12-1-2015

What do we see: number line estimation with eye tracking

Sarah Ann Salas
University of Nevada, Las Vegas, salassa@unlv.nevada.edu

WHAT DO WE SEE: NUMBER LINE ESTIMATION WITH EYE TRACKING

By

Sarah Ann Salas

Bachelor of Science - Mathematics
Texas A&M University – Commerce
2013

A thesis submitted in partial fulfillment
of the requirements for the

Masters of Arts - Psychology

Department of Psychology
College of Liberal Arts
The Graduate College

University of Nevada, Las Vegas
December 2015

UNLV | GRADUATE COLLEGE

Thesis Approval

The Graduate College
The University of Nevada, Las Vegas

September 25, 2015

This thesis prepared by

Sarah Salas

entitled

What Do We See: Number Line Estimation with Eye Tracking

is approved in partial fulfillment of the requirements for the degree of

Master of Arts – Psychology
Department of Psychology

Mark H. Ashcraft, Ph.D.
Examination Committee Chair

David E. Copeland, Ph.D.
Examination Committee Member

Colleen Parks, Ph.D.
Examination Committee Member

Gabriele Wulf, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

Abstract

The following paper presents a study investigating adult number line estimation patterns through use of an eye tracker. Estimation patterns were examined by changing the range of the number line on which the estimations occur from the typical ranges of 0-100 and 0-1000 to a more difficult range of 0-723. There were two main conditions of the experiment; in one condition the number to estimate and the number line were presented simultaneously, and in the other condition, the number line presentation was delayed. In each of the two conditions of the experiment, eye fixations and area of interest analysis were examined to help reveal the mathematical processes behind number line estimations, specifically how these estimations are formed. It was predicted that the 723 line would have significantly more errors and take longer to complete than the 1000 line. The results provide evidence that cognitive processes are involved in estimation and that estimation is in fact a slow process.

Keywords: estimation, psychophysics, cognition, number line, online, eye tracking

This thesis is dedicated to my family. Without them, I never would have been able to achieve this accomplishment.

Table of Contents

List of Figures

INTRODUCTION

Estimation is a skill used every day for tasks such as calculating how much money to leave for a tip or the distance and time it will take to get to the airport. Practical estimation is a common task, and people have become proficient in using estimation to guide them toward reasonable generalizations that help them deal efficiently with everyday tasks. Researching how people estimate using number line estimation tasks has yielded interesting results which can be analyzed to provide a basic understanding of the processes and proficiencies behind the practical application. The proposed research pursued the cognitive thought process of adult number line estimation through the use of an eye tracker and two number line estimation tasks on number lines from 0-1000 and 0-723.

The first to investigate the cognitive mechanisms behind number line estimation, Ashcraft and Moore (2012) tested 20 college students on a position-to-number task on a number line from 0-100 and as well as a number line from 0-1000. In a position-to-number task, the participant is presented a number line that has a vertical hatch mark somewhere along the line; their task is to estimate what number the hatch mark represents. In Ashcraft and Moore's study (2012), participants estimated 26 positions across the number line, speaking their estimates into a microphone for an accurate record of latency. Reaction times were measured and responses were recorded for error analysis (based on estimated value versus actual value). Reaction times and absolute errors showed a distinct M-shaped pattern. That is, reaction times and errors were lowest at the two endpoints and there was also a significant dip in reaction times and errors at the midpoints, with the slowest reaction times and highest errors falling at the quartiles (around 25% and 75% of the line); this pattern literally creating an "M" on the graph. Faster reaction times and fewer errors were seen at the midpoint, which was unidentified on the number line, suggesting that participants implicitly calculated the midpoint of the estimation line and used the calculated midpoint as a reference for their estimations. These results are consistent with the idea that participants are calculating and using the midpoint to estimate values along the line, a novel and significant insight into the cognitive estimation process.

Prior to Ashcraft and Moore's study, Barth and Paladino (2011) argued that number line estimation is a proportional reasoning task; a task in which a proportion is being judged, and is therefore better explained by perceptual psychophysics. They extended existing explanations of perceptual proportion judgment (Spence, 1990; Hollands & Dyre, 2000) to number line estimation suggesting that in order to make number line estimations, participants must judge the magnitude of the marked segment of the line as a proportion of the total length of the line. These judgments are biased by the participants' ability to make accurate perceptual proportion judgments and the cyclic power model can be used to measure the bias (Hollands & Dyre, 2000). The cyclic power model predicts one cycle, S-shaped functions when plotting the subjective estimates made by the participant against the actual values, i.e. the participant's error. These S-shape patterns have been found when making proportion judgments for many years across many different continuums, such as when asked to estimate the relative loudness of a sound, brightness of a light, or length of a line (Stevens, 1957). Because Barth and Paladino (2011) claim number line estimation is simply a proportional judgment task, they predicted S-shaped patterns would be found when plotting the participant's estimation errors.

Barth and Paladino (2011) had 5 and 7 year old children complete number-to-position estimation tasks for 26 numbers on a 0-100 number line. In a number-to-position estimation task, a number line is presented to the participant and they are asked to estimate a given number by indicating what position on the line represents that number, thus this is the opposite of the position-to-number task described earlier from the Ashcraft and Moore (2012) study. On all tasks in the Barth and Paladino (2011) study, the number to estimate was presented visually above the center of the number line. They found that the cyclic power model fit the estimation patterns. Because their research focused on children, they postulated that with increasing experience in math, specifically familiarity with larger numbers, older children and adults become more attuned to proportions and therefore give more accurate estimations. The data fit the S-shaped pattern, but the proportion judgment model does not make any predictions as to the actual processes involved in number line estimation. They simply concluded that number line estimation is a perceptual proportion judgment task, and that S-shape, or reverse S-shape patterns would be found for all number line estimation tasks.

Little is known about the cognitive processes in number line estimation. The results of Ashcraft and Moore (2012) produced the "M" graph response, indicating mathematical processes are involved in the completion of number line estimation tasks, specifically in the calculation of the midpoint and its use as a reference point. Conversely, Barth and Paladino's (2011) proportional judgment model yielded results that fit the data nicely but gave no explanation of the processes involved. The proportion judgment model states that participants simply make perceptual proportion judgments, but it does not explain how this is accomplished. To further investigate the cognitive mechanisms behind number line estimations, Moore, Durette, Salas, Rudig, and Ashcraft (2014) manipulated the computational ease of the number line estimation task by introducing a number line from 0-723. This uncommon endpoint of 723 is not as easily manipulated by participants as the commonly expected 0-100 and 0-1000 number lines. Most adults can easily calculate what the midpoint of 100 or of 1000 is while calculating the midpoint of 723 is much more difficult. Moore et al. (2014) hypothesized that if participants' estimations are made through perceptual proportion judgment, as proposed by Barth & Paladino (2011), then the 723 number line should not yield significant differences from the 0-100 and 0-1000 lines, as it differs from the other two number lines only at the endpoint.

In their experiments, Moore et al. (2014) had participants complete position-to-number estimates on number lines from 0-100, 0-723, and 0-1000. The participants were asked to estimate the value represented by a vertical hatch mark on the number lines. The same proportions were used for each line in order to allow a comparison between the three number lines. Three blocks of estimation were counterbalanced so that the participant completed all estimations on that specific number line before moving on to the next number line.

When asked to complete position-to-number estimates, the pattern of estimations on 0-100 and 0-1000 number lines followed the typical one-cycle model predicted with proportion judgment tasks such that estimates below the midpoint were overestimated, and those above the midpoint were underestimated, an over-then-under pattern. Surprisingly, the pattern of estimations on the 0-723 number line did not follow the typical over-then-under pattern; instead, the estimates below the midpoint were overestimated and those above the midpoint were overestimated again, over-then-over. When looking at absolute error rates, Moore et al. (2014) found the same M-shaped patterns as in the Ashcraft and Moore (2012) study for all three number lines, due to fewer errors at the endpoints and midpoint, and the highest errors around the quartiles; however, it should be noted that the 0-723 line had significantly more errors overall than the other two lines. When looking at reaction times, they again found M-shaped patterns for the 0-100 and 0-1000 lines, but there was no dip at the midpoint to create the M-shape for the 0-723 line. Consistent with the error data, the reaction times for the 0-723 line were also significantly slower than the other two lines. Another experiment, using a line from 0-472, replicated the pattern of results that was observed with the 0-723 line. The significant differences in reaction times and error rates of the number lines with the two atypical endpoints, the 0-723 and 0-472 lines, compared to the typical estimation lines of 0-100 and 0-1000, suggest that there are computational processes involved with number line estimation.

