

Response trajectories capture the continuous dynamics of the size congruity effect

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Abstract

In a comparison task involving numbers, the size congruity effect refers to the general finding that responses are usually faster when there is a match between numerical size and physical size (e.g., 2-8) than when there is a mismatch (e.g., 2-8). In the present study, we used computer mousetracking to test two competing models of the size congruity effect: an early interaction model, where interference occurs at an early representational stage, and a late interaction model, where interference occurs as dynamic competition between response options. In three experiments, we found that the curvature of responses for incongruent trials was greater than for congruent trials. In Experiment 2 we showed that this curvature effect was reliably modulated by the numerical distance between the two stimulus numbers, with large distance pairs exhibiting a larger curvature effect than small distance pairs. In Experiment 3 we demonstrated that the congruity effects persist into response execution. These findings indicate that incongruities between numerical and physical size are carried throughout the response process and result from competition between parallel and partially active response options, lending further support to a late interaction model of the size congruity effect.

Keywords: Size congruity effect, numerical distance effect, computer mousetracking

This article is in press at *Acta Psychologica*

The size congruity effect (Paivio, 1975) has been explored at the behavioral, computational, and functional levels by cognitive and developmental scientists over the past 40

years (Besner & Coltheart, 1979; Foltz, Poltrock, & Potts, 1984; Henik & Tzelgov, 1982; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Santens & Verguts, 2011). One reason this phenomenon provokes curiosity is because it provides an important window on basic questions such as whether the human brain is equipped with a shared mechanism to compare numbers and other magnitudes, what the parts of this mechanism are, and how these parts function together (see Cohen Kadosh, Lammertyn, & Izard, 2008; Walsh, 2003, for a review).

The size congruity effect typically arises in the context of a task similar to the following. Participants are shown two Arabic digits with varying numerical value and physical (i.e., font) sizes and instructed to make a judgment on either of these dimensions alone with a speeded key press response. Thus, numerical information is irrelevant in the ‘physical comparison task’ and physical size information is irrelevant in the ‘numerical comparison task’. Nevertheless, one typically finds that participants fail to completely ignore either dimension, which results in impaired performance in incongruent trials – when the two dimensions differ (e.g., 2-8) – compared to congruent trials – when the two dimensions provide the same information (e.g., 2-8). The 50-100 millisecond difference in response time between these two conditions is termed the size congruity effect. In the case of a physical size judgment, the presence of a size congruity effect is thought to index automatic processing of number’s magnitude because participants process the irrelevant dimension unintentionally, even when it is irrelevant or disadvantageous to optimal execution of the experimental task (Henik & Tzelgov, 1982).

Over the past two decades, various models have been put forth to explain the size congruity effect. Roughly, they break into two differing explanations: early interaction versus late interaction (see Cohen Kadosh et al., 2007; Schwarz & Heinze, 1998, for a discussion of these two explanations). Simply put, an early interaction model proposes that a digit’s physical and numerical magnitude are first mapped onto an integrated analog representation, upon which further processing leads to the activation of the correct response. The key premises of this model are that (1) congruity effects happen early, and (2) the digit’s magnitude properties do not have direct access to the response stage. Taken another way, all conflicting information is resolved independently from motor response execution.

The alternative is a late interaction model, which states that physical and numerical information are encoded in functionally independent pathways and each separately activate a task specific decision code. It is at this decision phase that these codes compete, and this competition feeds forward into the response activation stage to produce the observed size congruity effects. Such a late interaction model was elegantly elaborated upon in a recent computational model of Santens and Verguts (2011), called the Shared Decisions Account,

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The authors wish to thank Jonathan Herring, Brie Heidingsfelder, Kate Shaw, and Heather Wilson for help with data collection.

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where numerical and physical size comparisons automatically feed from a representational layer into a decision layer. When both decisions feed into the same “right larger” response node, as they do when numerical and physical size are congruent, activation rises quickly and the decision happens fast. When, on the other hand, the numerical and physical size comparisons feed into different response nodes, activation of the correct response does not happen as quickly, which explains the slower RTs in the incongruent condition. It is worth noting here that this model also does an excellent job of explaining the reverse numerical distance effect that happens in a size-congruity task (e.g., Santens & Verguts, 2011); that is, when the numbers are farther apart in numerical value, the congruity effect is larger. This is reverse from the intuition of the standard numerical distance effect (Moyer & Landauer, 1967), in which numbers that are farther apart are actually easier to compare.

Evidence for one model over the other has been mixed. For example, Schwarz and Heinze (1998) used the event-related potentials (ERP) technique to investigate the time course of the size-congruity effect. They found that relatively early ERP components – which are associated with stimulus processing – were modulated by the size-congruity effect. However, they found no such modulation in the case of a lateralized readiness potential (LRP) component. Because the LRP is believed to represent the preparation and execution of a response, the authors concluded that interference does not happen at the response stage. On the other hand, Szűcs and Soltész (2007, 2008) found the size-congruity effect in stimulus-related ERP and LRP components, suggesting that the interference takes place both on the stimulus and response related levels of processing. Furthermore, Cohen Kadosh et al. (2007) found via functional magnetic resonance (fMRI) that activation in the motor cortex was modulated by the size-congruity effect up to response selection phase. In a follow-up ERP experiment in this study, the authors showed evidence that supported both early and late interactions depending on task requirements, such as cognitive load.

Taking a step aside, we note that previous work investigating size congruity effects has been confined to discrete responses (e.g., keypresses) measuring only the speed and accuracy of decisions (with distribution of response times being the crucial measurement in these studies). Despite their usefulness, traditional measures are limited in distinguishing separate stages and determining at which processing step (in transition from perception to action) the interference effect between various dimensions occurs (Luce, 1986). This is because a keypress captures only the outcome of a completed decision at the end of the trial, and the real-time cognitive dynamics that occur during the trial are lost. Consequently, trial-level measures, such as errors and reaction times, lack inferential markers to understand how information-processing stages are temporally-structured. Partly for these reasons, computer mousetracking has become a popular way to supplement these data with rich, high resolution temporal data that reflect the dynamics of a decision process (see Song & Nakayama, 2009, for a review).

The now classic study that gave rise to this technique is that of Spivey, Grosjean, and Knoblich (2005) who measured hand movements during a language comprehension task. In their task, people were asked to choose the picture that corresponded to a word that was heard. In the case where the pictures were phonological competitors, the hand movements showed a continuous deflection toward the competitor, which Spivey et al. (2005) interpreted as the continuous competition of unstable, partially active mental representations that asymptotically converged throughout the decision process. This provided evidence that

these decisions did not take place in a truly feed-forward, stage-based fashion, but instead in a dynamic back and forth between perception and action. Since then, mousetracking has increased in popularity. It has been used in a wide variety of contexts from social cognition (e.g., Freeman & Ambady, 2009, 2011a) to numerical cognition (Song & Nakayama, 2008; Santens, Goossens, & Verguts, 2011; Faulkenberry, 2014; Marghetis, Núñez, & Bergen, 2014; Faulkenberry, Montgomery, & Tennes, 2015). The use of computer mousetracking to study cognitive processes in numerical cognition has received interest as of late (Fischer & Hartmann, 2014; Faulkenberry & Rey, 2014), due to the fact that hand trajectories, whether captured through the computer mouse or through 3d hand movements, can shed light on the dynamics of the decision processes involved in numerical cognition.

