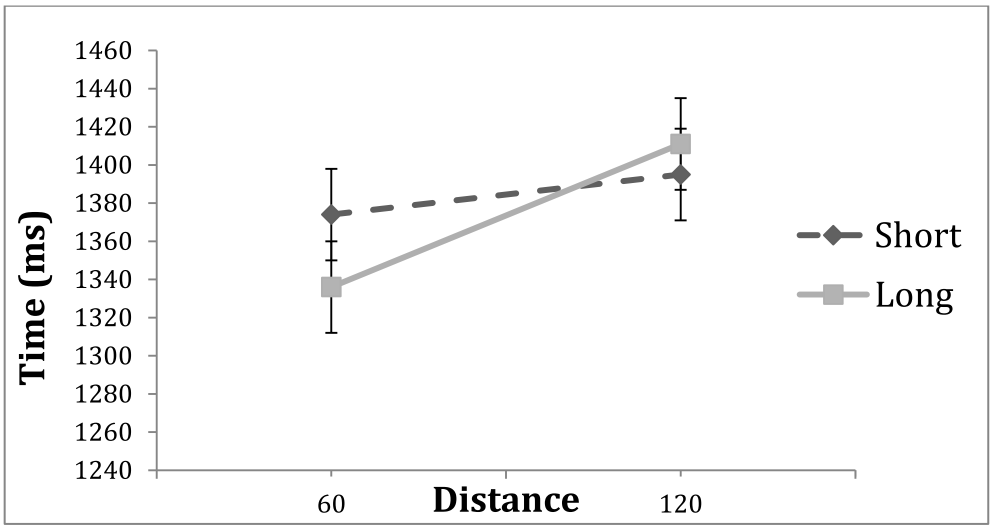

Figure 15. Mean Response Time (in ms) as a Function of Distance and Line Length.

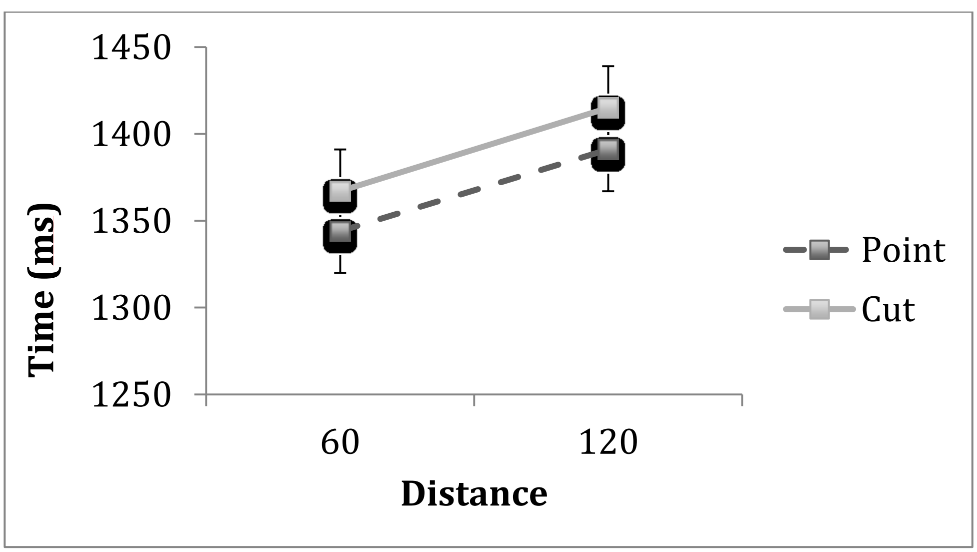

Figure 16. Mean Response Time (in ms) as a Function of Tool Type and Distance.

Accuracy (Root Mean Squared Error)

Two participants were eliminated from the RMSE analysis because their mean RMSE scores (collapsed across the eight conditions of the experimental design) were identified as outliers. The remaining data were submitted to a recursive outlier analysis procedure, which resulted in an elimination of 0.80% of the data. The results of the ANOVA indicated that there was no main effect of tool ($F < 1$). A significant main effect of line length, $F(1, 41) = 235.718$, $MSE = .001$, $p < .01$, $\eta^2 = .86$, showed that people were more accurate at bisecting long lines (M = .026, SE = .001) than short lines (M = .040, SE = .001). There was a significant main effect of distance, $F(1, 41) = 80.86$, $MSE = .001$, $p < .01$, $\eta^2 = .67$), with line bisection performance being more accurate when the line was far (M = .028, SE = .002) than when it was near (M = .031, SE = .002).