To account for these results, Moore et al. (2014) hypothesized that number line estimation involves two steps. First, participants convert the location on the line indicated by the vertical hatch mark into a proportion or percentage. The second step is to map that proportion on to the scale of the estimation line. For example, when shown a number line from 0-100 where the hatch mark is at 32, the participant must first convert the location of the line indicated by the vertical hatch mark into a proportion. If the participant estimates that the proportion is approximately 35%, then the participant must then map that proportion on to the scale of the estimation line. At that point, they would calculate that 35% of 100 is 35, which would be their response. The two steps of estimation are first conversion and then mapping.

To test the two step hypothesis, it was necessary to separate the two processes. To investigate the mapping step, Moore et al. (2014) simply asked participants calculation questions such as “What is 17% of 100?” and, “What is 17% of 472?”. They asked participants to estimate these percentages for all 13 of the points estimated in their previous experiments on these two number lines. Calculating the percentages took a constant amount of time for each line, but the amount of time was significantly longer for the 0-472 line, around 3570ms, than for the 0-100 line, around 775ms (Moore et al., 2014). This indicated that the mapping step takes a consistent amount of time, and that this time is relatively short for the 0-100 and 0-1000 lines which have common endpoints, but significantly longer for a line with an unusual endpoint such as a 0-472 line.

The results obtained by Moore et al. (2014) led them to argue against the traditional single step judgment view of number line estimation that had been previously proposed by some researchers (Hollands & Dyre, 2000; Spence 1990). Instead, their two step hypothesis suggests that the conversion stage of the overall estimation process is roughly the same for all line denominations and this process relies heavily on the midpoint strategy previously inferred from the M-shaped patterns with reaction times and error rates (Ashcraft & Moore, 2012). The mapping stage, which was not included in the previous models, such as the proportion judgment model, adds a constant amount of time for each denomination. The mapping stage is very fast when estimating on the 0-100 and 0-1000 lines as these calculations are fairly simple; however, the mapping stage is significantly longer when estimation occurs on an atypical endpoint such as the 0-723 line, where the calculations require more than moving a decimal point.

Preliminary Study

In a preliminary experiment I continued to investigate the two step hypothesis proposed by Moore et al. (2014), but focused my investigations on the judgment step (published in Moore et al., 2014, experiment 3). I again manipulated the ease of the estimation task by presenting three different number lines to the participants, 0-100, 0-1000, and 0-723, as was done by Moore et al. (2014). Participants completed position-to-number estimations on these three number lines in two counterbalanced blocks. For one of the blocks of the experiment, the participants were asked to estimate the number that represented the location of a vertical hatch mark on that number line. This is the typical position-to-number estimation task. Participants saw 30 vertical hatch marks evenly spaced across the line for each denomination. The positions of the vertical hatch marks were randomized within each number line, and the order of the number lines was randomized across participants. Participants spoke their answers out loud, which triggered a voice key to measure reaction times, and the participants' responses were entered by the experimenter.

For the other block of the experiment, participants saw the same three lines, with the same 30 positions marked. The only variation was that the participants were asked to indicate the percentage of the line segmented by the vertical hatch mark, not the number. This was done to investigate the conversion step of the two step model. The conversion step, converting the location indicated by the hatch mark into a percentage, should be the same no matter the end point, because the same locations were used for all three number lines. If the data revealed no significant differences in reaction times or errors in this second block, the argument for a consistent conversion step would be supported. However, differences in reaction times and errors are anticipated when completing the traditional task of estimating the number because of the additional mapping step, mapping the percentage on to the scale of the estimation line.

Using a repeated measures analysis of variance to analyze reaction times, I found that, there was a significant three way interaction between the trial type (number or percentage), the thirty different positions on the line, and the specific number line (0-100, 0-723, or 0-1000) , $F(58, 3712) = 2.81$, $p < 0.001$. As can be seen in Figure 1a, the reaction times are much higher for the 0-723 line. When comparing Figure 1a to Figure 1b, the reaction times when estimating percentages were significantly faster than those when estimating numbers. Also the M-shaped pattern, which has been found in previous research, is apparent in both graphs. But, critically, the reaction time patterns in the percentage estimation task were not significantly different for the three number lines. Reaction times for estimating the value (Figure 1a) were considerably slower for the 0-723 lines, showing the additional time needed for mapping - the second step of the estimation process.

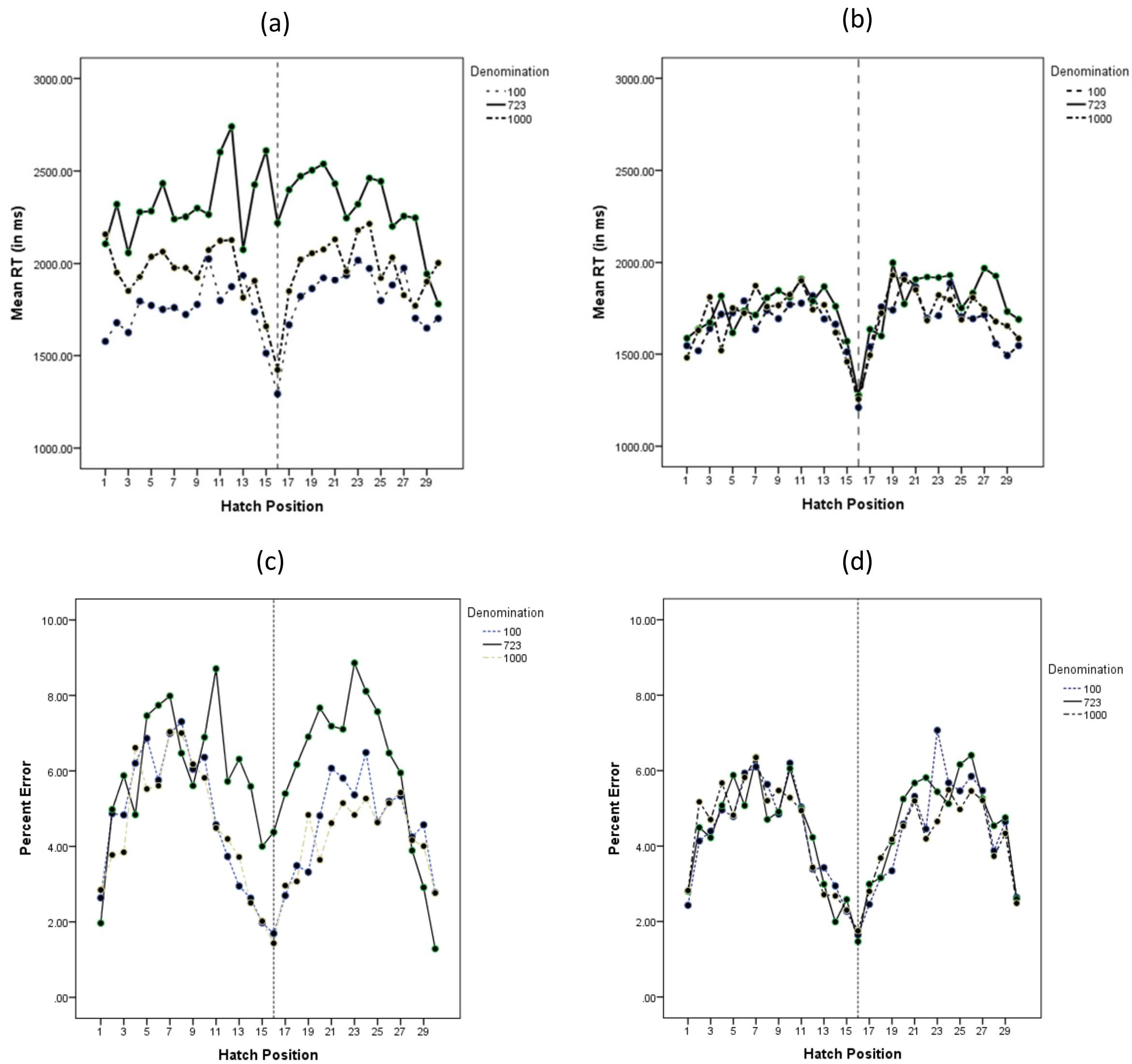

Figure 1 Preliminary study results. (a) Reaction times for number estimations across the three denominations. (b) Reaction times for percentage estimations across the three denominations. (c) Error rates for number estimations across the three denominations. (d) Error rates for percentage estimations across the three denominations.

Similarly, when looking at the absolute error rates, there was also a significant three way interaction, F (58, 3712) = 3.31, $p < 0.001$. Numbers were significantly more error prone than percentages, as can be seen when comparing Figure 1c to Figure 1d. Once again the M-shaped pattern emerges and the 0-723 line in Figure 1c is significantly higher than the rest of the lines, in this case, significantly more error prone. Analysis of directional errors showed the typical over-then-under S-shaped pattern as predicted by the proportion judgment model for the 0-100 and 0-1000 lines. An over-then-over pattern was found for the 0-723 line, which the proportion judgment model does not predict.