Whether and how the size congruity effect may be mapped onto dynamic hand movements is still an open question. This question forms the basis of our present study. It could be that interference effects in a size-congruity task are confined to an early representational stage, before motor-preparation begins (Schwarz & Heinze, 1998), or rather leak into response-related processing stages when the required motor response is selected and prepared (Santens & Verguts, 2011). To determine the dynamic processes involved in the size congruity effect, we used a continuous version of a physical size judgment task (e.g., Henik & Tzelgov, 1982) in which we asked participants to respond with a computer mouse rather than pressing keys. In this task, participants were presented with pairs of Arabic digits (one target and one distractor) in the top left and top right regions of a computer screen and were asked to move the mouse to click on the location of the physically larger number of the pair, ignoring the digits' numerical values. Participants began each upward mouse movement with origin at the starting position in the bottom center. The amount of motor conflict was determined by manipulating the congruence between numerical and physical size (Experiments 1, 2, and 3) and by manipulating numerical distance between digit pairs (Experiment 2). Combining size congruency and distance effects in a mousetracking procedure is advantageous for two reasons. First, this approach provides continuous measurements, allowing us to measure dynamic conflict stemming from the task-irrelevant dimension. In addition, we can also assess whether differences in the strength of this conflict depend on numerical distance, reflecting the need for inhibitory control of the irrelevant numerical magnitude. As such, the use of both factors serves as a more reliable measure of magnitude activation than congruity effects alone.

Thus, for the present study, our critical question is whether the task-irrelevant stimulus dimension of the digits interacts only in early representations, or whether instead the interaction feeds forward throughout the ongoing motor response. If the size congruity interference arises at an early representational stage, then the effects of interference should be confined to an initiation time period (i.e., the time between target onset and initiation of mouse movement), leaving temporal and spatial parameters of the reach unaffected (i.e., trajectory and mouse movement time). This is because under such an early interaction view, the interference between numerical and physical size arises during early processing of the potential targets and dissipates before response selection occurs. In contrast, if the size congruity interference arises as response competition during the preparation and execution of the manual response stage, then the effects of interference should be detectable in the trajectory and duration of the reaching movement. For incongruent trials, this competition would then be indexed by a greater attraction of movement trajectories toward the incorrect

response and longer movement times. Thus, the presence or absence of size congruity effects in movement parameters will be critical in providing evidence supporting either account.

Experiment 1

The purpose of Experiment 1 was to see how the size congruity effect mapped onto a computer mousetracking task and subsequently investigate whether such data lended better support for an early interaction model or late interaction model.

Method

Participants. Fifty-one undergraduate students (43 female, mean age = 21.5 years, age range 18 to 39) participated in this experiment for extra credit in their psychology classes. Four participants reported being left hand-dominant, but all reported that they used their right hand for the computer mouse. The experiment was reviewed and approved by the institutional review board at Tarleton State University.

Stimuli and apparatus. The experiment was implemented using the MouseTracker software package (Freeman & Ambady, 2010). All stimuli were presented using a 20 inch iMac desktop computer with a screen resolution of 1,280 x 1,024 pixels. We ran the MouseTracker program on the iMac using a virtual Windows XP environment via Parallels. Following the recommendations of Fischer and Hartmann (2014), we disabled the “dynamic acceleration” option and lowered the speed of the mouse movements on the screen to the second-lowest possible speed in the mouse settings dialog. This is done to prevent quick and erratic mouse movements, resulting in a smooth and more reliable record of participants’ hand movements. The resulting displacement ratio of the mouse to screen movement was 1 cm to 100 pixels.

For each trial, two numbers were displayed simultaneously at the upper (left and right) corners of a computer screen. The stimuli consisted of the Arabic numerals 1, 2, 8, and 9 displayed in Arial font, and presented in pairs in two different font sizes: 22 (small) and 28 (large). Ignoring order, there were 6 possible pairs of numerals: 1-2, 1-8, 1-9, 2-8, 2-9, and 8-9.

Procedure. Participants were told that they would be presented with number pairs at the top-left and top-right corners of the screen and were asked to categorize these numbers by quickly clicking with the computer mouse on the appropriate label. Figure 1 depicts the sequence of stimuli in each experimental trial. The specific instruction was to judge on which side the physically larger number was presented, while ignoring the numerical value. While participants categorized these numbers, we recorded the streaming x, y - coordinates of the computer mouse (using a software-determined sampling rate of approximately 70 Hz). Before the presentation of each number pair, participants had to click on a START button located at the center bottom of the screen. As soon as the participants clicked this button to initiate the trial, a number pair appeared at the top left and right corners of the computer screen, and the computer mouse became responsive to participants’ hand movements, allowing them to begin moving the pointer toward the two response options. After clicking the appropriate response to indicate their answer, the mouse pointer was automatically relocated to the bottom center of the screen with x, y - coordinates of (0,0) after an inter-trial interval of 500 milliseconds. Number pairs were presented in a randomized order.

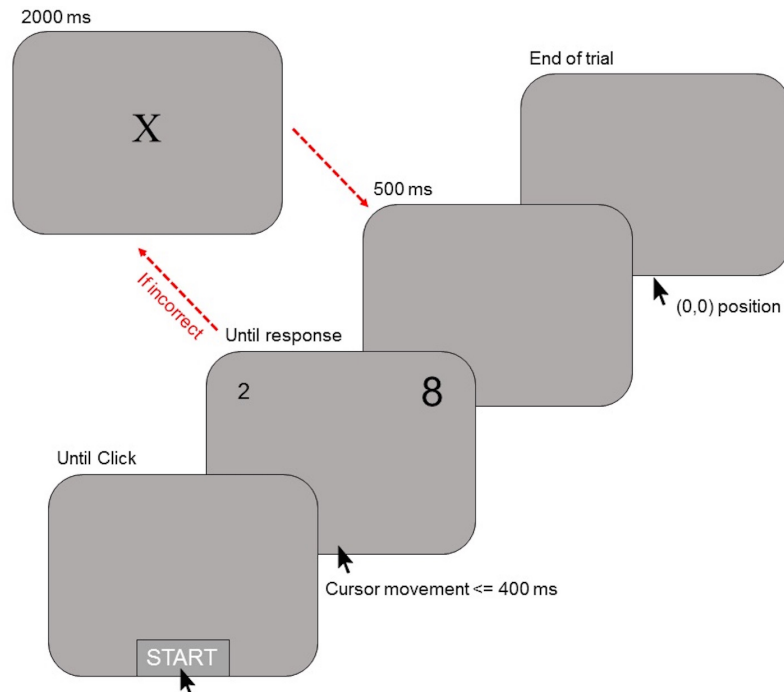


Figure 1. Trial design for the physical-size judgment task that was used in Experiments 1 and 2. The four panels from bottom-left to top-right show an example of a standard correct trial. The top-left panel shows the feedback given after incorrect response. In Experiment 3, the initiation deadline for cursor movement (second panel from the bottom-left) was removed, so the participants could initiate movement at their own pace.

