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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 mouse tracking 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 sizes 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.

The size congruity effect 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; Santens & Verguts, 2011; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003). 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 magnitudes 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.

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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, 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 sizes 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 and 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 (Faulkenberry, 2014; Faulkenberry, Montgomery, & Tennes, 2015; Marghetis, Núñez, & Bergen, 2014; Santens, Goossens, & Verguts, 2011; Song & Nakayama, 2008). The use of computer mousetracking to study cognitive processes in numerical cognition has received interest as of late (Faulkenberry & Rey, 2014; Fischer & Hartmann, 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 sizes (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 sizes 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.

1. Experiment 1

The purpose of Experiment 1 was to see how the size congruity effect mapped onto a computer mousetracking task and subsequently