The behavioral results from the preliminary experiment show that the estimation task was significantly more difficult when estimating numbers on the 0-723 line, both significantly slower and significantly more error prone. This contradicts the idea that number line estimations are made simply from a proportion estimate; there are more steps involved. This further supports the idea that number line estimations are made using the two step hypothesis proposed by Moore et al. (2014) because it shows evidence that the conversion step is consistent across all three denominations.

Eye Tracking

Recent research on number line estimation has used eye tracking to investigate estimation processes. This has been done through the eye mind assumption (Just & Carpenter, 1980, Rayner, 1998) which states that participants fixate on the momentary object of cognitive processing, and they also make longer and more frequent fixations when a task is cognitively difficult. Using these ideas, Sullivan, Juhasz, Slattery, and Barth (2011) applied eye tracking to adult number line estimation to characterize the relationship between early task processing and eventual estimation. Adult participants made number-to-position estimations on a line from 0-1000. The participant heard a spoken number, and then looked at a gaze contingent box to make the estimation line appear. Once the line appeared on the screen, the participant used the cursor to indicate the location they felt best represented the number to be estimated. They did this for

20 locations across the 0-1000 number line. Participants' eye movements were tracked from the moment the line appeared until the participant clicked to indicate their estimations.

Sullivan et al. (2014) found that participants' initial eye movements were strongly related to the target number's location and indicative of the participants' final estimate. The line was dissected into twenty equal sections, or areas of interest, to determine which areas of the line received more fixations, with the midpoint regions (451-500 and 501-550) receiving the most fixations. Areas of Interest were also used to analyze the correct location, the one containing the hatch mark, and the regions immediately to the left and right of the correct location in order to determine how many fixations were made within the correct area of the line. Analysis of the estimation errors followed the predicted psychophysical models of proportion estimates, namely the one cycle, S-shaped functions (Sullivan et al., 2011). This is consistent with other research on 0-1000 number line estimation (Booth & Siegler, 2006, Booth & Sigler, 2008). Sullivan et al. (2011) concluded that participants make rapid and precise estimations, with the first fixation indicating the final estimation, due to the fact that 50% of the fixations were made in the three regions which surrounded and included the correct location. They also concluded that participants were making proportion judgments as predicted by the proportion judgment model.

Proposed study

Sullivan et al. (2014) claimed that number line estimation was rapid and precise; however, they did not present reaction times to support this claim. In the Sullivan et al. (2014) study, participants heard the number to be estimated and then had to look at box in the corner to make the number line appear. There was no recording of reaction times or fixation patterns during the time period before the number line appeared, which, therefore, missed information about the initial processes. In this thesis, I proposed an experiment similar to the one conducted by Sullivan et al. (2011). However, I included estimations on an atypical number line, a line from 0-723, as well as a replication of the 0-1000 line. In order to replicate what was done by Sullivan et al. (2011), and expand the research, this experiment had two different conditions. Condition 1, the Simultaneous Condition which most closely replicates the typical estimation task used in the literature, and Condition 2, the Delayed Condition, which replicates what was done by Sullivan et al. (2011). In the Simultaneous Condition, the number line and the number to be estimated were presented simultaneously which is the typical way the task is presented. In the Delayed Condition, the participant controlled when the number line was displayed to replicate the research done by Sullivan et al. (2011). However, for both conditions, reaction times and fixations were recorded as soon as the number to be estimated was presented. This allowed for the differences between the two conditions to be examined, as well as a measure of exactly how much time passes before the participant decided to make the number line appear. As a key indicator, an exact measure of how long the estimation process takes, overall reaction time, was established for both conditions.

Sullivan et al. (2011) found that their results fit the proportion judgment model, claiming that participants estimate by making proportion estimates. However, they only had participants estimate on a 0-1000 line, but not on a line with an unusual endpoint, such as 0-723. I included estimations on both a 0-1000 and 0-723 line to further investigate whether the proportion judgment model accurately predicts estimation behavior for all number lines. The previous research with position-to-number estimates on the 0-723 line (Moore et al., 2014) has shown that the proportion judgment model did not fit the pattern of results. I included the 0-723 line with a number-to-position task to help show through the use of an atypical endpoint that estimations are being made with the implicit calculation of the midpoint and through the two step process, not simply by proportion judgments as predicted by the proportion judgment model.

Participant's individual differences can often affect a participant's math performance. Two individual difference variables were examined in the proposed study. The first was math achievement. Math achievement has had an effect in previous research using estimation tasks (Moore et al., 2014) and so it was examined in the proposed study as well.

Math anxiety was also examined. Math anxiety is defined as "a feeling of tension, apprehension, or fear that interferes with math performance" (Ashcraft, 2002). Math anxiety has been shown to have detrimental effects on math performance in some tasks. Lyons and Beilock (2012) found that in anticipation of having to complete a math problem, the same neural pathways as pain were activated in high math anxious participants. Since math anxiety can have such detrimental effects, and participants could view number line estimation as a mathematical task, it was included as an individual difference variable even though previous work has yet to find any differences with math anxiety on number line estimation tasks.

Method

Participants

Undergraduate participants were recruited from the University of Nevada, Las Vegas psychology subject pool in exchange for partial course credit. Participants were required to have normal or corrected to normal vision. Participants were randomly assigned to conditions before they arrived for the experiment. In Condition 1, the Simultaneous Condition, there were 60 participants, 20 male and 40 female. In Condition 2, the Delayed Condition, there were 58 participants, 27 male and 31 female. The mean age overall was 21.3 years old with a standard deviation of 4.5 years. Of the overall sample 40% selected Caucasian for their racial background, 25% Hispanic, 20% Asian, 9% African-American, and 5% selected Other.

Materials

A video-based eye tracker, Eyelink iView X hi-speed 1250 by SensoMotoric, was used to track participants' eye movements and fixations. The iView X has a chin rest to help insure participants stay in the same location throughout the experiment. A computer monitor displayed the stimuli to the participant. The stimuli consisted of a solid horizontal line with the left end point marked with a 0 and the right end point varying between the two denominations, 1000 and 723, for each block. The numbers to be estimated were presented aurally through computer speakers to the participants. A researcher's voice was recorded speaking each number, so the numbers would be the same for all participants.

Additionally, the Wide Range Achievement Test (WRAT) was used to assess math achievement, and the Abbreviated Math Anxiety Scale (AMAS) questionnaire was used to assess math anxiety (Hopko, Mahadevan, Bare, & Hunt, 2003). The WRAT consists of 40 math problems of increasing difficulty which the participants had fifteen minutes to complete.

Participants' scores are the total number of problems answered correctly in the twenty minute period. A median split was used to categorize participants into high and low achievement groups. The AMAS questionnaire is a short questionnaire which addresses the level of anxiety aroused by different activities one might encounter which could induce math anxiety. Participants' scores indicate their level of math anxiety, and participants were again split into high and low math anxiety groups by a median split.

Procedure

For both conditions, participants were first provided an informed consent, and then completed a demographic form and the AMAS. Once these measures were completed, a nine-point calibration on the eye tracker was obtained and then the participants completed two blocks of estimation, one on the 0-1000 line and one on the 0-723 line. Participants were given a short break of about a minute after each block of estimation. After each break, participants performed the calibration sequence again in order to accurately track their eye movements for the rest of the experiment.

In both conditions participants were asked to perform a number-to-position estimation task. In each trial, the number to estimate was presented aurally through the computer speakers. The participants were asked to fixate their gaze at the location on the line which they felt best represented that number. The participants then clicked the mouse to indicate that they felt they were looking at the correct position. The click of the mouse also initiated the next trial. To avoid any extraneous eye movements the cursor remained hidden throughout the experiment. For both conditions there were two blocks of estimation, one for each number line. At the beginning of each block, the participants first completed two practice trials to make sure they understood the procedure and that the eye-tracker was working properly. If there were any issues, those were resolved before the participant moved on to the actual trials. The numbers to estimate represented the same 13 locations (8%, 18%, 22%, 28%, 32%, 38%, 48%, 58%, 68%, 72%, 78%, 82%, and 88%) for both lines. These locations corresponded to the numbers 80, 181, 220, 279, 320, 380, 479, 578, 680, 721, 780, 817, and 880 for the 0-1000 line. For the 0-723 line, the numbers equaled 58, 131, 159, 202, 231, 275, 346, 418, 492, 521, 564, 591, and 636. These locations were evenly distributed across the number line, and the participants were asked to estimate each location twice for a total of 26 estimates per line. The order of the lines was counterbalanced across participants to eliminate order effects, and no significant order effects for either condition were found.