We manipulated physical-numerical size congruity: in the congruent condition, the numerically larger number was also physically larger (e.g., 1 8). In the incongruent condition, the numerically larger number was physically smaller (e.g., 1 8). The position of the correct response was counterbalanced across trials. Half of the trials were presented with the correct answer on the left side and half of the trials were presented with the correct answer on the right side. For incorrect responses, the program displayed an “X” for 2000 ms. To ensure that trajectories reflected online processing, participants were encouraged to begin their movements as early as possible and were warned if initiated movement later than 400 ms following number pair presentation. This instruction is customarily included in mousetracking studies so that trajectories reflect the dynamics of a decision process rather than simply reflecting the kinematics of a response choice after the choice has already been made (Freeman & Ambady, 2009; Spivey et al., 2005). The 6 pairs of single-digit Arabic numbers were presented four times each (once for each condition obtained by crossing physical-numerical size congruity and order) in eight blocks, giving a total of 192 trials per participant.

Results

Participants completed a total of 9,792 trials. Of these, 54 trials were responded to incorrectly (0.56%). From these trials, we excluded an additional 114 trials for which

Table 1
Mean performance measures for trajectories in Experiment 1

Measure	Experimental condition		Statistic	
	Congruent	Incongruent	Cohen's d	t
	Rightward Trajectories			
MT (msec)	1118	1170	0.88	6.28***
Init (msec)	159	155	0.19	1.37
AUC	0.53	0.94	1.02	7.32***
	Leftward trajectories			
MT (msec)	1103	1156	0.90	6.42***
Init (msec)	154	159	0.33	2.34*
AUC	0.66	1.13	1.36	9.71***

Note. *** $p < 0.001$, * $p < 0.05$

reaction times exceeded 3 standard deviations from the mean reaction time across all correct trials (1.2%). All subsequent analyses were conducted on the remaining 9,624 trials.

Time analyses. For each trial, we recorded two temporal performance measures: reaction time (RT), the total time elapsed between clicking the START button and the target mouse click; and initiation time (Init), the time elapsed between target onset after clicking the START button and the onset of mouse movement. From these two measures, we calculated movement time (MT), the actual duration of mouse movement, via the relationship $MT = RT - \text{Init}$.

Mean movement and initiation times are presented in Table 1. For rightward trajectories, participants exhibited a large size-congruity effect, with movement durations lasting 52 ms longer for incongruent trials compared to congruent trials, $t(50) = 6.28$, $p < 0.001$, $d = 0.88$. No significant difference in movement initiation time (Init) was found between conditions, $t(50) = 1.37$, $p > 0.17$. A similar picture emerged with leftward trajectories, where participants again exhibited a large size-congruity effect, with movement durations lasting 53 ms longer on incongruent trials, $t(50) = 6.42$, $p < 0.001$, $d = 0.90$. There was a small significant effect of numerical-physical size congruity on initiation times, with incongruent trials taking 5 msec longer to initiate compared to congruent trials, $t(50) = 2.34$, $p < 0.05$, $d = 0.33$.

Trajectory analyses. To investigate the dynamics of the manual responses that participants enacted while making judgments of physical size, we analyzed the hand trajectories as measured by recording the streaming x, y - coordinates of the computer mouse during each trial. Following the convention of Freeman and Ambady (2010), we used the Mousetracker software to rescale all hand trajectory data into a standard coordinate space of $[-1, 1] \times [0, 1.5]$. To remove the effects of differing response times, we normalized all trajectories (via linear interpolation) to consist of exactly 101 timesteps. As in previous studies, this step is important so that trajectories in different conditions can be directly compared without the confounding effect of response time.

Average hand trajectories in each of the two physical-numerical size congruity conditions are depicted in Figure 2. As can be seen for both leftward and rightward trajectories, response trajectories for incongruent trials (e.g., 1 8) are significantly deflected toward the

incorrect response alternative (e.g., the numerically larger digit) throughout much of the duration of the response. To index this behavior, we compared the mean x -coordinates in each condition for each of the 101 timesteps via paired-samples t -tests (c.f., Spivey et al., 2005). We found that the x -coordinates of leftward trajectories differed significantly ($p < 0.05$) between the 26th and 76th timesteps, whereas the x -coordinates of rightward trajectories differed significantly between the 23rd and 73rd timesteps. This pattern of trajectories is indicative of dynamic competition between parallel and partially active responses.

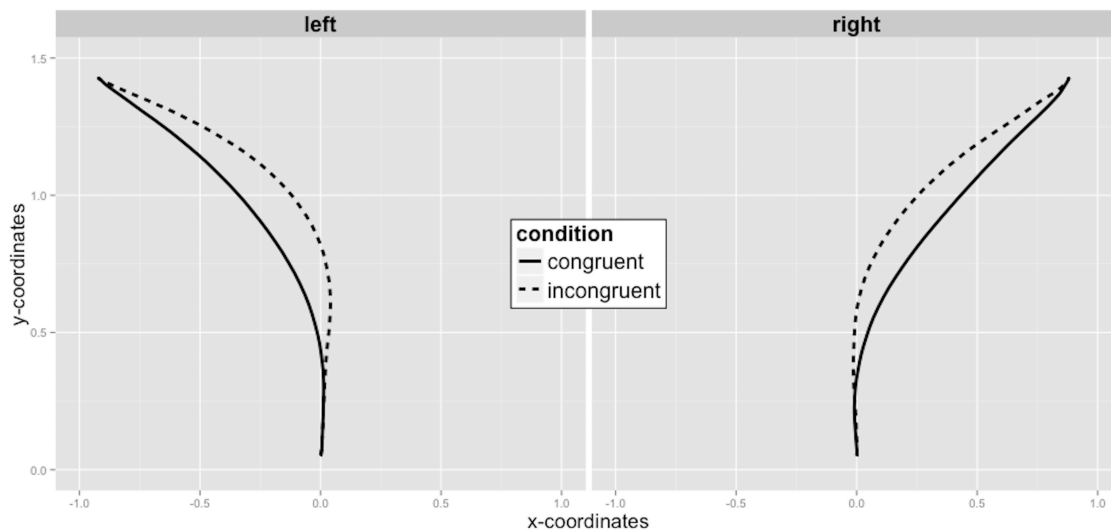


Figure 2. Mean response trajectories in Experiment 1 as a function of response side (left versus right) and physical-numerical size congruity (congruent versus incongruent).

While the intuition gained from looking at average response trajectories does readily yield such interpretation, it does not provide us a quantitative measure that we can subject to a hypothesis test. To this end, we used area under the curve (AUC) to index the amount of partial activation of the incorrect response alternative on each trial. The AUC values were then averaged for each of the 51 participants by condition (congruent, incongruent) and then compared via a paired-samples t -test. As can be seen in Table 1, for leftward trajectories, physical-numerical size congruity had a very large effect on AUC values ($AUC_{\text{congruent}} = 0.66$, $AUC_{\text{incongruent}} = 1.13$), $t(50) = 9.71$, $p < 0.001$, $d = 1.36$. A similar result was found for rightward trajectories; ($AUC_{\text{congruent}} = 0.53$, $AUC_{\text{incongruent}} = 1.02$), $t(50) = 7.32$, $p < 0.001$, $d = 1.02$.

