

Reaching Into Response Selection: Stimulus and Response Similarity Influence Central Operations

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To behave adaptively in complex and dynamic environments, one must link perception and action to satisfy internal states, a process known as response selection (RS). A largely unexplored topic in the study of RS is how interstimulus and interresponse similarity affect performance. To examine this issue, we manipulated stimulus similarity by using colors that were either similar or dissimilar and manipulated response similarity by having participants move a mouse cursor to locations that were either close together or far apart. Stimulus and response similarity produced an interaction such that the mouse trajectory showed the greatest curvature when both were similar, a result obtained under task conditions emphasizing speed and conditions emphasizing accuracy. These findings are inconsistent with symbolic look-up accounts of RS but are consistent with central codes incorporating metrical properties of both stimuli and responses.

Public Significance Statement

To perform most tasks, our cognitive system must link incoming sensory information with an appropriate action (e.g., depressing the accelerator when a traffic light turns green), a process known as response selection. In this study, movements of a computer mouse were affected by both the similarity of the possible stimuli and the similarity of the possible responses, suggesting that metrical information from input and output processes is present during response selection. These results run counter to traditional theories of response selection and help inform theories of human performance.

Keywords: mouse tracking, cognition, response selection, similarity, choice-reaction time (RT) task

Performing a goal-directed action, even one as simple as picking up a can of soda, requires the precise coordination of perceptual-motor processes. Consider, for example, a situation in which you reach for your can of soda among many other cans that belong to other people. This task requires distinguishing your soda from

other objects, including similar cans, and then selecting a motor program that avoids any obstacles on the way to your soda. Thus, this type of flexible, goal-based behavior requires the ability to quickly translate incoming sensory information into the appropriate action in the face of other competing possible actions, a process known as RS.

RS has traditionally been conceived of as an information processing stage distinct from stimulus identification and response initiation (Sanders, 1967; Sternberg, 1969). Although there have been a variety of formulations regarding the exact number and nature of the stages through which information flows (Sternberg, 1969), early models of information processing hold that these stages are discrete, a basic notion that dominates accounts of RS. Discrete stage models hold that processing for one stage does not begin until the preceding stage is complete. Such models continue to provide popular accounts of the performance on choice reaction time (RT) tasks (i.e., tasks that require mapping a stimulus to a particular response; e.g., Anderson et al., 2004; Meyer & Kieras, 1997; Pashler, 1994; Salvucci & Taatgen, 2010). For example, the

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widely cited response-selection bottleneck model (Pashler, 1994) posits that RS processes receive the output of stimulus classification processes and translates these into an abstract response code. This means that, as in other discrete stage models, features of the stimulus and response are not represented at the same stages (Pashler, 1994; but see, Hommel, 1998). A variant of this perspective is a symbolic production system (Adaptive Control of Thought-Rational (ACT-R); Anderson et al., 2004; Anderson & Lebiere, 1998) in which RS takes place through the implementation of production rules that activate representations of potential responses in working memory based on the identity of the stimulus. In these models, RS operates over abstract symbols rather than modal representations that preserve irrelevant metrical properties (i.e., relating to scalar feature values as opposed to nominal or categorical information; see, e.g., Barsalou, 2008).

An alternative approach to explaining interactions between stimulus and response features abandons the requirement that stages must be completed before others begin and instead emphasizes the continuous dynamics of real-time action. These continuous models stress the overlap between perceptual and motor processes as activation cascades from one process to another. Such models propose that the output of a process is continuously available to subsequent or concurrent processes (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen & Schultz, 1979; McClelland, 1979). Thus, information from an early process (e.g., stimulus classification) can serve as input to a later process (e.g., RS) before the early process has completed.

Historically, RS has been studied with experimental paradigms in which a discrete motor response (such as a button press) is made in response to a specific stimulus in the environment. Patterns of accuracy and RT are used to infer how perceptual processes map to discrete motor responses (Hazeltine & Schumacher, 2016). One limitation of these dependent measures is that they assess only the final outcome of task operations, imposing discreteness on the underlying processes that may be better characterized as continuous (Spivey, Grosjean, & Knoblich, 2005). That is, by considering only the end result of RS (i.e., what button was pressed and when), this approach may be insensitive to the underlying dynamics. Moreover, the task demands may encourage participants to adopt strategies that mimic discrete stage models. When the desired responses are small movements (e.g., button presses when the finger is initially resting on the button), participants may necessarily withhold engaging in any motor processing before perceptual processes have achieved a relatively stable state.