For Condition 1, the Simultaneous Condition, the line always appeared simultaneously with the aurally presented number. Condition 2, the Delayed Condition, differed only in the presentation of the number line. The participants still heard the number to be estimated through the computer speakers at the beginning of the trial, however, the participant controlled when the number line appeared. Participants were instructed that when they were "ready to estimate", they should click the mouse to make the number line appear. Processing times were recorded from the moment the participants heard the number to be estimated until they clicked the mouse to indicate they were fixating in the correct location for both conditions.

Results

Reaction Times

Participants' estimation patterns on the two number lines, 0-1000 and 0-723, were analyzed in order to examine the cognitive processes involved with number line estimation and to show that number line estimation is actually a multi-step procedure involving cognitive processes. Reaction times were analyzed separately by condition using analysis of variance (ANOVA). In the Simultaneous Condition, when the number to estimate and the number line appeared simultaneously, a 2 (line) x 13 (positions) ANOVA revealed a significant main effect of position F (12, 624) =7.300 $p<.05$, η_p^2 =.123, see Figure 2. The results showed that position 1, the position nearest to the origin, had the fastest overall reaction time. The two number lines did not differ significantly from each other F (12, 624) =1.579 p=.093, η_p^2 =.029. The predicted M-shape patterns were not found (Ashcraft & Moore, 2012, Moore et al. 2015) as there was no significant dip at the endpoint on the right side of the graph, or at the midpoint, see Figure 2. The M-shape patterns did exist however for the error patterns (see Figure 11) suggesting that the lack of M-shape pattern for reaction times is simply a result of a speed accuracy trade off; this is explained in more detail in the Accuracy section. The overall average reaction time for this Simultaneous Condition when estimating on 0-1000 line was 4556ms and 0-723 line was 4501ms; there were no significant differences between these two reaction times.

For the Delayed Condition, the number to estimate was presented aurally and the participant was instructed to click the mouse when they were ready to estimate, making the number line appear. This was a replication of the research done by Sullivan et al. (2011). In order to examine the estimating processes involved during this experiment reaction times were

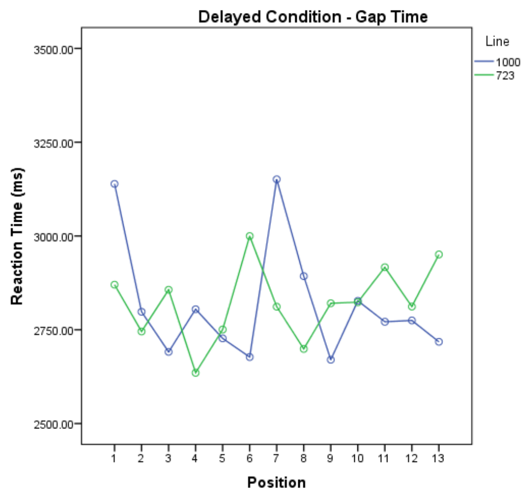

Figure 2 Overall reaction times for Simultaneous Condition. Vertical axis: reaction time in milliseconds, horizontal axis: position, and separate lines for the two number lines. No significant differences between the two number lines.

split into three separate analyses. The first was gap time, which is the time before the number line appeared. The second was duration time, which is the period of time after the participant makes the number line appear until the end of the trial. Finally there was overall reaction time, which was the sum of gap time and duration.

When analyzing gap time there was a significant main effect of position, F (12,600) = 10.377 $p<.05$, η_p^2 =.172 such that when estimating close to the origin and the midpoint, participants took significantly longer before clicking to make the number line appear than they did for the other positions (see positions 1 and 7, Figure 3). Though there was no significant main effect of line, there was a significant interaction between line and position F (12,600) = 17.549 $p<.05$, η_p^2 =.26 such that participants took longer before making the line appear when estimating close to the origin or the midpoint, and that extra time was significantly less for the 0-1000 line than for the 0-723 line. This pattern created a W or upside down M-pattern on the

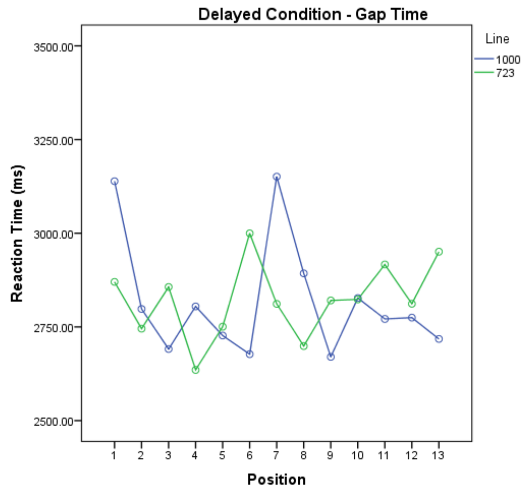

Figure 3 Reaction times for Delayed Condition, gap time. Vertical axis: reaction time in milliseconds, horizontal axis: position, and separate lines for the two number lines. Significant interaction between line and position.

graph, see Figure 3, suggesting that participants were already estimating where the origin and midpoint were located on the number line before the number line was displayed on the screen. Because they had already started estimating at these positions, participants took longer to make the number line appear when the number to estimate was near the origin or the midpoint. When given a number to estimate that wasn't near the origin or midpoint, participants simply waited until they made the line appear to start the estimation processes. This is further evidenced in the results from the duration time analysis.

When analyzing the duration time, the time after the number line appeared, there was a significant main effect of position $F\ (12{,}600) = 5.439$ $p<.05$, $\eta_p^2 = .098$ and a significant interaction between number line and position $F\ (12{,}600) = 3.419$ $p<.05$, $\eta_p^2 = .064$. Participants were much faster at estimating at the midpoint and the origin than at the other points on the

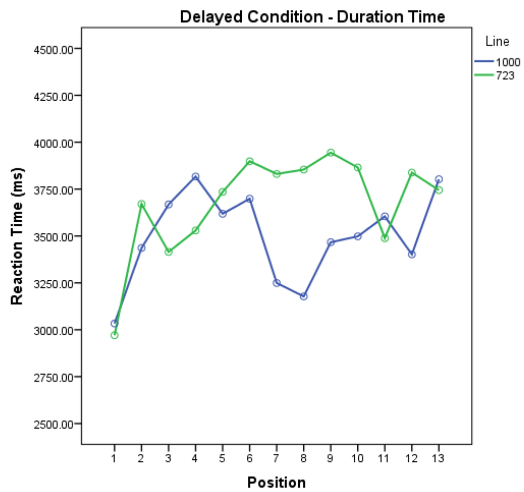

Figure 4 Reaction times for Delayed Condition, duration time. Vertical axis: reaction time in milliseconds, horizontal axis: position, and separate lines for the two number lines. Significant interaction between line and position, and a M-shape pattern only for 0-1000 indicating use of the midpoint as a reference for estimations.

number line for the 0-1000 line. This created the typical M-shape pattern, as can be seen in Figure 4.

Instead of an M-shaped pattern, the participants' estimations were only faster at the origin for the 0-723 line creating an upside down U-shaped pattern. The M-shape pattern found on the 0-1000 line supports the results of the gap time analysis. Because participants had already begun estimating at the origin and midpoint before revealing the line, once the line was revealed, they were faster to complete their estimations at these positions. Even though the same pattern of estimating before the number line appeared was found on the 0-723 line in the gap time analysis, an M-shaped pattern was not found for the 0-723 line in the duration analysis or in the error analysis (see Figure 11). This indicates that even though the participants had begun the estimation process, estimating near the midpoint on the 0-723 line is still a very difficult task, as it was slower and more error prone than estimating the midpoint on the 0-1000 line. Reaction times were explored further by analyzing overall reaction time.

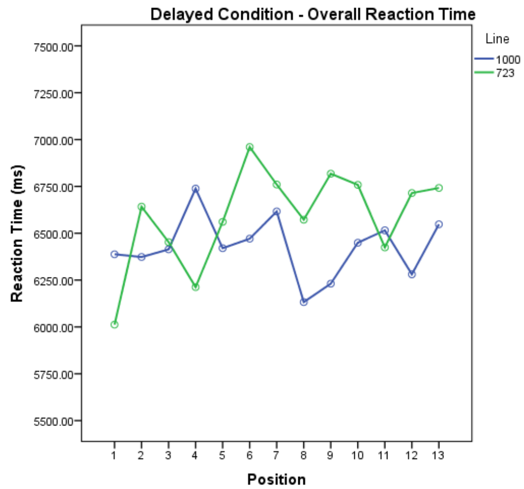

Figure 5 Overall reaction times for Delayed Condition. Vertical axis: reaction time in milliseconds, horizontal axis: position, and separate lines for the two number lines. Significant interaction between line and position, but no distinct estimation patterns.