Distribution of trajectories. To cement the claim that the curvature patterns seen in Figure 2 result from competition between parallel and partially active responses, we need to rule out the possibility that the wide trajectory deviations seen on incongruent trials result from averaging across two types of hand movements that would be consistent with an early interactions account of the size congruity effect. One of these types would be a fairly straight path toward the correct answer, whereas the other would be initially headed toward the incorrect alternative, but then sharply corrected midflight. This discrete behavior is consistent with an early interactions account, as the interference effects would be localized to a pre-motor stage instead of a competition throughout the motor response.

Such behavior, when averaged across many trials, could potentially appear as a smooth curve, even though it is composed of discrete processes.

To rule out such an alternative, we analyzed the distribution of trajectories on incongruent trials as indexed by AUC (e.g., Freeman & Dale, 2012). If indeed the smooth trajectories we are seeing are the result of discrete processes, these processes should show up as a multimodal distribution of AUC values. Two common tools for assessing multimodality are the bimodality coefficient (SAS Institute Inc., 2012) and Hartigan’s dip test (J. A. Hartigan & P. M. Hartigan, 1985). We computed the bimodality coefficient to be 0.396, which is less than the value of 0.555 that is generally considered necessary for a distribution be considered a bimodal. Additionally, we used the R package `diptest` (Maechler, 2013) to compute the Hartigan dip statistic as $D = 0.0027$, $p > 0.99$, indicating that the distribution of AUC values is not multimodal. Both computations imply that the distribution of trajectories on incongruent trials is unimodal, and thus, the curvature patterns seen in Figure 2 are the result of competition between parallel and partially active responses throughout the decision process.

Discussion

In Experiment 1 we found tentative support for a late interaction model of the size congruity effect (e.g., Santens & Verguts, 2011). Indeed, average computer mouse trajectories on incongruent trials were significantly deflected toward the incorrect response alternative throughout 50% of the response trajectory. Such results indicate that resolution of the inconsistency between numerical and physical size occurred throughout the motor response stage and was not isolated to early representational stages. Distributional analyses confirmed our interpretation of the wide trajectory deflections as resulting from smooth, graded competition between response alternatives rather than discrete behaviors such as midflight corrections after an initial incorrect response trajectory.

It is important to note that while the movement and trajectory data does indicate support for the late interactions model, we did get a small, statistically significant effect (5 msec) on movement initiation time for leftward trajectories. This effect was absent on rightward trajectories, and as such is likely not evidence for an early interaction effect. Furthermore, the critical test for early interaction is whether the interference is limited to only the initiation times and not carried through into the actual movement times (Buc Calderon, Verguts, & Gevers, 2015). At present, our data indicates just the opposite; namely, the effects of size congruity seem to persist into the movement phase of the response. Nevertheless, our current position is only tentative and needs to be confirmed in another experiment.

Experiment 2

With Experiment 2, we attempted to replicate the results of Experiment 1 while adding the factor of numerical distance to our design. Specifically, we wanted to investigate how numerical distance interacts with physical/numerical size congruity. Schwarz and Ischebeck (2003) found that increasing the numerical distance in a physical size comparison task increased the size congruity effect, which they explained in terms of an early interaction model. Alternatively, the dual-route architecture model of Santens and Verguts (2011) also

predicts a modulation of the size congruity effect by numerical distance, which they explain in terms of a late interaction model. Their explanation is that when numerical distance is large, activation of the numerically larger digit is stronger (i.e., the numerical distance effect), resulting in greater competition between the physical and numerical route. This greater competition manifests as a stronger size congruity effect.

While both of the previously mentioned studies (Schwarz & Ischebeck, 2003; Santens & Verguts, 2011) explained this modulation of physical comparison by numerical distance, both of the studies used a general close/far classification of numerical distance. In Experiment 2, we tested this modulation on numerical distances from 1 to 4. If we interpret the size congruity effect on computer mouse trajectories observed in Experiment 1 as the result of competition among parallel and partially active response options, then we should observe a monotonic increase in these competition effects (e.g., increased movement times and increased AUC) as numerical distance increases from 1 to 4.

Method

Participants. Forty-one undergraduate students (32 female, mean age = 23.8 years, age range 19 to 50 years) participated in this experiment for extra credit in their psychology classes. All the participants reported being right-hand dominant. The experiment was reviewed and approved by the institutional review board at Tarleton State University.

Stimuli and apparatus. The apparatus was identical to the one used in Experiment 1. The stimuli consisted of the Arabic numerals 2, 3, 4, 5, 6, 7, and 8 displayed in Arial font, and presented in pairs in two different font sizes: 22 (small) and 28 (large). We chose pairs in order to manipulate the numerical distance between numerals. Ignoring order, there were 12 possible pairs of numerals: 2-3, 3-4, 4-5 (distance 1); 2-4, 3-5, 4-6 (distance 2); 2-5, 3-6, 4-7 (distance 3); 2-6, 3-7, 4-8 (distance 4).

Procedure. The procedure for each trial was identical to Experiment 1. In addition to manipulating physical-numerical size congruity (congruent, e.g., 1 8, vs. incongruent, e.g., 1 8), we also manipulated numerical distance (1, 2, 3, or 4). The 12 pairs of numerals described above were presented four times each (once for each condition obtained by crossing physical-numerical size congruity and order) in eight blocks, giving a total of 384 trials per participant.

Results

Participants completed a total of 15,744 trials. Of these, 44 trials contained an incorrect response (0.28%). From the remaining trials, we excluded an additional 68 trials for which RTs exceeded 3 standard deviations from the mean RT across all trials (0.43%). All subsequent analyses were conducted on the remaining 15,632 trials.

Time analyses. Mean movement times and initiation times are presented in Table 2. Both measures were separately submitted to a 2 (physical-numerical size congruity: congruent vs. incongruent) x 4 (numerical distance: 1, 2, 3, 4) repeated measures analysis of variance. For rightward trajectories, there was a significant main effect of physical-numerical size congruity on MTs. Critically, participants moved 46 ms longer on incongruent trials compared to congruent trials, $F(1, 40) = 40.31$, $p < 0.001$, $\eta_p^2 = 0.50$. There was no significant main effect of numerical distance, $F(3, 120) = 1.44$, $p > 0.23$. The interaction

between size congruity and distance did not quite reach significance, $F(3, 120) = 2.56$, $p = 0.058$, $\eta_p^2 = 0.03$ (see Figure 3). However, a linear model fit the observed trend of an increasing size congruity effect by distance, as confirmed by a significant within-subjects linear contrast, $F(1, 40) = 6.13$, $p = 0.02$, $\eta_p^2 = 0.16$. Initiation times did not differ between conditions on any factor (all F -ratios were less than 0.68).