Computer-Mouse Tracking and the Dynamics of RS

Recently, behavioral methodologies have been developed that emphasize the dynamics of RS (Duran, Dale, & McNamara, 2010; Spivey et al., 2005). For example, by tracking the pixel-coordinate trajectories of computer-mouse movements as the cursor is moved to a presented stimulus, one can obtain an action-based index of the coactivation of stimulus-response (S-R) alternatives (Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2006, 2008, 2009; Spivey et al., 2005). The continuous nature of the movement trajectories can provide more direct evidence for competition between response options that cannot be easily detected when RT is

the primary measure (Eriksen & Eriksen, 1974; Miller, 1988, 1993).

In support of this method, several studies link the neural dynamics that underlie the evolution of the decision process and neural activity in motor cortex (Cisek & Kalaska, 2005; Gold & Shadlen, 2007; Tosoni, Galati, Romani, & Corbetta, 2008). Moreover, reaching movements display both attraction and repulsion to distractors during flight, consistent with the emergence of the motor program as decision processes unfold (Song & Nakayama, 2006). When competing motor commands are being generated at the same time, the observed motor movement can reflect a weighted combination of the two commands, resulting in an action that moves in the direction of a target response location or to a region in between two potential movement destinations (Cisek & Kalaska, 2005). These results have been interpreted as evidence that the moment-to-moment evolution of a cognitive decision is manifested in the real-time motor output (Gold & Shadlen, 2001). Portions of trajectories that move toward regions in between visual targets may be indicative of simultaneous partial activation of competing S-R alternatives that correspond to those targets, indicating a continuous flow of information through the system.

Spivey et al. (2005) exploited these properties of mouse tracking to show that competitor words were activated during spoken-word recognition. In their task, participants moved a mouse cursor to one of two targets on the computer screen depending on the identity of the aurally presented word. The two targets were pictures of either phonologically similar items (cohort condition; e.g., candy/candle) or dissimilar items (control condition; e.g., candy/jacket). Participants were instructed to start moving the mouse as soon as they heard the name of the object to which they should move the mouse. In the cohort condition, trajectories showed greater deviation toward the incorrect object than did trajectories in the control condition. Moreover, mouse movements in the control condition reached the target earlier than mouse movements in the cohort condition. The authors took this as evidence for continuous uptake of phonological information (but see van der Wel, Eder, Mitchel, Walsh, & Rosenbaum, 2009; and Spivey, Dale, Knoblich, & Grosjean, 2010 for their reply) as well as direct evidence of competition between phonetically similar items.

RS and Two Types of Similarity

This approach has since been adopted across a range of domains, and the experimental results have consistently demonstrated that hand movements (as measured by the trajectories of the computer mouse or other devices) systematically reflect ongoing cognitive processes in a wide range of tasks (for reviews of this literature, see Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009). Much of this work has used identification tasks (i.e., visual world paradigm) focusing on an examination of the curvature of mouse-movement trajectories when there is a competing item present in the display compared with when it is not. Typically, these experiments report that perceptual or more abstract representational similarity between a target stimulus and a competitor produces attraction to the competitor as subjects ultimately move to the correct location in a multiple-object display (e.g., Farmer, Anderson, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Freeman, Dale, & Farmer, 2011; Song & Na-

kayama, 2009). This pattern of data is taken as evidence of coactivation between the possible responses as the RS processes unfold over time, and the magnitude of curvature toward a distractor can serve as a graded index of the degree to which the competitor was active across the decision process.

Such findings suggest that the degree of perceptual similarity among multiple items in an environment produces graded attraction toward a competitor during a movement to a correct location. But, just as objects in a display can vary in the degree of similarity they share with a target stimulus, movements themselves can be more or less similar to each other, and this affects motor programming processes (Ghahramani, Wolpert, & Jordan, 1996; Rosenbaum, 1980). In contrast to the effects of *stimulus* similarity, little experimental work has been conducted on the manner in which *response* similarity affects RS and reaching. In the present study, we use the term “response similarity” to refer to the nearness of the possible reaching targets in space. One exception (McDowell, Jeka, Schoner, & Hatfield, 2002) reported that RTs were faster when reaching to response locations that were close together in space compared with locations that were far apart. One interpretation of this result is that similar response locations involve overlapping response codes, and this overlap can reduce the work required by RS processes.