When analyzing overall reaction time, for the Delayed Condition, there was still a main effect of position F (12,600) =1.937 p<.05, η_p^2 =.037 and a significant interaction between line and position F (12,600) =3.128 p<.05, η^2=.059. However, there were no clear patterns found on the graph, see Figure 5. It is not surprising that no distinct patterns were found, as this analysis combined the gap time and duration time which had roughly opposite patterns; gap time had a W-shape for both lines, and duration had a M-shape for the 0-1000 line and a upside down U-shape for the 0-723 line. The average overall reaction time for Delayed Condition for the 0-1000 line was 6258ms and for the 0-723 line was 6602ms. As was expected, these times are slower than the times for the Simultaneous Condition due to experimental design. During the Delayed Condition, the first 2000ms consisted of the aural presentation of the number before the number line appeared whereas in the Simultaneous Condition, the number to estimate and the number line were presented at the same time. If these extra 2000ms for the Delayed Condition are taken into account, the average overall reaction time for the 0-1000 line was 4258ms and for the 0-723 line was 4602ms which did not differ significantly from the overall average reaction time for the Simultaneous Condition which was 4556ms on the 0-1000 line and 4501ms on the 0-723 line.

Areas of Interest

To analyze the eye tracking data, the line was first split into areas of interest in order to examine which areas of the line received the most fixations and answer the question of where participants were looking on the number line. To replicate the analysis done by Sullivan et al, (2011), the line was divided into twenty areas of interest which encompassed the entire number line. Each area of interest was 37 pixels wide and 400 pixels tall which accounted for 5% of the number line. The eye tracking data was examined by two different measures; total fixation duration, the average amount of time spent looking in that particular area of interest across trials, and, average number of fixations within each area of interest across trials. Each of these measures, fixation duration and number of fixations, were analyzed in a 2 (condition) x 20 (areas of interest) mixed ANOVA with condition (Simultaneous or Delayed) as the between subjects variable. Fixation duration was examined first. When looking at fixation duration, there was a significant main effect of position $F\ (12, 624) = 7.300$ $p<.05$, $\eta_p^2 = 1.23$ and a significant interaction between condition and area of interest $F\ (19, 2185) = 5.886$, $p<.05$, $\eta_p^2 = .048$. This main effect, which can be seen in Figure 6, is such that when estimating on the 0-1000 line, participants spent the most time fixating at the areas located near the midpoint. However when estimating on the 0-723 line, participants spent the most time looking at the first half of the number line, peaking around 25% of the number line. Though the first half of the number line was oversampled (one more position to estimate below the midpoint than above), the pattern of estimations on 0-723 suggests that participants were spending much more time on the first half of the number line than on the second half, even when accounting for the oversampling. This

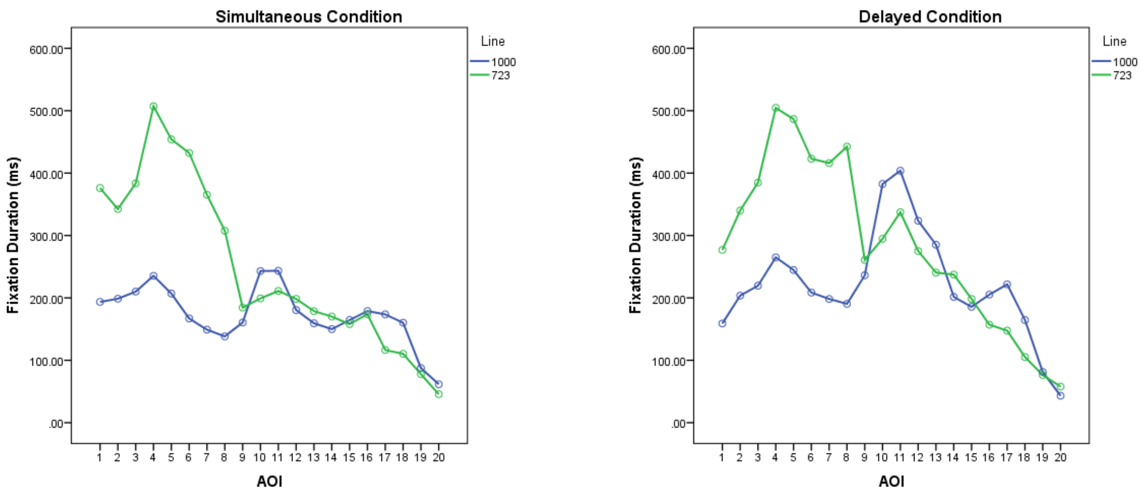

Figure 6 Average fixation duration across trials when line split into 20 AOIs. Separate graphs for Simultaneous Condition and Delayed Condition. Vertical: Number of Fixations, horizontal: AOIs. Figure 6 Graph of average fixation duration across trials when line split into 20 AOIs: Separate graphs for Simultaneous Condition and Delayed Condition. Vertical: Number of Fixations, horizontal: AOIs.

result was surprising, but did replicate what was found when participants were asked to do position-to-number estimations on 0-723 by Moore et al. (2015). It could simply indicate that participants are less efficient at estimating on the 0-723 line and spend more time trying to orient themselves on the first half of the number. Further research would be need to explain what is indicated by this unique pattern on the 0-723 line.

The significant interaction between condition and area of interest F (19, 2185) = 5.886, $p<.05$, η_p^2 =.048 can also be seen in Figure 6. In the Delayed Condition participants spent longer looking at the line overall than in the Simultaneous Condition. This is not surprising because again there was the added 2000ms when the number was being presented without the line present for the Delayed Condition. When analyzing the number of fixation made in each region similar

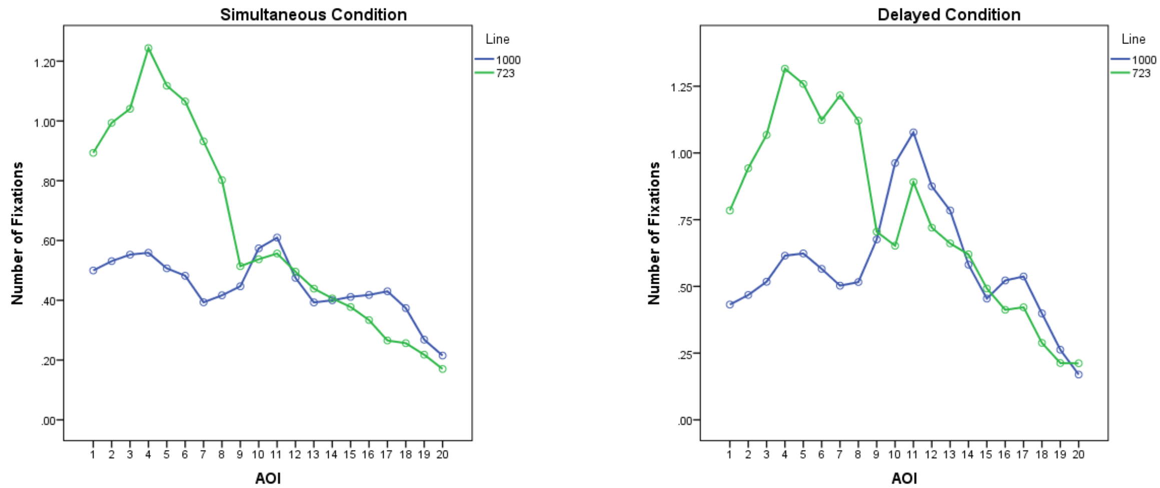

Figure 7 Average number of fixations across trials when line split into 20 AOIs. Separate graphs for Simultaneous Condition and Delayed Condition. Vertical: Number of Fixations, horizontal: AOIs.

significant effects were found. There was a significant interaction of condition by area of interest F (19, 2204) =7.523 $p<.05$, η_p^2 =.061 such that, as can be seen in Figure 7, in the Delayed Condition there was a greater number of fixations made around the midpoint for both number lines than was made in the Simultaneous condition.