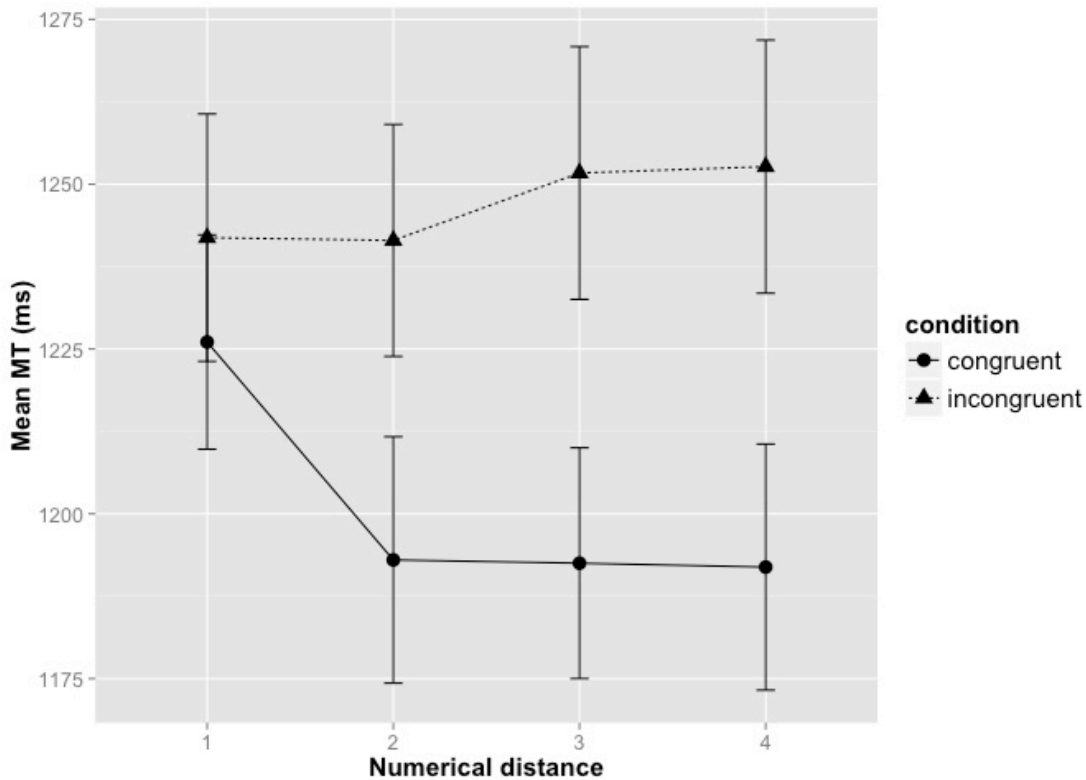


Figure 3. Mean movement times on rightward responses in Experiment 2 as a function of physical-numerical size congruity (congruent versus incongruent) and numerical distance (1, 2, 3, and 4). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).

Leftward responses revealed a similar pattern (see Figure 4). As above, both mean MT and initiation time were separately analyzed via a 2 x 4 repeated measures analysis of variance. Again, there was a significant main effect of size-congruity on MT, $F(1, 40) = 37.66$, $p < 0.001$, $\eta_p^2 = 0.48$. Overall, participants moved 46 ms longer on incongruent trials compared to congruent trials. There was no significant effect of numerical distance, $F(3, 120) = 0.56$, $p > 0.64$. There was a significant interaction between size congruity and distance, $F(3, 120) = 4.04$, $p = 0.009$, $\eta_p^2 = 0.09$. Again, the size congruity effect increased linearly with numerical distance, $F(1, 40) = 14.13$, $p = 0.001$, $\eta_p^2 = 0.32$. As with rightward responses, there were no statistically significant effects of any factor on initiation times (all F -ratios less than 2.1).

Trajectory analyses. Similar to Experiment 1, we analyzed the average time-normalized trajectories for congruent and incongruent trials crossed with the numerical

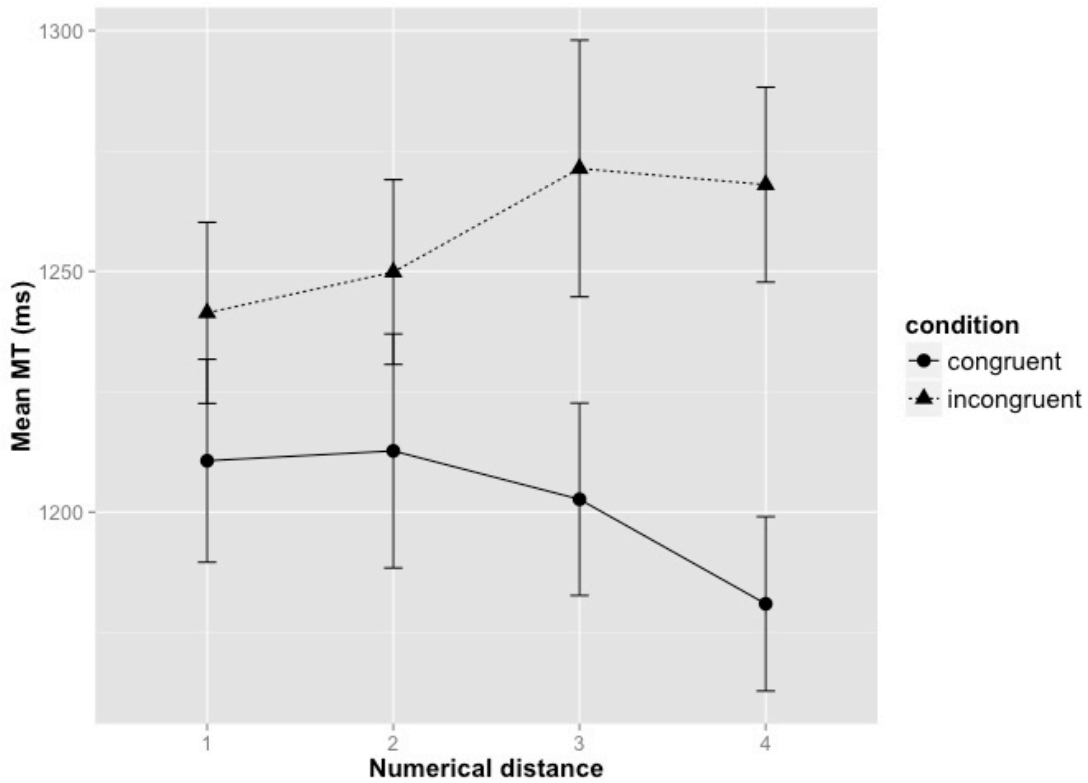


Figure 4. Mean movement times on leftward responses in Experiment 2 as a function of physical-numerical size congruity (congruent versus incongruent) and numerical distance (1, 2, 3, and 4). Error bars represent within-subject 95% confidence intervals as recommended by Morey (2008).