There was also a significant distance by line length interaction, $F(1, 41) = 10.07$, $MSE = .00006$, $p < .01$, $\eta^2 = .197$). As can be seen in Figure 17, the effect of line length was larger at 60 cm than at 120 cm. None of the other interactions reached significance, including the Tool by Distance interaction ($F < 1$) as seen in Figure 18.

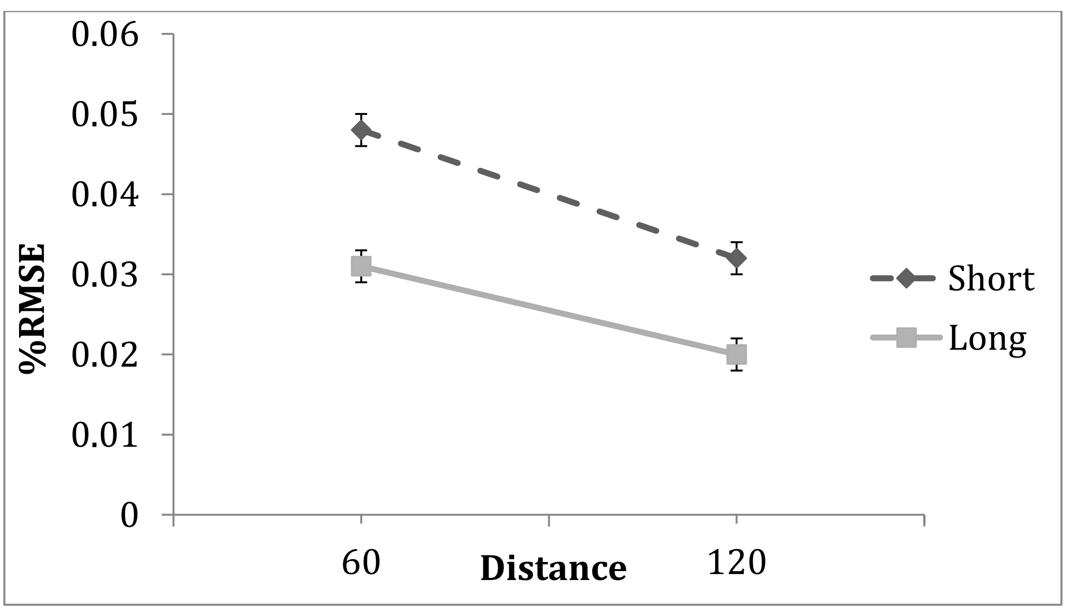

Figure 17. Mean RMSE as a Function of Distance and Line Length.

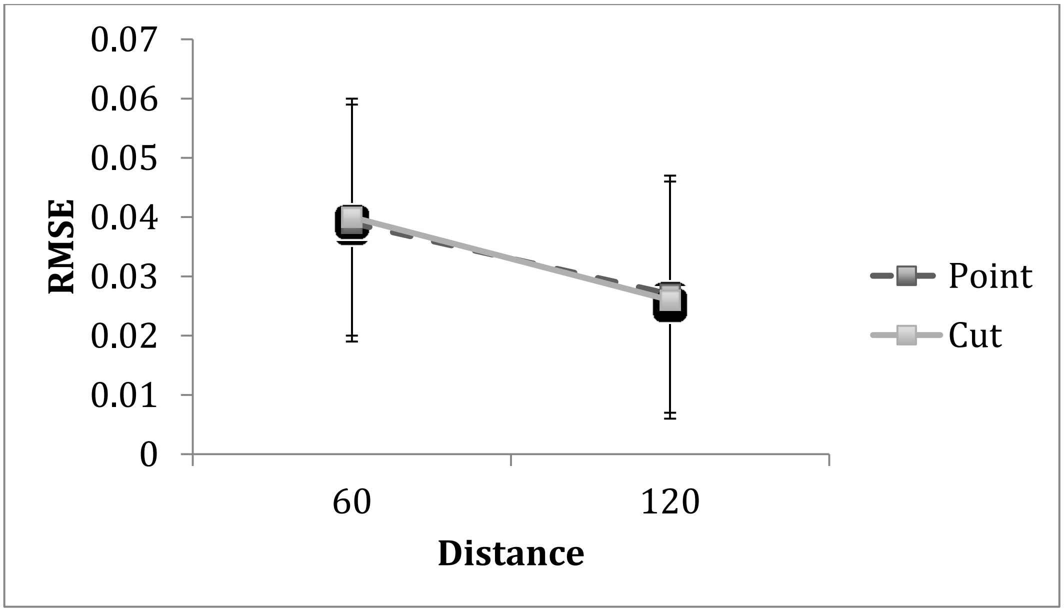

Figure 18. Mean RMSE as a Function of Tool Type and Distance.