Thus, previous work has demonstrated that different types of similarity can have divergent effects. Similarity among the stimuli, in general, hurts performance by making the discrimination more perceptually difficult whereas similarity among the responses can facilitate performance by increasing the overlap among motor programs. In this way, the available data suggest that the two forms of similarity affect separate processes.

However, if RS takes place at a level of representation that includes both stimulus and response information, then stimulus and response similarity should produce an interaction. That is, if stimulus and response similarity increase competition between response options (Farmer, Anderson, et al., 2007; Farmer, Cargill, et al., 2007; Freeman et al., 2011; Spivey et al., 2005; Wifall, McMurray, & Hazeltine, 2014), then an overadditive interaction should be observed; decrements in performance associated with stimulus similarity should be greater when there is more similarity among the possible responses. This is predicted because greater stimulus similarity should lead to the coactivation of S-R alternatives, and this coactivation should be more robust when there is more overlap among the motor programs associated with the candidate responses. In short, having both similar stimuli and similar responses should elicit the most competition between the S-R alternatives.

Thus, determining how stimulus and response similarity affect performance, and whether the two factors interact, will have broad implications for models of RS. Specifically, continuous models provide a straightforward way to conceptualize and model differences in mouse trajectories that vary systematically as a function of both stimulus and response similarity. According to such accounts, evidence accrues for different response options over time, and differences in movement trajectories that are made during the decision process reflect the weighted coactivation or blending of multiple motor responses that correspond to different response options, removing the theoretical necessity of a discrete “stage” of RS.

In general, a choice-RT task is one where a particular stimulus (out of a larger stimulus set) is paired with a particular response (out of a larger response set) and the location of the stimulus and response are separate (e.g., a visually presented green square is associated with a right-hand button press). Given the success of the mouse tracking tasks at revealing competition during central operations, we sought to apply this methodology to probe RS processes during a choice-RT task. Manipulations of stimulus similarity have been used with mouse-tracking tasks to reveal coactivation of representations during RS. A critical indicator of RS processes is interactions between stimulus and response properties (Simon, 1969; Simon & Rudell, 1967). Thus, we wished to extend the established mouse-tracking approach by manipulating both stimulus and response similarity and determining whether these factors interacted in measurements of curvature. The implications of the results provide a deeper understanding of central operations and the importance of considering the relationship between the stimulus and response features of a task.

Goals of Current Work

The goal of this study is to explore how stimulus and response similarity impact RS during a choice-RT task. Previous studies (e.g., Fitts & Seeger, 1953; Simon, 1969; Simon & Rudell, 1967) have shown that stimulus and response properties interact when there is a correspondence between them (e.g., a spatial relationship). To account for such interactions, dual-route models are often invoked in which stimulus information automatically activates representations of response options through a direct pathway that bypasses standard RS stages (Eimer, Hommel, & Prinz, 1995; Hommel, 1998; Kornblum, Hasbroucq, & Osman, 1990; Lien & Proctor, 2002). In principle, these dual-route models can account for a broad array of empirical phenomena, including the Simon effect (De Jong, Liang, & Lauber, 1995), the Stroop effect (Lu & Proctor, 1995), and reductions in dual-task costs (Lien & Proctor, 2002).

In the present experiments, we examine how relational properties among stimuli and among the responses affect mouse trajectories when there is no correspondence (i.e., no systematic relationship) between the stimuli and responses. A finding that stimulus and response properties produce an interaction in curvature would be difficult to account for with dual-route accounts, because it would be unclear what information was conveyed along the direct route to produce the interaction. That is, existing studies examining how stimulus and response properties interact have focused on manipulations that affect the correspondence between relevant or irrelevant stimulus properties and response properties. Such interactions are accommodated by dual-route models because it can be assumed that the correspondence leads to activation of a response via the direct pathway. However, in the present study, we manipulate the similarity of the stimuli by varying the distance of them in color space, and we manipulate the similarity of the responses by varying the ending locations of mouse movements. Because there is no correspondence between the varying stimulus property, color, and a varying response property, location, there should be no interactions between manipulations of these two factors according to symbolic S-R translation models, even when dual routes are included. In contrast, a continuous model based on representations that preserve metrical properties predicts that the

two forms of similarity should interact, given that the representations integrate stimuli and response properties. Therefore, S-R competition should be greatest when both the stimuli and responses are similar (see below). Such a finding would present a novel behavioral phenomenon and provide evidence that RS takes place on representations that include metrical information from both the stimuli and responses.