Table 2

Mean performance measures for trajectories in Experiment 2

Numerical distance	Congruent Trials				Incongruent Trials			
	1	2	3	4	1	2	3	4
Rightward trajectories								
MT (msec)	1226	1193	1193	1192	1241	1241	1252	1253
Init (msec)	129	129	125	131	125	127	127	127
AUC	0.57	0.51	0.46	0.47	0.76	0.79	0.85	0.94
Leftward trajectories								
MT (msec)	1211	1213	1203	1181	1241	1250	1271	1268
Init (msec)	127	128	126	121	120	131	121	125
AUC	0.63	0.55	0.54	0.48	0.76	0.80	0.83	0.86

distances 1, 2, 3, and 4. These average hand trajectories are depicted in Figure 5. We submitted mean AUC values for each participant to a 2 (physical-numerical size congruity: congruent vs. incongruent) \times 4 (numerical distance: 1, 2, 3, 4) repeated measures analysis of variance (see Table 2). For AUC values on rightward trajectories, there was a significant main effect of physical-numerical size congruity, $F(1, 40) = 73.05$, $p < 0.001$, $\eta_p^2 = 0.65$, once again indicating that response trajectories for incongruent trials were significantly deflected toward the incorrect response alternative (e.g., the numerically larger digit) throughout the response. There was no main effect of numerical distance, $F(3, 120) = 1.01$, $p > 0.39$. However, congruity interacted with numerical distance, $F(3, 120) = 5.07$, $p < 0.003$, $\eta_p^2 = 0.11$. Trajectory deviations generally increased as a function of numerical distance, indicating increased competition effects with increased numerical distance. As with MTs, a linear model fit the trend well, as confirmed by a significant within-subjects linear contrast, $F(1, 40) = 14.39$, $p < 0.001$, $\eta_p^2 = 0.27$.

Leftward trajectories revealed an identical pattern. For AUC values on leftward trajectories, there was a significant main effect of physical-numerical size congruity, $F(1, 40) = 42.19$, $p < 0.001$, $\eta_p^2 = 0.51$. There was no main effect of numerical distance, $F(3, 120) = 0.222$, $p > 0.88$. Finally, congruity interacted with numerical distance, $F(3, 120) = 3.58$, $p < 0.02$, $\eta_p^2 = 0.08$. Trajectory deviations generally increased as a function of numerical distance, indicating increased competition effects with increased numerical distance. Again, a linear model fit the trend well, as confirmed by a significant within-subjects linear contrast, $F(1, 40) = 11.11$, $p = 0.002$, $\eta_p^2 = 0.21$. Taken together, these data appear to confirm our prediction that competition between parallel and partially active response options increased as a function of numerical distance.

Distribution of trajectories. As we argued in Experiment 1, to confirm that the trajectory patterns in Figure 5 are the result of continuous competition and not discrete trial types, we must confirm that the distribution of trajectories on incongruent trials is unimodal. To this end, we computed the bimodality coefficient to be 0.442. Since this value is less 0.555 we can argue that this distribution is not bimodal. Additionally, we computed the Hartigan dip statistic as $D = 0.0021$, $p > 0.99$, indicating that the distribution of AUC values is not multimodal. As in Experiment 1, both of these computations imply that the distribution of trajectories on incongruent trials is unimodal, and thus, the curvature patterns seen in Figure 5 are the result of competition between parallel and partially active responses throughout the decision process.

Discussion

In Experiment 2 we again found that computer mouse trajectories for incongruent trials were significantly attracted toward the incorrect response alternative, replicating the main finding of Experiment 1. In addition, we found that this attraction is modulated by numerical distance; that is, the effect of physical-numerical size congruity increased as a function of numerical distance. This critical result is predicted by both early interaction models (e.g., Schwarz & Ischebeck, 2003) and late interaction models (e.g., Santens & Verguts, 2011) of the size congruity effect. However, we found that this modulation of interference by numerical distance was carried throughout the response process, which is predicted only by the late interaction model. In addition, we found no effects of congruity or distance on the times to initiate computer mouse movements, indicating that the inter-

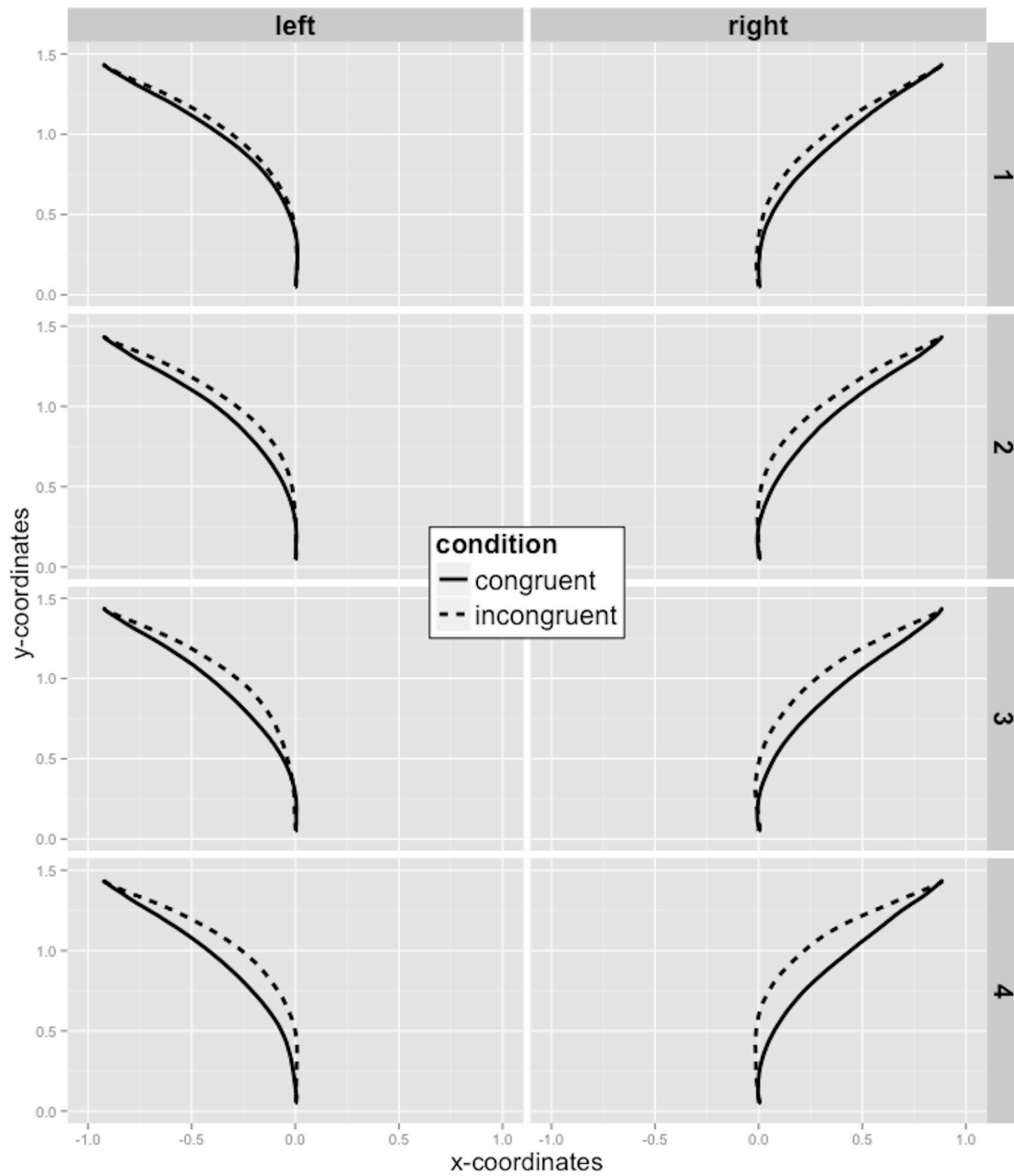


Figure 5. Mean response trajectories in Experiment 2 as a function of response side (left versus right), physical-numerical size congruity (congruent versus incongruent), and numerical distance (1, 2, 3, and 4).

ference is carried into the response stage and not isolated to an early pre-motor stage, as would be predicted by an early interaction account. As such, the present data provides support for a late interaction model of the size congruity effect.