Directional Bias (Percentage Error)

The same trials that were identified as outliers in the RMSE analysis were eliminated here. There was no main effect of tool (F < 1). There was, however, a significant main effect of distance F(1, 43) = 63.19, MSE = 3.151, $p < .01$, $\eta^2 = .56$) with greater leftward biases when the line was near (M = -2.464, SE = .202) than when it was far (M = -.960, SE = .159). A significant main effect of line length F(1, 43) = 53.96, MSE = 1.816, $p < .01$, $\eta^2 = .56$) revealed that there was a greater leftward line bisection bias when the line was short (M = -2.240, SE = .191) than when it was long (M = -1.184, SD = .148). Again, errors were always to the left of the midpoint regardless of line length.

As shown in Figure 19, there was an interaction between distance and line length F(1, 43) = 6.12, MSE = 1.094, $p < .05$, $\eta^2 = .16$), with a greater difference in line bisection bias between short and long lines when the lines were near than when they were far. Errors were always made to the left of the midpoint. No other interactions were significant, including the Tool x Distance interaction (F < 1) as seen in Figure 20.

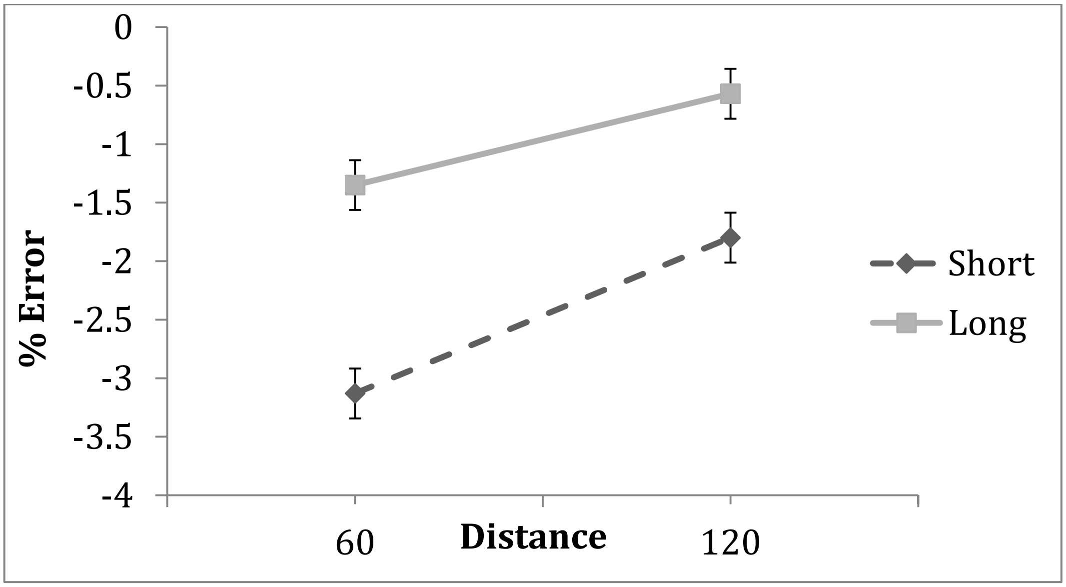

Figure 19. Mean Percentage Error as a Function of Distance and Line Length.