General Method

To examine how RS processes unfold in the face of metrical manipulations of stimulus and response similarity, we modify the mouse-tracking procedure so that it is more analogous to a choice-RT task. In typical mouse-tracking experiments, mouse movements are made toward one of several simultaneously presented stimuli. Thus, the stimuli and possible responses are the same in such cases, and the critical measurement is the amount of deviation toward a particular irrelevant stimulus/incorrect response when the ultimately correct response is executed. However, in the present study, we employ a design that separates the cue that indicates which response should be made from the possible response locations, as in a typical choice-RT task. That is, we display all of the possible response locations on every trial, but there is only a single cue (the presented stimulus) indicating the correct target location and this cue is not presented at any of the response locations. There are a small number of possible cues (4), and participants must remember the assignments of the cues to these unlabeled location boxes, just as in choice-RT tasks in which participants must remember the S-R mapping. With this approach, all possible response locations must be displayed on every trial so that it is necessary to decode the identity of the stimulus to determine which response to make. The cue is placed at the same location on every trial. This location is distinct from the response locations, such that deviations toward the cue always result in

curvature toward the center of display regardless of the appropriate response or identity of the cue (Figure 1). In sum, the procedure is similar to typical mouse-tracking experiments in that participants are required to move the mouse from a starting point to a target location based on a presented cue. However, the procedure is similar to choice-RT experiments in that the cue is presented in a distinct location from the responses, whose locations are consistently mapped to cues throughout the experiment.

Using this approach, we report three experiments that probe whether central operations are sensitive to metric influences of the stimuli and responses by determining the degree to which stimulus (i.e., color similarity) and response similarity (i.e., location similarity) affect computer-mouse trajectories. Experiment 1a emphasizes the speed of the response and Experiment 1b emphasizes response accuracy. Experiment 2 is conducted to rule out the possibility that the results from the first two experiments were driven solely by the speed of perceptual processing. All three experiments followed the same general procedure described below.

Previous computer-mouse tracking experiments have been designed to encourage participants to initiate their movement before the cue appears (e.g., Huette & McMurray, 2010; Spivey et al., 2005) to ensure that the target would be selected during the movement. However, this procedure is unlike many real-world tasks in which movements are initiated after or while the stimulus is perceived. Also, the instruction to initiate the response before the onset of the cue differs from a standard choice-RT task. Therefore, in the present experiments, participants were instructed to initiate their movements once the cue was presented, as in a typical choice-RT task and in other reaching tasks (e.g., Buetti & Kerzel, 2009; Kerzel & Buetti, 2012).

We were concerned that participants might adopt different strategies depending on the speed/accuracy demands of the task. For