In order to further examine participants' fixations, the line was split into three new areas of interest and examined in order to determine if these three areas, 25%, 50%, and 75% of the number line, were being used as references when estimating. These three areas of interest contained the 40 pixels surrounding the 25%, 50%, and 75% points on the number line. Trials which required participants to estimate positions that were located within the fifteen percent of the line which made up each of these regions were removed from the analyses (5/13 trials). For example, the trials where participants were asked to estimate 479 on the 0-1000 line were removed from the analysis, as this fell within the fifteen percent of the line contained in the 50% area of interest. These trials were excluded in order to remove any confounding effects of the

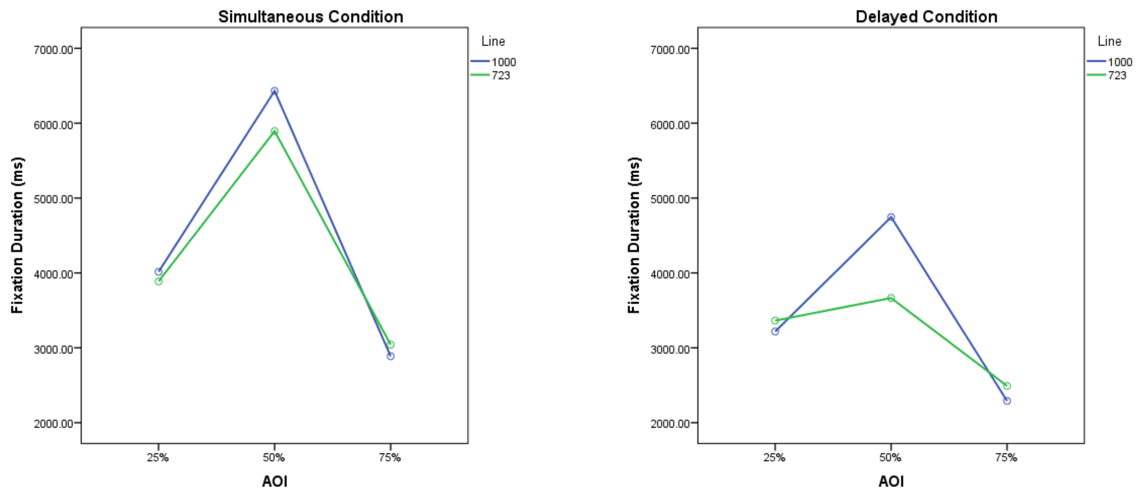

Figure 8 Fixation durations when the line is split into 3 AOIs. Separate graph for each condition, Simultaneous or Delayed. Vertical: Number of Fixations, horizontal: 1=25%, 2=50%, and 3=75%. Line 1=1000, 2=723

correct location being located within the area of interest being examined as a reference. Total fixation duration across the remaining trials, and total number of fixations across the remaining trials were analyzed in 2 (condition) x 3 (area of interest) mixed ANOVA with condition (Simultaneous or Delayed) as the between subjects variable. Analysis of total fixation duration revealed a significant main effect of area of interest F (2, 244) =27.929 p<.05, $\eta_p^2 = .194$ which can be seen in Figure 8. Participants had longer total fixation durations in the 50% area of interest as compared to either the 25% or the 75% area of interest. The 25% and 75% areas also differed significantly from each other, with the 25% area of interest being significantly longer than the 75% area of interest. As was found with pervious reaction time data, these patterns indicate that the midpoint, 50% of the line, is used at a reference when estimating, even when the position to estimate is not close to the midpoint (Ashcraft & Moore, 2012, & Moore et al., 2015). This differs from the results found when the line was split into 20 AOIs because the results from

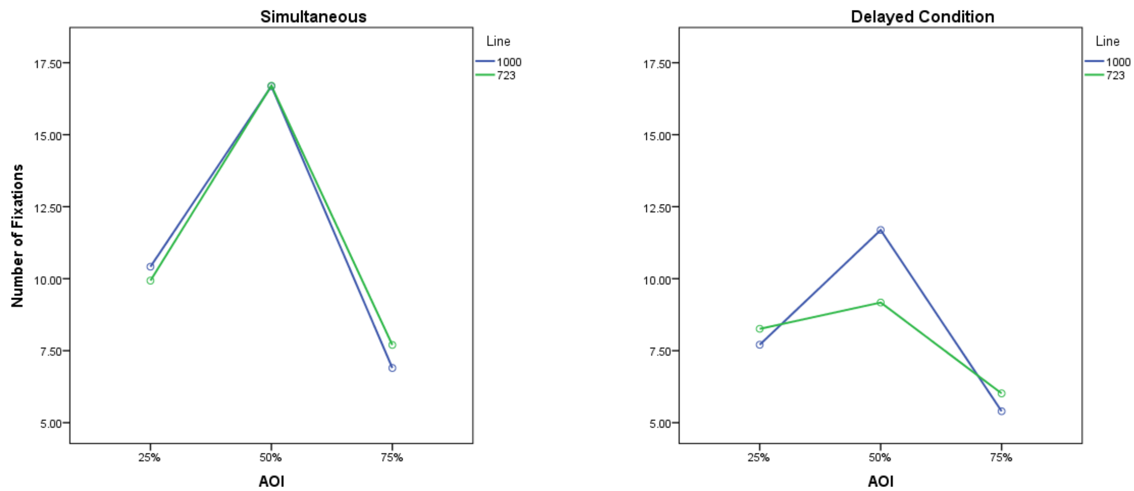

Figure 9 Number of fixations when the line is split into 3 AOIs. Separate graph for each condition, Simultaneous or Delayed. Vertical: Number of Fixations, horizontal: 1=25%, 2=50%, and 3=75%. Line 1=1000, 2=723.

this analysis are the total fixations across the trials not the average across trials. When trials which were located within the area of interest were removed from the analysis to examine analyzing total number of fixations across the remaining trials, the same significant main effect of area of interest was found, $F\ (2,244) = 37.089\ p<.05$, $\eta_p^2 = .244$ (see Figure 9), again indicating that the midpoint is the most commonly fixated point on both number lines, with both variables of interest.

Accuracy

In order to examine the accuracy of the participants' estimations, the relationship between the first fixation, the target number, and the final fixation was examined. The first fixation was in the correct region (the correct AOI, one AOI to the left, and one AOI to the right) only 12% of the time for both the Simultaneous and the Delayed Conditions, and only predicted the final fixation 13% of the time. This was much lower than what was found by Sullivan et al. (2011). In their research, Sullivan et al (2011) found that the first fixation was accurate 50% of the time. Sullivan et al. (2011) only tested participants on a line from 0-1000, and the number line presentation was delayed. I reexamined the accuracy data, only estimates on 0-1000, from the Delayed Condition, which replicated the research done by Sullivan et al. (2011). Participants' first fixation was again only accurate 12% of the time. Sullivan et al. (2011) did not record fixations until after the participants made the number line appear. In my study, I recorded fixations as soon as the participants started the trial. This delay before recording participants data most likely led to the more accurate fixations found by Sullivan et al (2011). As was indicated by the eye tracking data as well as the reaction time data, participants had already begun to estimate and had already fixated where the number line would be before the number line appeared on the screen. The participants' first fixation was not very accurate, and therefore could not accurately predict the location of the final fixation. To examine how accurate participants' fixations were, both directional and absolute error patterns were analyzed next.

First, directional error was analyzed to examine the validity of the proportion judgment model. Previous work with position-to-number tasks found that the S-shape pattern predicted by the proportion judgment model did not occur when estimating on the 0-723 line (Moore, et al. 2015). In order to examine whether the proportion judgment model fit the data with the number-to-position task used here, participants' directional error was calculated by computing the distance between the actual location of the number and the location of the final fixation of the participant. The final fixation indicated the location the participant felt was the correct location for that number. Analysis of directional error showed a significant main effect of position $F(12, 1392) = 49.185$, $p<.05$ $\eta_p^2 = .298$, a main effect of line $F(1,116) = 15.244$ $p<.05$, $\eta_p^2 = .116$ and a significant interaction between position and line $F(12, 1392) = 19.163$ $p<.05$, $\eta_p^2 = .142$. There were no significant differences between the two conditions. As can be seen in Figure 10, for

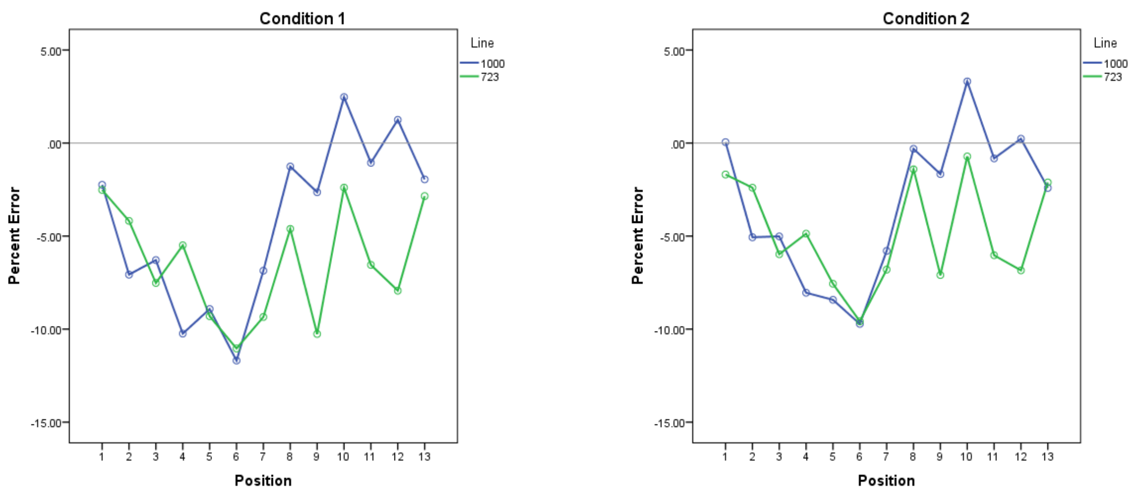

Figure 10 Directional errors. Separate graphs by condition. Vertical: Percent Error. Horizontal: Position, Blue=1000 and Green = 723.