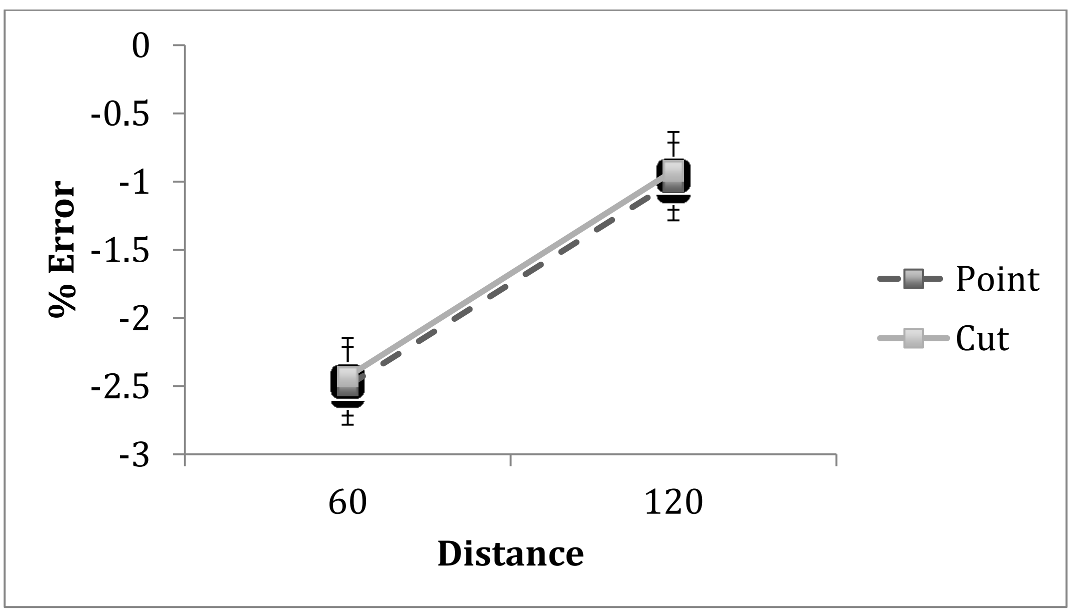

Figure 20. Mean Percentage Error as a Function of Tool Type and Distance.

Discussion

Experiment 2 replicated Gamberini et al.'s (2013) finding that the type of tool used (i.e., a pointer vs. a cutter) did not affect line bisection performance, but that the distance between the user and the to-be-bisected line (60 cm vs. 120 cm) did impact performance. However, the main effect of distance observed here was not in the same direction as the main effect of distance reported by Gamberini et al. (2013). Gamberini et al. found that participants bisected the lines to the left of the midpoint when the lines were in peripersonal space and bisected the lines to the right of the midpoint when the lines were in extrapersonal space. In the current experiment, there was a consistent leftward bias on the line bisection task, regardless of whether it was performed in peripersonal space (60 cm) or in extrapersonal space (120 cm). This leftward bias in the line bisection task replicates what was observed in Experiment 1. Further, there was also an inconsistency in the response time data for the main effect of distance reported by Gamberini et al. and that observed in Experiment 2. Gamberini et al. reported that participants required more time to bisect a line when it was in peripersonal space than when it was in extrapersonal space. In contrast, Experiment 2 found longer bisection response times when the line was in extrapersonal space than when it was in peripersonal space ($p < .01$). Longer response times for lines in extrapersonal space were also reported in Experiment 1.

Experiment 2 yielded a significant main effect of line length, with long lines being bisected more accurately and with less directional bias than short lines. This replicates the pattern of data observed in Experiment 1. It is unclear whether Gamberini et al. found this same line length effect because, even though line length was manipulated in their experiment, they did not report analyzing it.

The most theoretically important finding is that Experiment 2 failed to replicate Gamberini et al.'s (2013) tool by distance interaction in which tool type had no impact on line bisection performance when the line was in peripersonal space, but using a cutting tool reduced line bisection errors relative to a pointer when the line was in extrapersonal space. In the present experiment, tool and distance had additive effects on response time, RMSE, and percentage error ($Fs < 1$).

As discussed above, Gamberini et al. (2013) interpreted their tool by distance interaction as evidence that peripersonal space is determined by an action's consequence. That is, the action consequence of breaking the line resulted in users interpreting their tool as a cutter, which resulted in better performance on the line bisection task relative to when the line remained solid and the tool was interpreted as a pointer. Researchers hypothesized that when a tool can physically change a stimulus after interacting with it, then the space where interaction took place will then be coded as peripersonal space due to the physical feedback. Therefore, when the tool is interpreted as a "cutter", the space where cutting took place is then referred to as peripersonal space because the tool brought far space near.

The present finding that tool (and its action consequence) and the distance of an object from the user (in peripersonal or extrapersonal space) have additive effects on response time, accuracy, and directional bias on a line bisection task is inconsistent with Gamberini et al.'s (2013) theory. The present research suggests that action consequence of a tool has no impact on line bisection performance, regardless of whether the to-be-bisected line is in peripersonal or extrapersonal space. The current results rule out the possibility that the additivity between tool and distance observed in Experiment 1 was due to the presence of a laser "beam" that extended from the user's tool to the surface of the white panel. In the present experiment, the laser beam was removed such that only a laser dot was visible on the surface of the white panel, which more closely represented how the task appeared in Gamberini et al. (2013). This manipulation had no impact on the joint effects of tool and distance, which, again, were clearly additive.