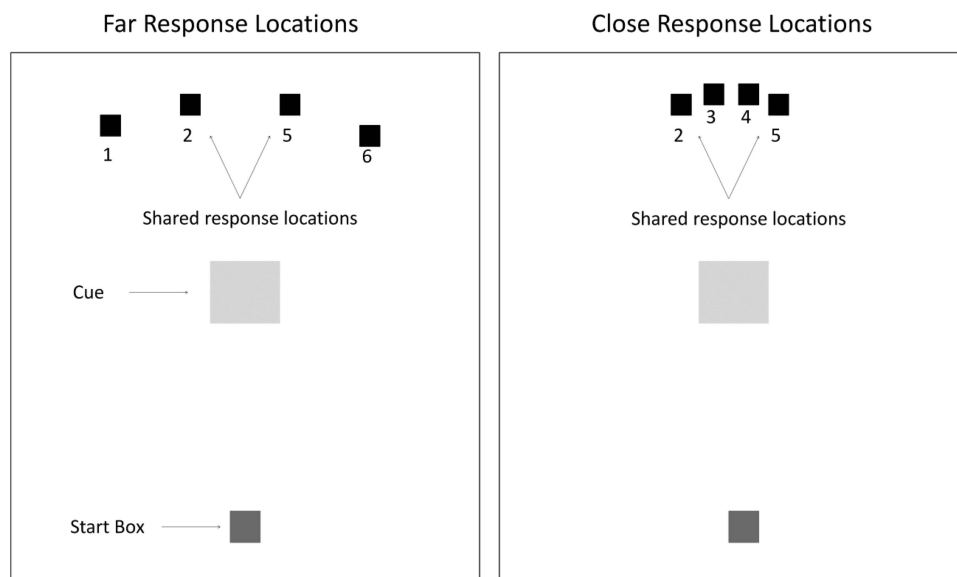


Figure 1. The layout of the display seen by participants, including the start box and response locations. Locations 2 and 5 are in the same spatial locations across close and far response conditions. Note that this is not drawn to scale.

example, if participants are pressured to be very accurate, they might not begin their movements until after completing the motor programming process. This, in turn, might prevent the effects from being evident in the trajectories because the conflict would be resolved before the movements were initiated. Thus, we conducted two versions of our initial experiment, one in which participants were required to complete their movements quickly and one in which they were required to make the movements accurately.

For each experiment, two factors were manipulated between subjects: the similarity of the stimuli and the similarity of the responses, resulting in a 2×2 design: stimulus close, response close (SC-RC); stimulus close, response far (SC-RF); stimulus far, response close (SF-RC); and stimulus far, response far (SF-RF). Similar stimuli and similar responses are referred to as close and dissimilar stimuli and dissimilar responses are referred to as far, to parallel the response locations that were either close or far in proximity. We employed a between-subjects design to ensure that participants were not exposed to variable S-R mappings across conditions, which has been shown to be detrimental to performance (e.g., Schneider & Shiffrin, 1977).

The stimuli were presented and responses collected using PC computers running Visual Basic software. The cues were presented as filled color patches with the size of 100×100 pixels on a black background. The red-green-blue (RGB) values of the far cues were: 237, 28, 36 (red), 255, 242, 0 (yellow), 34, 177, 76 (green), 0, 0, 255 (blue); the RGB values of the close cues were: 74, 128, 182 (blue), 35, 134, 167 (bluish green), 39, 137, 145 (greenish blue), 70, 138, 120 (green).

The layout of the display can be seen in Figure 1. The start box was gray and had a size of 25×25 pixels. Each of the four response boxes was equidistant from the center of the start box (788 pixels away). The x and y coordinates for the close condition were: 485, 129; 579, 118; 661, 118; 755, 129 (with participants sitting 66 cm away from the screen this resulted in a visual angle of 2.51° between close boxes); for the far condition, they were 230, 222; 485, 129; 755, 129; 1010, 222 (with participants sitting 66 cm away from the screen this resulted in visual angle of 7.14° between far boxes), respectively. The mapping of color to location was constant for each participant. For instance, in the SF-RF condition, the color red was associated with the left-most response, yellow the second left-most response, green the second-most right response, and blue with the right-most response. Across the two response conditions there are a total of six different locations, with Locations 2 and 5 shared by both the close and far conditions. This allowed us to restrict the analyses to responses that share the same spatial location. To aid in performance, the response locations were marked by small boxes (10×10), which remained visible for the entirety of the experiment.

A trial proceeded as follows: upon moving the cursor into the start box at the bottom center of the screen, participants were instructed to not move the cursor for 1,000 ms at which point the cue was displayed. Participants then moved the cursor to one of the four response locations that corresponded with the identity of the cue. Participants moved the cursor using the computer mouse with their preferred hands. After each trial, we provided feedback as to where the participant had responded and location of the correct response. This was done in part because participants were not told which cue corresponds with which response location prior to the beginning of the experiment, thus emphasizing the learning component of the

task. To begin the next trial, the participant had to move the cursor into the start box and keep it stationary for 1,000 ms, at which point the stimulus was presented.