Note that in both Experiments 1 and 2, we asked participants to begin moving their computer mouse as quickly as possible after clicking the start button. This was done to ensure that the recorded mouse trajectories reflected online processing so that we could measure how the physical size decision evolved over time (e.g., Freeman & Ambady, 2009). However, it is possible that this exact task instruction may unfairly bias our procedure in favor of the late interaction model. To rule out this possibility, we conducted another experiment in which we replicated the procedure from Experiment 1 with one exception; namely, we removed the 400 ms initiation time threshold.

Experiment 3

With Experiment 3, we attempted to rule out the possibility that specific task instructions bias our results unfairly toward the late interaction model¹. While at first glance 400 ms seems long enough to allow any early representation effects to appear (especially in light of early ERP work by Schwarz & Heinze, 1998), Santens and Verguts (2011) demonstrated that the congruity effects in a physical size comparison task can appear within 400 to 500 ms. So it is entirely possible that our current 400 ms cutoff does not allow a hypothesized early representational stage to be completed, which would thus force our participants to begin moving before the end of this representational stage. This would then force the congruity effects stemming entirely from early representational overlap to leak into the response stage and appear to be the result of dynamic response competition.

To eliminate this possibility, then, we removed the instruction that participants should begin their mouse movements within 400 ms. All other experiment parameters were the same as in Experiment 1. The early interaction account would predict that the size congruity effect should be confined to only the initiation times, with no difference in actual mouse movement times (Buc Calderon et al., 2015). On the other hand, the late interaction account predicts that the size congruity affect should appear in the movement times (as well as, potentially, the initiation times) and the mouse trajectories.

Participants. Forty-six undergraduate students (38 female, mean age = 20.3 years, age range 18 to 36 years) participated in this experiment for extra credit in their psychology classes. Six participants reported being left-handed but all reported that they use their right hand for the computer mouse. The experiment was reviewed and approved by the institutional review board at Tarleton State University.

Stimuli and apparatus. The apparatus and stimuli were identical to those used in Experiment 1.

Procedure. The procedure for each trial was identical to Experiment 1, except that we removed the instruction to begin moving the mouse as quickly as possible. We did ask participants to respond as quickly and accurately as possible, but made no mention of beginning mouse movement within any specified time threshold.

¹We thank the anonymous reviewers for raising this issue and suggesting this experiment.

Table 3
Mean performance measures for trajectories in Experiment 3

Measure	Experimental condition		Statistic	
	Congruent	Incongruent	Cohen's d	t
	Rightward Trajectories			
MT (msec)	1238	1278	0.53	3.60***
Init (msec)	192	185	-0.27	1.82
AUC	0.36	0.64	1.01	6.86***
	Leftward trajectories			
MT (msec)	1242	1274	0.51	3.46**
Init (msec)	183	190	0.25	1.67
AUC	0.36	0.67	1.06	7.18***

Note. *** $p < 0.001$, ** $p < 0.01$

Results

Participants completed a total of 8,832 trials. Of these, 62 trials contained an incorrect response (0.70%). From the remaining trials, we excluded an additional 88 trials for which RTs exceeded 3 standard deviations from the mean RT across all trials (1.00%). All subsequent analyses were conducted on the remaining 8,682 trials.

Time analyses. Mean movement and initiation times are presented in Table 3. For rightward trajectories, participants exhibited a moderate size-congruity effect, with mouse movements on incongruent trials taking 40 ms longer to complete than on congruent trials, $t(45) = 3.60$, $p < 0.001$, $d = 0.53$. Initiation times did not differ significantly between conditions, $t(45) = 1.82$, $p = 0.08$. A similar outcome appeared with leftward trajectories, where participants' mouse movements on incongruent trials taking 32 ms longer to complete compared to congruent trials, $t(45) = 3.46$, $p = 0.001$, $d = 0.51$. Again, there was no statistically significant effect of congruity on initiation times, $t(45) = 1.36$, $p = 0.10$.

Trajectory analyses. Average hand trajectories in each of the two physical-numerical size congruity conditions are depicted in Figure 6. As we saw in each of the previous two experiments, response trajectories for incongruent trials were significantly deflected toward the incorrect response alternative throughout much of the duration of the response. Indeed, the x -coordinates of leftward trajectories differed significantly between the 26th and 84th timesteps, whereas the x -coordinates of rightward trajectories differed significantly between the 26th and 90th timesteps. As before, we also compared the dynamic complexity of trajectories via AUC measures. As can be seen in Table 3, physical-numerical size congruity had a large effect on AUC values for leftward trajectories ($AUC_{\text{congruent}} = 0.36$, $AUC_{\text{incongruent}} = 0.67$), $t(45) = 7.18$, $p < 0.001$, $d = 1.06$, as well as rightward trajectories ($AUC_{\text{congruent}} = 0.36$, $AUC_{\text{incongruent}} = 0.64$), $t(45) = 6.86$, $p < 0.001$, $d = 1.01$. Overall, this pattern of trajectories indicates that, even without the initial speeded response instructions, the effects of physical-numerical size congruity leaked into the response stage, and hence these effects are not isolated to a pre-response early representational stage.

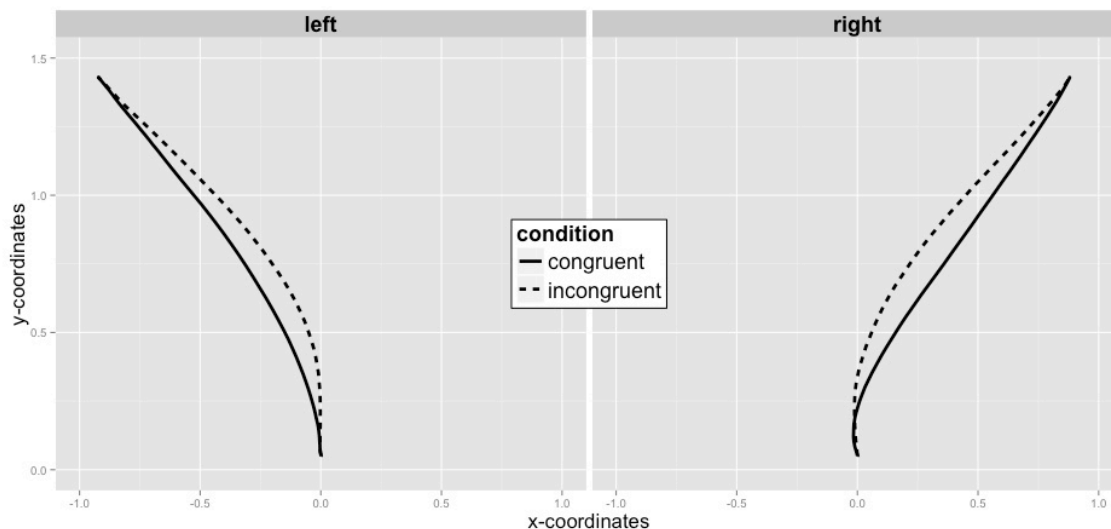


Figure 6. Mean response trajectories in Experiment 3 as a function of response side (left versus right) and physical-numerical size congruity (congruent versus incongruent).