The results from Experiment 2 showed that line length and distance interacted for all performance measures (response time, RMSE and percentage error). It is important to note, however, that the pattern of the line length by distance interaction differed across performance measures. The response time and directional bias measures showed similar patterns in that there was a greater effect of line length when the lines were in peripersonal space than when they were in extrapersonal space. In contrast to Experiment 1, where the distance manipulation had a greater impact on long lines for the response time and directional bias measures, in

Experiment 2 the distance manipulation had a larger effect on long lines for response time, but a smaller effect on long lines for directional bias. Consistent with Experiment 1, however, there was a speed-directional bias trade-off for lines in extrapersonal space in which lines were bisected more slowly but with less directional bias. For RMSE, the pattern of the line length by distance interaction observed in Experiments 1 and 2 was the same. Specifically, the effect of line length was greater when the lines were in peripersonal space than when they were in extrapersonal space.

The finding that performance increased for RMSE and percentage of error when moving from peripersonal space to extrapersonal space is consistent with previous studies that found an interaction between distance and line length (McCourt, 2001; McCourt & Jewell, 1999; Nicholls et al., 2016; Thomas et al., 2015).

This finding is also consistent with results from Experiment 1. The significant (one-tailed) three-way Tool x Distance x Line Length interaction that was observed in the directional bias data in Experiment 1 was not replicated in Experiment 2 ($F < 1$). This could be taken as evidence that the three-way interaction in Experiment 1 was a Type I error. In sum, rather than reproducing Gamberini et al.'s (2013) tool by distance interaction, Experiment 2 found the same distance by line length interaction that was reported in Experiment 1. That said, the patterns of the tool by distance interactions were qualitatively different across Experiments 1 and 2 for the response time and percentage error measures of performance. This will be taken up further in the General Discussion.

GENERAL DISCUSSION

The purpose of this thesis was to replicate Gamberini et al. (2013), most notably their reported tool by distance interaction. In contrast to Gamberini et al, there was no evidence for a tool by distance interaction in either Experiment 1 or 2. It was hypothesized that the failure to replicate this finding in Experiment 1 was due to the visualization of the pointer/cutter, which differed from Gamberini et al., in that a laser "beam" extended from the tip of the pointer/cutter to the surface of the white board. The presence of the laser beam may have resulted in participants interpreting both the pointer and cutter as extensions of their arm or as a stick that could be used to interact with objects in extrapersonal space. It has been shown that tools that allow users to physically interact with objects in extrapersonal space effectively extend the mental representation of peripersonal space to now include those objects (Berti & Frassinetti, 2000; Gamberini et al., 2008; Gamberini et al., 2013; Longo & Lourenco, 2006). If participants interpreted the pointer and the cutter as being the same tool by virtue of the laser beam extending the boundaries of peripersonal space, then this may have caused the additivity between tool and distance observed in Experiment 1.

Experiment 2 examined whether removing the laser beam such that only a laser "dot" was visible on the surface of the white board, which was a more accurate representation of the visualization used in Gamberini et al. (2013). This manipulation also eliminated the possibility of participants mentally extending peripersonal space wherein the laser beam allowed them to physically interact with objects in extrapersonal space. Despite this modification to the visualization of the cutter/pointer, tool and distance continued to show additive effects on response time, accuracy (RMSE), and directional bias (percent error). Thus Gamberini et al.'s (2013) tool by distance interaction was not replicated in either Experiment 1 or 2.

In addition to the observed additivity between tool and distance, Experiments 1 and 2 yielded remarkably consistent main effects and interactions. Specifically, there was no main effect of tool type in either experiment, both experiments produced main effects of distance in which lines in extrapersonal space were bisected more accurately and with less directional bias than lines in peripersonal space (but took significantly longer to bisect), and both experiments showed that long lines were bisected significantly more accurately and with less directional bias than short lines. Experiments 1 and 2 both yielded distance by line length interactions for response time, accuracy (RMSE), and directional bias (percent error). A closer inspection of the distance by line length interactions across dependent measures and across experiments revealed that the patterns of the interactions were different. Before discussing the pattern of interactions in Experiment 1 and 2, it is important to note that the range of error was drastically different from Experiment 1 (.050 to -.475) to Experiment 2 (-.570 to -3.130) showing that error was approximately ten times greater in Experiment 2.