Each block consisted of 32 trials with each possible cue presented an equal number of times in a random order. Two warm-up trials were added to the beginning of every block. There were a total of 20 identical blocks, the first of which was excluded from the analysis. In Experiment 1a, we limited the amount of time available for subjects to complete the response in order to encourage them to move while RS processes were still unfolding. This procedure made the task fairly difficult, and subjects produced trajectories that did not terminate near the correct location on a substantial proportion of trials. Many of these trials were ambiguous regarding the response, given that the endpoint of the movement was between two potential locations when the time-out occurred. To address this concern, we report the results from the experiments using both liberal and conservative criteria for assessing accuracy, and find a similar pattern of results across both sets of analyses. Moreover, in Experiment 1b no time pressure was imposed on participants, but responses were made by clicking the mouse within a response box, thereby eliminating ambiguity regarding the correct response locations. This design allowed us to consider how task demands (accuracy vs. speed) influence the movements.

Experiment 1a: Time Pressure

The purpose of Experiment 1a was to assess how stimulus and response similarity affected performance in a mouse-tracking experiment. Specifically, we sought evidence for coactivation of representations as indexed by increased curvature. Moreover, we wished to determine how this competition was affected by similarity among the stimulus and response alternatives.

Method

Participants. A total of 85 University of Iowa undergraduates participated for course credit. We dropped five participants because of poor behavioral performance (see the Results section for criteria), which resulted in 20 in each condition. Ages ranged from 18–23.

Procedure. The experiment followed the procedure presented in the General Method section. Participants had 930 ms to make their response. At the end of 930 ms, the current location of their cursor was considered the final location.

Results

Trials in which the initiation time (IT; time from when the stimulus appeared to when the mouse cursor had an acceleration of greater than 2 pixels/ms) was less than 50 ms or the movements resulted in a final position more than 45 pixels away from the correct location were removed from the analyses. The neighboring boxes were 95 pixels away in the near response condition so 45 pixels were chosen as the cutoff to ensure the final position was closer to the correct location than to any other location. No trials were excluded because of movement time (MT; time from the initial movement until when their velocity dropped below 2 pixels/ms), but the movement was considered complete 930 ms after the

presentation of the stimulus. These criteria ensured that participants were making movements toward the correct location and not settling in between two of the locations. This was a difficult task, given the time pressure; these criteria eliminated 42% of the data, but the same pattern of results was observed when more lenient criteria were used.¹ We report the data derived using the strict criteria because these trials most clearly correspond to correct responses. Moreover, Experiment 1b imposed different constraints and produced very similar trajectories, so we are confident that the observed patterns do not stem from the trimming procedure.

Movement trajectories. To evaluate if stimulus and response similarity interacted we first considered the time course of the movement. Each trajectory was first aligned to a common x , y starting position and then each trial was normalized by resampling at equal time-spaced values (101 time slices) and computing, by means of linear interpolation, the corresponding x and y coordinates (similar to Spivey et al., 2005). The normalized trajectories were then averaged for each participant. All of the analyses reported below were restricted to the shared locations (Figure 2).

First, we assessed the overall amount of curvature toward the center by calculating the area under the curve for each trajectory (Miles & Proctor, 2011). This analysis focused on the trajectories to locations that were shared across conditions, so we use the subscript “shared” to indicate that the reported statistics are based on only these trials. Curvature was submitted to a 2×2 (Stimulus \times Response) between-subjects analysis of variance (ANOVA) where stimulus, $F_{\text{shared}}(1,76) = 4.85$, $\eta_p^2 = .060$, $f^2 = .064$, $p = .031$, response, $F_{\text{shared}}(1,76) = 17.00$, $\eta_p^2 = .183$, $f^2 = .224$, $p < .001$, and the interaction were significant, $F_{\text{shared}}(1,76) = 4.73$, $\eta_p^2 = .058$, $f^2 = .062$, $p = .033$. The overall curvature data mirror the error data in that the SC-RC condition resulted in more curvature toward a distractor than any of the other conditions (Figure 3A), as revealed by paired-samples t -tests: SC-RC versus SC-RF

$t(38) = 3.93$, $d = 1.28$, $p < .001$; SC-RC versus SF-RC $t(38) = 2.77$, $d = .90$, $p < .01$; SC-RC versus SF-RF $t(38) = 3.79$, $d = 1.23$, $p < .001$. Critically, the interaction suggests that when both the stimulus and response dimensions were close, more competition between the representations resulted in an overadditive increase error and curvature. The overadditive interaction between stimulus and response similarity indicates that response similarity had a much stronger effect on curvature when the stimuli were similar than when they were dissimilar. This suggests that when both stimuli and responses are close, there is more competition among S-R pairs.