both the Simultaneous Condition and the Delayed Condition, an under-then-over pattern of estimation was found on the 0-1000 line but an under-then-under pattern of estimation was found on the 0-723 line. The proportion judgment model states that when given a number-to-position estimation task, participants will underestimate the values located below the midpoint of the line and then overestimate the values above the midpoint. For bother number lines, participants underestimated values below the midpoint. However they continued to underestimate the values above the midpoint on the 0-723 line. This under-then-under pattern found on the 0-723 line is not what is predicted by the psychophysical model (Barth & Paladino, 2011), indicating that this model is not valid when an atypical endpoint is used on a number-to-position task. Moore et al (2015) found that the proportion judgment model did not hold up for a position-to-number task when using an atypical endpoint such as a line from 0-723. Taken together with the results of Moore et al. (2015), the lack of the predicted S-shape patterns indicates that estimation is not

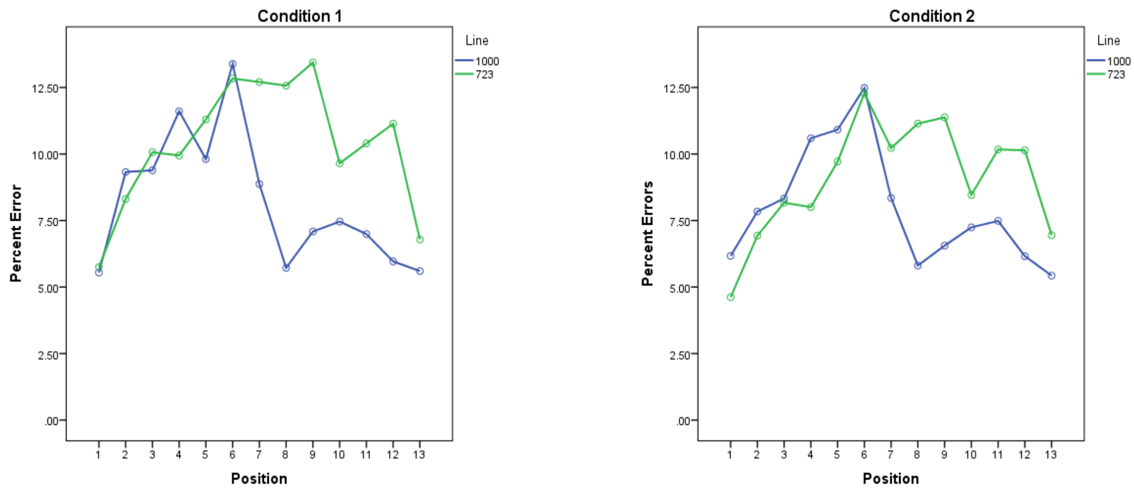

Figure 11 Absolute errors. Separate graphs by condition. Vertical: Percent Error. Horizontal: Position, Blue=1000 and Green = 723.

simply a perceptual judgment task as was suggested by the proportion judgment model, but that estimation is in fact a complex task consisting of cognitive processes.

Finally, to examine error patterns further, absolute error was calculated by taking the absolute value of the distance measurement used in the directional error analysis above. This was done in order to calculate how much the participant's estimate differed from the exact location. Absolute error was analyzed in a 2(Condition) x 2(line) x13(position) ANOVA. There was a significant main effect of line $F\ (1,116) = 20.652$ $p<.05$, $\eta_p^2 = .151$, position $F\ (12, 1392) = 35.090$, $p<.05$, $\eta_p^2 = .232$, and a significant interaction between line and position $F\ (12, 1392) = 24.197$, $p<.05$, $\eta_p^2 = .153$; however, there were no significant differences between the two conditions. This significant interaction can be seen by the M-shaped pattern, with a significant dip at the midpoint and endpoints, which was found on the 0-1000 line but not on the 0-723 line (see Figure 11). This M-shaped pattern was found on the 0-1000 line for both conditions, and indicates that participants were more accurate when estimating near the midpoint region. An upside down U- shaped pattern was found on the 0-723 line, indicating that participants were most accurate at the endpoints, and did not have the dip in error at the midpoint that was found on the 0-1000 line. The lack of this pattern on the 0-723 line is not surprising as it replicates the results found by Moore et al. (2015). Though the participants started estimating before the number line even appeared when close to the midpoint for both the number lines (See Figure 3), the participants were slower and more error prone at the midpoint on the 0-723 line.

Individual Differences

Both Math Anxiety (AMAS) and Math Achievement (WRAT) measures were analyzed. No significant differences were found due to either of the individual difference measures on any of the statistical analysis. Some effects of Math Achievement have been found before (Moore et al., 2015), however this replicated the results of the preliminary study in which no significant differences were found due to individual differences.

General Discussion

Although the reaction time analysis for Condition 1, Simultaneous Condition, did not reveal the expected M-shaped patterns, the absolute error analysis did reveal the predicted M-shaped pattern. Previous research has found the M-shaped patterns for both reaction time and accuracy, indicating heavy reliance on the midpoint and the endpoints as references, when examining estimations on a line from 0-1000 (Ashcraft & Moore 2012, More et al. 2015). However, this M-shaped pattern was still found in the absolute error analysis on 0-1000 indicating that participants were taking longer in order to be more accurate when the position to estimate was close to the midpoint, a speed accuracy trade off. Even though it was not revealed in the reaction time analysis, the absolute error analysis revealed the expected typical M-shape pattern indicating heavy reliance on the midpoint as a reference point when estimating.

For Condition 2, Delayed Condition, an upside down M-shaped pattern, or W-shaped pattern, was found when analyzing the time before the number line appeared, gap time, and a M-shaped pattern when looking at the time after the number line appeared, duration time. The upside down M-shape for gap time indicates that participants were taking extra time, as they first began to estimate, when the number to estimate was close to the midpoint or the origin before the number line even appeared on the screen for both number lines. Then, when the number line was revealed, they were faster when the number to estimate was close to the origin and the midpoint then at any other location on the line, because they had already started the estimation process creating the M-shape pattern for duration times for the 0-1000 number line. For the 0-723 number line, an upside down U-shaped pattern was found after the number line appeared. This pattern indicates that even though they had already begun to estimate when the number to estimate was close to the origin or the midpoint, they were still slow to estimate when the number to estimate was near the midpoint. The upside down M-shaped, or W-shaped pattern is important because Sullivan et al. (2011) did not track reaction times or eye movements during the gap time, and therefore missed some of the estimation processes which were occurring during the gap.

The analysis of the eye tracking data when the line was split into twenty areas of interest indicates that participants look more frequently and for a longer period at the midpoint on the 0-1000 line, which was again expected from previous research with reaction times (Ashcraft & Moore, 2012). For the 0-723 line, the participants looked most at the 25% quartile region indicating that this area is a more difficult region of the line for estimation, and that the midpoint was not used as a reference like it is for the 0-1000 line. However there was a decline in the number of fixations made and the overall fixation duration at the 75% quartile, this could be due to the oversampling of the lower half of the number line. There was one point closer to the origin (8% of the line) than there was to the endpoint (nearest point 88% of the line). This likely contributed to the fact that there were more fixations and participants spent more time at the 25% quartile on the 0-723 line. However, this does not account for such a big disparity between the 25% quartile and the 75% quartile. This result could simply indicate that participants are less efficient at estimating on the 0-723 line and spend more time trying to orient themselves on the first half of the number, however further research would be required to explain what is indicated by this unique pattern on the 0-723 line.

The participants' eye tracking data was examined further when the number line was split into only three areas of interest, one at 25% of the line, one at 50% of the line, and one at 75% of the line. Trials which required participants to estimate positions that were located within the fifteen percent of the line which made up each of these regions were removed from the analyses.