In terms of response time, the pattern of the distance by line length interactions was different across Experiments 1 and 2. In Experiment 1, there was no effect of line length in the near condition (60 cm), with line bisection for long lines taking significantly longer than for short lines in the far condition (120 cm). In Experiment 2, long lines were bisected significantly faster than short lines at 60 cm, with no effect of line length at 120 cm. In both cases, however, the distance manipulation had a larger impact on long lines than short lines. In sum, the bisection of long lines takes significantly longer as the lines move from near space (peripersonal) to far space (extrapersonal). This is inconsistent with Gamberini et al.'s (2013) finding that participants took longer to bisect lines when in peripersonal space regardless of line length.

The pattern of the line length by distance interaction was similar across Experiments in terms of accuracy (RMSE). In both cases, the effect of line length was greater at 60 cm than at 120 cm, with the distance manipulation affecting short lines more than long lines. In both Experiments 1 and 2, long lines were bisected more accurately than short lines, especially when they were bisected in extrapersonal space.

In terms of directional bias (percentage error), the pattern of the line length by distance interaction was different across experiments. In Experiment 1, there was less directional bias when bisecting long lines than when bisecting short lines at 120 cm, with no difference in directional bias at 60 cm. In Experiment 2, long lines were always bisected with less directional bias than short lines, but, in contrast to Experiment 1, the size of this line length effect was larger at 60 cm than it was at 120 cm. Overall, there was less directional bias when long lines were bisected at 120 cm. This finding is consistent with Nicholls et al.'s (2016) finding that showed less directional bias for bisecting long lines when the bisection took place in extrapersonal space.

Gamberini et al. (2013) hypothesized that tool use would have an affect on performance such that when using a cutter to interact with objects in far space, performance would be similar to when interacting with objects in near space because the action consequence of breaking the line would extend peripersonal space. Gamberini et al. reported that tool interacted with distance whereby the type of tool used to bisect a line (pointer vs. cutter) had no impact on performance when the line was in peripersonal space (60 cm), but using a pointer resulted in significantly greater directional bias (greater error to the right) than when using a cutter when the line was in extrapersonal space (120 cm). To review, Gamberini et al. hypothesized that the action consequence of using a "cutter" is what modulates the perception of near and far space and that the visual feedback of a line breaking changes the participant's interpretation of what constitutes far space. This hypothesis suggests that if a tool enables a manipulation, just as our hands or arms can, then the tool is now referred to as being similar to the areas of our bodies that allow tactile manipulation.

In the present research the absence of a tool by distance interaction is surprising given that the methodology was almost identical to that used by Gamberini et al. (2013). The current research consisted of 84 healthy participants across two separate experiments. Outliers in the data sets were accounted for and the data was analyzed for two separate measures of accuracy (RMSE and percentage of error). Since Gamberini et al.'s experiment, VR technology has improved, which suggests that if there was a robust tool by distance interaction, then it would have been observed using the advanced technology used in the current experiments.

It is possible that the tool by distance interaction reported by Gamberini et al. (2013) was a Type I error. It's interesting to note that the tool by distance interaction was reported in both Gamberini et al. (2008) and

Gamberini et al. (2013), even though the apparatus and stimulus were different across these two experiments. In the former, participants used a tactile stick that was tracked in the virtual environment as well as a joystick to simulate the effect of a laser dot. In the latter, participants used a Wiimote controller, which was similar to the controller used here. When considering the evolution of technology and the major computing platforms that have been used by humans, there is often a change in how humans interact with the technology based on the applications for it. Sometimes technology can carry the same design metaphors and interaction methods over to newer technology but sometimes they need to be completely re-invented. For example, the desktop computer used to run on a command-line interface and then eventually moved to the graphical user interface once the desktop metaphor was introduced as an alternative design method. Since the desktop metaphor and the GUI were invented, the user experience of interacting with a computer increased tremendously. The same should be considered when designing and developing for VR. It should not be assumed that what we do with desktop computers or mobile phones is going to transfer well to VR. VR requires a more in-depth understanding of the human perceptual system and how the world is represented in VR before it can be designed to feel truly immersive. Aiming to replicate the same patterns in VR that are found in the traditional line bisection task is one example of trying to better understand how the world is represented in VR. The current research examined how people interpret extrapersonal and peripersonal space in VR when using different tools and to identify the patterns in response time, accuracy, and directional bias when performing a line bisection task. The line length by distance interaction was consistent with previous research that was performed in the real world. However, the additivity between tool type and distance reported here was inconsistent with what has previously found in VR and in the real world (see Gamberini et al., 2008; 2013). Regarding directional bias, there was no shift in direction when line bisection took place in near or far space, which has previously been reported in real world and VR studies. The inconsistencies between the current research and previous research using VR technology and the real world confirms that more research in VR is necessary before making widespread assumptions about the similarities and/or differences between VR and real world studies.