To identify the point within the movement at which the differences between conditions could be first detected, we divided the temporally normalized movement into 10 equally spaced (in time) points and the deviation from straight at each time slice was submitted to a 2×2 between-subjects ANOVA. To account for where the movement had been, all the previous time slices up to that point in time were used as covariates. Both the fifth and sixth time slices had a significant Stimulus \times Response interaction, $F_{\text{shared}}(1,73) = 10.16$, $\eta_p^2 = .122$, $f^2 = .139$, $p = .002$, $F_{\text{shared}}(1,72) = 7.11$, $\eta_p^2 = .090$, $f^2 = .099$, $p = .009$, suggesting that the SC-RC condition was still resolving competition later on in the movement compared with the other conditions.

For the RC conditions the shared locations were the extremes (i.e., the leftmost and right-most locations), whereas for the RF conditions they were not. Thus, a shared location in the close conditions has all of its competitors on one side of it, whereas a shared location in the far conditions has two competitors on one side and one competitor on the other (see Figure 1). If the increase in curvature for the RC conditions (and the difference between the SC and SF conditions) was solely due to the location of the competitors, then in the RF conditions there should be more curvature in the SC-RF condition than the SF-RF condition at the endpoint locations (Locations 1 and 6). To rule out that the location of the competitors lead to the interaction, we analyzed curvature to the endpoints (Locations 1 and 6) for the RF conditions. There was no difference in curvature between the SC-RF and SF-RF for Locations 1 or 6, $t_s < 1$, and the mean difference between close and far stimuli for the RF conditions was 10 pixels compared with 66 pixels difference between close and far stimuli in the RC conditions. Thus, the location of the competitors does not affect the difference between the close and far stimuli. Rather, the spatial distance between response locations appears to be the critical factor driving the interaction.

Can the interaction between stimulus and response similarity on curvature result from competition among central codes? The SF-RC condition had the second-most total curvature and had the same initial curvature as the SC-RC condition (see Figure 3B). Therefore, it could be the case that when the responses were close participants adopted the strategy of moving straight toward the center of the set of possible responses before deciding on the

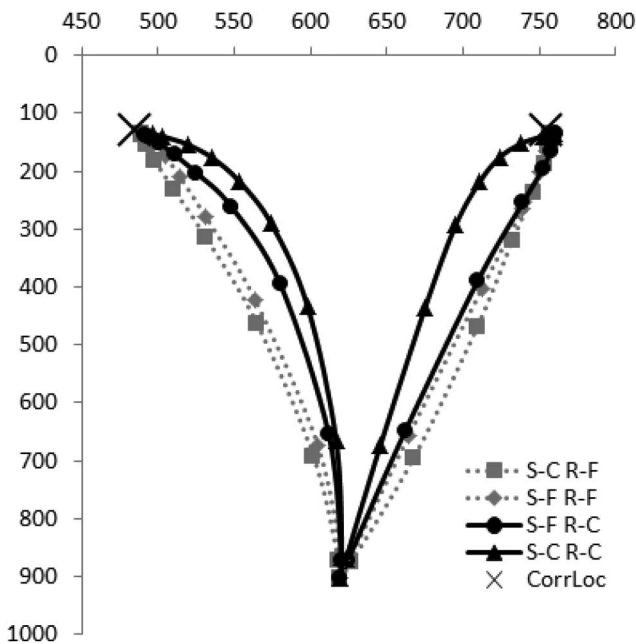


Figure 2. Mean trajectories across all conditions for Locations 2 and 5.

¹ For the more lenient criteria we used a 95 pixel cutoff from the final mouse position to the correct target. This resulted in only throwing out 24% of the trials. Even with this more lenient criterion the stats and pattern of data are nearly identical to the stricter criterion (reported in the paper). The only difference was in the 2×2 curvature analysis where the effect of stimulus was no longer significant with the more lenient criteria, $F_{\text{shared}}(1,76) = 2.16$, $\eta_p^2 = .028$, $p = .146$.