This was done to examine the overall looking patterns at the three areas of interest, when estimating a number which was located in a different position on the line. As expected, the midpoint was looked at the most frequently for both number lines, which again indicates that the midpoint is used as a reference for estimating. The 25% quartile was looked at significantly more than the 75% quartile, which is most likely due to oversampling of numbers to estimate on the lower half of the number line as was explained above.

The absolute error analysis again showed that participants use the midpoint as a reference for the 0-1000 line but not for the 0-723 line. The positions close to the midpoint had significantly fewer errors on the 0-1000 line but did not differ from the surrounding regions on the 0-723 line, as was discussed above in the reaction time analysis. This M-shaped pattern was only found for the 0-1000 line in both the Simultaneous Condition and the Delayed Condition. All of this research shows evidence that the midpoint is used a reference for estimations on both number lines. Yet, the use of the midpoint as a reference does not increase accuracy as much on the 0-723 line as on the 0-1000 line. This can be seen, refer to Figure 11, by the lack of a dip at the midpoint on the 0-723 line but the appearance of this dip on the 0-1000 line. Combined with the reaction time results, these results indicate that participants were slower and more error prone at the midpoint on the 0-723 line then on the 0-1000 line.

In order to test if the proportional judgment model fit the data, directional error was analyzed. The analysis found the predicted under-then-over pattern for the 0-1000 line in both conditions, replicating what was found previously by Sullivan et al. (2011). For the 0-1000 line, participants underestimated on the first half of the number line, and then overestimated on the second half of the number line, the typical S-shaped pattern. Conversely, for the 0-723 line, an under-then-under pattern was found indicating that participants underestimated for all positions both above and below the midpoint on the 0-723 line. The directional error analysis on the 0-723 line did not fit the predicted S-shape. An under-then-under pattern goes against the proportion judgment model (Barth & Paladino, 2011), and shows that the proportion judgment model does not take in to account all of the estimation processes. This replicated the research done by Moore et al. (2015) who found that when completing position-to-number estimation task on 0-723 the proportion judgment model did not accurately fit the data. Taken together, these results show that the proportion judgment model, stating that estimation is simply a perceptual judgment task, does not hold up with an atypical endpoint for either estimation task. Number line estimation is in fact a complex procedure consisting of cognitive processes.

Contrary to what was claimed by Sullivan et al., (2011), estimation, is in fact fairly slow, averaging 4407ms on the 0-1000 line and 4552ms on the 0-723 line across both conditions. This is significantly slower than the estimation times for the preliminary experiment, which used position-to-number tasks and did not involve eye tracking. This is also slower than the estimation times found in Moore et al. (2015), where position-to-number estimation on the 0-723 line took above 3000ms, and estimations on the 0-1000 line were even faster. Since this is a number-to-position task, these differences in overall reaction times are most likely a result of the task used. The number-to-position task might inherently take longer, but as a direct comparison of tasks was not run in this experiment, more research would be needed to investigate these differences.

Sullivan et al. (2011) also claimed that estimation was precise based on of the accuracy of the first fixation. They found that participant's first fixation was in the correct region of the line 50% of the time. Accuracy analysis revealed that participants' were only accurate 12% of the time, even when only analyzing estimations from the 0-1000 line only from the Delayed

Condition, which replicated the task done by Sullivan et al. (2011). This disparity in accuracy is most likely due to the fact that Sullivan et al. (2011) did not record fixations until after the participant made the number line appear. From the reaction time analysis it is apparent that some of the estimation process begins before the number line appears. Having this gap before the first recorded fixation led to the higher level of accuracy found in Sullivan et al. (2011). When analyzing the first fixation made during the gap, participants' accuracy, 12%, was very poor. Estimation is not simple a perceptual process which is rapid and precise, it is a complex process involving mathematical steps to be able to estimate accurately.

Further work with number line estimation and eye tracking should be completed in order to investigate the processes of number line estimation, and to continue to explore the more general processes of how humans estimate in a variety of situations. Are reference points used to increase accuracy in other estimation situations? What if the situation is unusual, are the same processes used? Exploring these questions will help reveal the processes of estimation.

References

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science*, *11*(5), 181-185. doi:10.1111/1467-8721.00196

Ashcraft, M., & Moore, A. M., (2012). Cognitive process of numerical estimation in children. *Journal of Experimental Child Psychology, 111*(2), 246-267. doi: 10.1016/j.jecp.2011.08.005

Barth, H., & Paladino, A.M. (2011). The development of numerical estimation: Evidence against a representational shift. Developmental Science 14, 125-135.

Booth, J.L., & Siegler, R.S. (2006). Developmental and individual differences in numerical estimation. Developmental Psychology, 41, 189-201.

Hollands, J.G., & Dyre, B. (2000). Bias in proportion judgments: The cyclical power model. *Psychological Review. 107*, 500-524. doi:10.1037/0033-295X.107.3.500

Hollands, J. G., Tanaka, T., & Dyre, B. P. (2002). Understanding bias in proportion production. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(3), 563-574. doi:10.1037/0096-1523.28.3.563

Hopko, D. R., Mahadevan, R., Bare, R. L., & Hunt, M. K. (2003). The abbreviated math anxiety scale (AMAS) construction, validity, and reliability. *Assessment*, *10*(2), 178-182. doi:10.1177/1073191103010002008

Just, M. Am., & Carpenter, P. A. (1980).A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*, 329-354.

Lyons, I. M., & Beilock, S. L. (2012). Mathematics anxiety: Separating the math from the anxiety. *Cerebral Cortex*, *22*(9), 2102-2110. doi:10.1093/cercor/bhr289

Moore, A. M., Durette, R. T., Salas, S. A., Rudig, N. O., & Ashcraft, M. H. (2014). Magnitude estimation in adults: Cognition versus psychophysics. Unpublished manuscript.

Rayner, K. (1988). Eye movements in reading and information processing; 20 years of research. *Psychological Bulletin, 124*, 372-422.

Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 683-692. doi:10.1037/0096-1523.16.4.683

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review, 64,* 153-181.

Sullivan, J., Juhasz, B., Slattery, T., & Barth, H. (2011). Adults' number-line estimation strategies: Evidence from eye movements. *Psychonomic Bulletin & Review, 18,* 557-563. doi: 10.3758/s13423-011-0081-1.

Curriculum Vitae

Sarah Salas

164 Royal Lane | 903.274.9114

Commerce TX 75428 | sa.salas0514@gmail.com

Educational Background

University of Nevada, Las Vegas - 2015

Masters of Arts-Psychology

Master's Thesis: "What do we see: Number line estimation with eye tracking"

Texas A&M University – Commerce - 2013

B.S. in Mathematics

Honors Thesis: "Measuring the working memory requirements of mental addition"

Honors & Awards

Scholarships

Dean's List 2011-2013

Rachel Lafferty Math Scholarship 2011-2013

Bale & Bedgood Scholarship 2011-2013

Manuscripts Under Review

Faulkenberry, T., Montgomery, S. A., & Tennes, S. A. (2015) "The Dynamics of Representing Fractions: Components are Processed First". Psychological Bulletin and Review. 38

Manuscripts in Preparation

Moore, A. M., Durrette, R. T., Salas, S. A., Rudig, N. O., & Ashcraft, M. A. (2015) “Magnitude estimation in adults: Cognition versus psychophysics”.

Faulkenberry, T., & Salas, S. A. (2015) “Working Memory and Carrying”.

Conference Presentations

“The Primacy of Components in Numerical Fractions”

Poster Presentation at the Annual Psychonomics Meeting – 2012

“Two Mathematical Models for Measuring Working Memory Capacity”

Presentation at the Mathematical Association of America – Texas Section – 2012

Teaching Experience

Private Tutor – 2011-2014

Grades 8-12. Pre-Algebra through Algebra 2. Saxon Mathematics

Academic Success Center Tutor – 2012

Conducted Review Sessions, Grading, Tutoring, Organization.

Teaching Assistant to Professor Aslan in “Business Mathematics” and “College Algebra” – 2013

Graded all homework assignments and collaborated on test grading. Administered Exams.

Research Experience

University of Nevada, Las Vegas 39

Graduate Assistant at the Baby Rebel Lab - 2013-2014

Eye tracker, BioPak, and Eprime. Photoshop, Excel Macros, Community Recruitment.

Texas A&M University – Commerce

Research Assistant 2011-2013

Grant Research, Running participants, Managing time slots, Preliminary data analysis.

Professional References

Dr. Mark Ashcraft

Department of Psychology

University of Nevada, Las Vegas

mark.ashcraft@unlv.edu

Dr. Thomas Faulkenberry

Department of Psychology

Tarleton State University

faulkenberry@tarleton.ed

Dr. Jennifer Rennels

Department of Psychology

University of Nevada, Las Vegas

jennifer.rennels@unlv.edu