Future Directions

Given that the past and current research shows conflicting results, more studies need to be performed using the same methodology and apparatus to adjudicate between these discrepant findings. There has been conflicting evidence as to whether or not the direction in which a line is scanned prior to line bisection (i.e., left to right or right to left) affects performance and specifically influences directional bias (Varnava, McCarthy, & Beaumont, 2002). It would be interesting to see if manipulating scanning direction affects line bisection performance in VR. The current research required participants to keep their hand at a fixed location on a desk and all participants had to use their right hand regardless of hand dominance. This was to keep the methodology consistent with Gamberini et al. (2013). However, this instruction may have caused issues because it may not have felt as natural to the participant's had they been able to hold the remote at any location they found most comfortable. In the current research a large difference in the range of errors between Experiment 1 and Experiment 2 was found, which suggests that people are better at performing the line bisection task when they are using a laser "beam", rather than a laser "dot". Further examination as to why the range was so different may help with the design of VR interfaces to help make the experiences of using VR feel more natural and precise. Previous research on traditional and virtual line bisection tasks showed a left-to-right bias but the current research only found a leftward bias. In Longo and Lourenco's (2006) study a constant leftward bias was also found when participants used a series of different sticks regardless of which space interaction took place in. A leftward bias in previous studies was found when participants were interacting in peripersonal space, which moved rightward in extrapersonal space. Perhaps virtual reality induced the feeling of being in two different areas within peripersonal space, which could explain the constant leftward bias found in the current research.

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Appendix A – SONA Posting

Study Name: Using Tools in Virtual Reality

Experimenters: Melanie Buset, M.A. Student, Human-Computer Interaction
Dr. Matthew Brown, Research Scientist, Carleton University

Experimenter's Phone: 613-520-2600 ext. 2487

Experiment Location: VSIM Building, room 2201

Description: In this experiment you will be asked to wear an Oculus Rift head-mounted display on which a virtual office will be shown. The office will consist of a whiteboard on a desk. A single horizontal line will be drawn on the whiteboard. Your task will be to indicate the midpoint of this line using a remote that controls the location of a red dot (like a laser pointer). The whiteboard and desk will either appear close to you or far from you. Following completion of this line bisection task, you will be asked to provide some demographic information (e.g., handedness) and describe previous experiences (if any) in gaming and interacting with immersive virtual environments. Some follow-up questions about your gaming and/or virtual reality experiences may be asked by the experimenter. This research was 6by the Carleton University Research Ethics Board – B (Project Approval 16-00-1) on January 6, 2016.

Eligibility Requirements: Normal or corrected-to-normal visual acuity

Duration: One hour

Remuneration: 1.0 % course credit

Preparation: None

Potential Risks/Discomfort: This study comes with a slight risk of motion sickness due to the immersiveness of the virtual environment. It is therefore recommended that you do not sign up if you are prone to motion sickness.

Exclusions: Please do not sign up for this study if you are prone to motion/car sickness.

Appendix B – Informed Consent Form

Project Title: Using Tools in Virtual Reality

Faculty Sponsor: Dr. Chris Herdman, Department of Psychology, Carleton University, tel. 520-2600 x. 8122

The purpose of this informed consent form is to ensure that you understand both the purpose of the study and the nature of your participation. The informed consent must provide you with enough information so that you have the opportunity to determine whether you wish to participate in the study. This research was cleared by the Carleton University Research Ethics Board – B (Project Approval 16-00-1) on January 6, 2016. Please ask the researcher to clarify any concerns that you may have after reading this form.

Research Personnel: In addition to the Faculty Sponsor named above, the following people are involved in this research and may be contacted at any time should you require further information about this study:

Name	Title	Department	Email	Phone
Melanie Buset	M.A. Student	Human-Computer Interaction	Melanie.buset@carleton.ca	520-2600 x. 2487
Matthew Brown	Research Scientist	Psychology	matthew.brown@carleton.ca	520-2600 x. 2487

Other Contacts: If you have any ethical concerns regarding this study, then please contact:

Name	Contact Info.
Carleton University Research Office	ethics@carleton.ca
Dr. Shelly Brown, Chair, Carleton University Research Ethics Board - B	520-2600 x. 1505

Purpose: The purpose of this study to determine how people use simulated tools in an immersive virtual environment. We are interested in whether visual feedback associated with the tool's usage and the perceived distance at which a tool is being used have an effect on a participant's behavioural responses with the tools and their intended purpose.