Discussion

In Experiment 3, we again found that computer mouse trajectories for incongruent trials were significantly attracted toward the incorrect response alternative throughout a large portion of the manual response, replicating the main findings of Experiments 1 and 2. Critically, we removed the requirement for speeded initiation of mouse movement to allow enough time for any possible effects of early representational interference to finish before mouse movement began. We hypothesized that if such effects were being obscured by the speeded initiation instructions of Experiments 1 and 2, then we should observe differences in initiation time, but no differences in actual mouse movement duration. We found exactly the opposite; there were no statistically significant differences in movement initiation times between congruity conditions, but there was a moderate effect of congruity on mouse movement durations, as well as a large effect of congruity on the complexity of the movement trajectories. These findings lend solid support to the late interaction model of Santens and Verguts (2011).

General Discussion

In the present study we conducted 3 experiments in which we used computer mouse-tracking with a physical comparison task to measure the dynamics of size congruity effect. We tracked participants' hand movements via the computer mouse as they selected the physically larger digit from among two response options varying in both physical and numerical size. In all 3 experiments, we found a robust size congruity effect. As is usually found in studies of the size congruity effect, responses took longer when numerical and physical sizes were incongruent (e.g., 2 - 8) compared to congruent pairs (e.g., 2 - 8). We additionally found that the average computer mouse trajectories for incongruent trials were significantly pulled toward the incorrect response alternative. Distributional analyses con-

firmed that this dynamic size congruity effect was due to competition between parallel and partially active response options. To the best of our knowledge, this is the first study to use computer mousetracking to demonstrate this dynamic version of the size congruity effect.

Beyond the novelty of demonstrating the size congruity effect via computer mouse-tracking, we also demonstrated evidence for a late interaction model of the size congruity effect. Indeed, the observed trajectory patterns confirm the predictions of a dual route model of Santens and Verguts (2011), who hypothesized that the size congruity effect occurs because of dynamic competition between response options. In their model, which they called the Shared Decisions Model, physical and numerical inputs from stimuli enter two functionally independent pathways. In a physical comparison task such as ours, the representation of physical size is a task-relevant path, whereas the representation of numerical magnitude is a task-irrelevant path. According to the model, these paths interact at the decision level, with the correct response being chosen as the result of a race between rising activations for each of the two potential response nodes (either left - larger or right - larger). The hand trajectory patterns we observed in Experiments 1 and 2 provide further evidence in favor of this model, as incongruent trials are significantly pulled toward the incorrect answer compared to congruent trials. This smooth, graduated pattern of trajectories is typically interpreted as dynamic competition between parallel and partially active response options (Spivey, 2007).

Further evidence in favor of the late interaction model of the size congruity effect comes from the effects of numerical distance that we observed in Experiment 2. Numerical distance usually interacts with physical/numerical size congruity in the following manner: as numerical distance between digits increases, the size congruity effect increases (Schwarz & Ischebeck, 2003; Santens & Verguts, 2011). In their dual route model, Santens and Verguts (2011) predicted that this modulation of the size congruity effect is due to the processing of physical size and numerical magnitude in independent pathways. When the to-be-compared digits are farther apart, their numerical magnitudes are easier to compare (Moyer & Landauer, 1967). Hence, the decision node that is fed information from the numerical magnitude pathway is highly activated. This means that for incongruent trials, it takes longer for the activation in the correct decision node to “win” over the incorrect decision node. Moreover, this model predicts that the farther apart the two digits are numerically, the harder it is for the correct decision to win. Thus, one should see a monotonic increase in the size congruity effect as numerical distance increases. This is exactly what we found. Not only did the movement time differences between incongruent and congruent trials show a monotonic increase with numerical distance, additionally we saw a similar monotonic increase in trajectory complexity. That is, the trajectory patterns showed increased competition effects as numerical distance increased. These results lend further support for a late interaction model.

Finally, in Experiment 3, we tested against the possibility that the speeded mouse initiation instructions of Experiments 1 and 2 might be unfairly biasing the results in favor of the late interaction account. The explanation of such a bias is that if size congruity effects are truly isolated to early, pre-motor representational stages, the 400 ms threshold for mouse movement might force participants to begin moving the computer mouse before the early representational conflict was resolved. This would then cause the representational conflict to feed into the response trajectories, which might then appear incorrectly as response

competition. To test against this explanation, we removed the speeded initiation instruction and simply asked participants to respond quickly and accurately. The results mirrored those of Experiments 1 and 2, where size congruity effects were critically reflected in the mouse movement times, indicating that the effects of congruity were temporally spread throughout the manual response process (e.g., Buc Calderon et al., 2015). It is perhaps interesting that we did not observe differences in initiation times in Experiment 3. However, we do not think this null effect particularly clouds our present interpretation of the data. It could be the case that with our sample size, the small effects of congruity on initiation time could not be detected. Nonetheless, we were able to detect rather large effects of congruity on movement duration, which is the critical piece of evidence in favor of the late interaction account.

In summary, we believe the present work lends solid support to a late interaction account of the size congruity effect. However, it is worth noting that there could be alternative ways to conceptualize the debate about the origins of the size congruity effect. For example, it could be the case that the nature of the representational conflict might be better reflected via a hybrid model that includes both early and late interactions between physical and numerical size. This is not out of the question, as previous work has found both early and late interaction effects in electrophysiological data (Cohen Kadosh et al., 2007). Also, there are a number of topics in numerical cognition that are well-explained by hybrid models, such as the holistic/componential debate in fractions (e.g., Meert, Grégoire, & Noël, 2009; Faulkenberry & Pierce, 2011) and multi-digit numbers (e.g., Nuerk, Weger, & Willmes, 2001; Zhou, Chen, Chen, & Dong, 2008; Moeller, Fischer, Nuerk, & Willmes, 2009). At present, however, no such hybrid model has been elaborated for the size congruity effect, so such questions remain a promising area of future research.

More generally, we believe that the present data add to the growing body of literature that investigates numerical cognition using the computer mousetracking technique (e.g., Fischer & Hartmann, 2014; Faulkenberry, 2014; Marghetis et al., 2014; Faulkenberry et al., 2015). This approach of studying cognitive processing via tracking manual hand movements has been fruitful in solving problems in stereotype formation (Freeman & Ambady, 2009), language comprehension (Spivey et al., 2005), memory (Abney, McBride, Conte, & Vinson, 2014; Papesh & Goldinger, 2012), and face processing (Freeman & Ambady, 2011b; Hehman, Carpinella, Johnson, Leitner, & Freeman, 2014).

Altogether, the present data provides the first demonstration of the size congruity effect in computer mouse trajectories. By tracking hand movements through recording the positions of the computer mouse during participants' responses to a physical comparison task, we showed that the size congruity effect arises as dynamic competition between parallel and partially active response options. Further, we showed that as numerical distance increases, these competition effects increased. These data provide support for a late interaction model of the size congruity effect.

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