Task: You will be asked to sit at a desk while wearing an Oculus Rift head mounted display. A virtual environment consisting of a whiteboard placed on top of a desk will be shown on the head mounted display. You will place your right hand at a predetermined location on the (real) desk while holding a remote that controls the position of a red dot (like a laser pointer) in the virtual environment. A single horizontal line will be drawn on the whiteboard. Your task is to use the remote to place the red dot at the midpoint of the line. Once you believe that the red dot is at the midpoint, you will be asked to press a button on the remote to confirm your decision. Once this midpoint selection task is completed, you will be asked to fill out a demographic questionnaire and to answer some questions about your experiences with gaming hardware/software and virtual reality.

Duration, Locale & Compensation: Testing will take place in VSIM 2201 and will take approximately one hour. You will receive 1.0% course credit for your participation.

Potential Risks/Discomfort: This study comes with a slight risk of motion sickness due to the immersiveness of the virtual environment. Consequently, some participants may feel a bit nauseous. Please alert the experimenter if you need a break or wish to stop.

Anonymity/Confidentiality: All data collected in this experiment will be kept strictly confidential through the assignment of a coded number and securely stored on a local computer for a maximum of ten years. Similarly, this Informed Consent form will be kept for a maximum of ten years before being destroyed. The information provided will be used for research purposes only. You will not be identified by name in any reports produced from this study. Further, the information is made available only to the researchers associated with this experiment

Benefits: As virtual reality becomes an increasingly viable option for training, exploration, and learning, understanding the similarities and differences between how we perceive and interact with real and virtual environments (e.g., how we interact with and use virtual tools) will inform the design and implementation of virtual environments to improve realism and immersiveness.

Right to Withdraw/Omit: You have the right to withdraw from this experiment without academic penalty. Should you choose to withdraw, you will still receive full credit and your data will be deleted. If you do not want your data to be included in this study, then you must inform the experimenter either during the experiment or immediately following it. Your participation in this experiment is completely voluntary.

I have read the above description of the study on using tools in virtual reality using a head-mounted display. By signing below, this indicates that I agree to participate in the study, and this in no way constitutes a waiver of my rights.

Name:______________________________ Date:______________________________

Signature:___________________________ Witness:___________

Appendix C – Debriefing Form

Using Tools in Virtual Reality

Thank you for your participation!

The purpose of this research is to further our understanding of immersiveness and realism in virtual environments. In so doing, we will be able to determine the strengths and limitations of the current immersive virtual environment technologies used in video games and training. Given the recent advances in virtual reality, using affordable and widely available visualization technologies (e.g., the Oculus Rift) for training purposes is imminent. It is therefore important to explore the interactions humans have with external devices in a virtual world as these external devices can act as tools and provide training in finer detail with a more realistic interpretation.

If you are interested in learning more about this study or the topic, please see the following:

Gamberini, L., Carlesso, C., Seraglia, B., & Craighero, L. (2013). A behavioural experiment in virtual reality to verify the role of action function in space coding. *Visual Cognition*, *21*(8), 961-969.

Gamberini, L., Seraglia, B., & Priftis, K. (2008). Processing of peripersonal and extrapersonal space using tools: Evidence from visual line bisection in real and virtual environments. Neuropsychlogia, 46(5), 1298–1304.

This research was cleared by the Carleton University Research Ethics Board – B (Project Approval 16-00-1) on January 6, 2016. Should you have any ethical concerns regarding this study then please contact:

Name	Contact Info.
Carleton University Research Office	ethics@carleton.ca
Dr. Shelly Brown, Chair, Carleton University Research Ethics Board - B	520-2600 x. 1505

Should you have any other concerns about this study then please contact any of the following individuals:

Name	Title	Department	Study Role	Contact Info.
Melanie Buset	M.A. Student	Human-Computer Interaction	Principal Researcher	Melanie.buset@carleton.ca
Dr. Matthew Brown	Researcher	Psychology	Co-Investigator	matthew.brown@carleton.ca
Dr. Chris Herdman	Professor	Psychology	Faculty Advisor	chris_herdman@carleton.ca