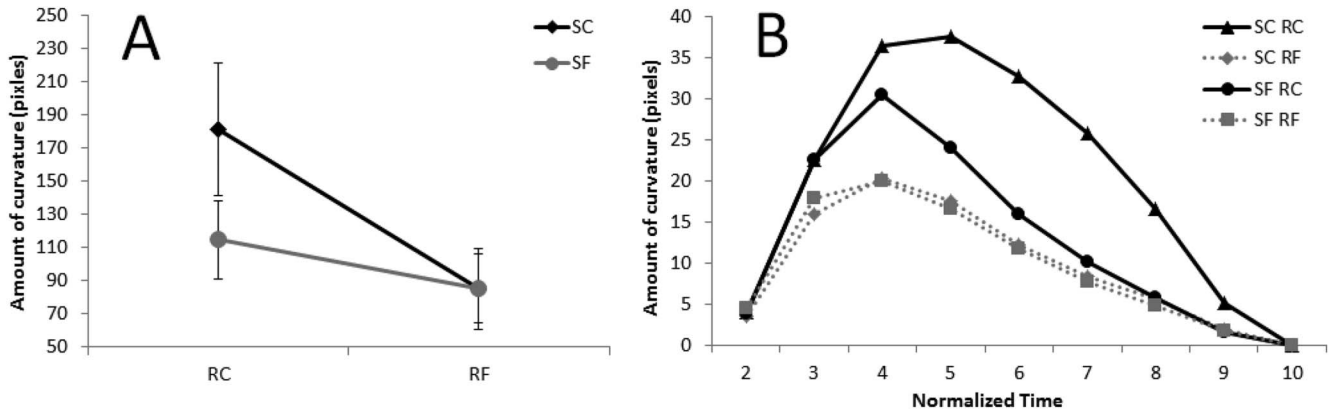


Figure 3. (A) Total curvature across conditions. (B) Deviation from a straight path \times normalized time. S-C = stimulus close, R-F = response far. Error bars are SEMs.

target, causing more curvature in the mouse trajectory. The implication of such an account is that the angle of the initial movement should not differ for the two shared locations when the responses are close, because movements to either location would begin by moving toward the center.

To test this, we identified the time point at which the angle of movement was statistically different for movements toward Locations 2 and 5. Each trial's trajectory was resampled at 40 Hz, and the angle of the movement was computed at each time slice. The mean angles were compared at each time slice for movements to Locations 2 and 5. The results indicated differences in the angles of movement were found relatively early on (325 ms) for the SC-RC and SF-RC, SF-RF conditions and at 400 ms for the SC-RF condition. Thus, even though the SC-RC condition displayed the most curvature, the trajectories to the different targets diverged as early as the other conditions, suggesting that the interaction found in the curvature analysis was not the result of participants in the SC-RC condition using a strategy in which they moved straight ahead at the onset of the stimulus and began deviating toward the target later once the stimulus cue had been categorized. While participants may indeed adopt such a strategy, it did not appear to be used to a greater degree by those in the SC-RC condition; the trajectories differentiate as early in the SC-RC condition as any in the other conditions.

To test whether the differences in curvature resulted from some participants in the SC-RC condition moving forward before choosing a target, we removed individuals who did not show significant differences in the angle of their movement to Targets 2 and 5 in the first 10% of the normalized movement and reran the same Stimulus \times Response \times Time analysis. We did this to test whether participants who produced highly curved trajectories (potentially by deciding late) were driving the difference between SC-RC and SF-RC conditions. This trimming procedure left 16 participants in the SC-RC condition, nine participants in the SF-RC condition, 11 participants in the SC-RF condition, and 17 participants in the SF-RF condition. Even with only these participants, the Time \times Stimulus \times Response interaction remained significant, $F_{\text{shared}}(8,472) = 4.77$, $\eta_p^2 = .078$, $f^2 = .085$, $p < .001$, and the Stimulus \times Response interaction was significant for the total amount of curvature, $F_{\text{shared}}(1,59) = 6.22$, $\eta_p^2 = .095$, $f^2 = .105$, $p = .015$.

In sum, when both dimensions were close, there was more curvature and error in the trajectories. This finding provides evidence that stimulus and response similarity affect performance in a way that indicates that metrical properties of both the stimuli and responses are represented during RS. A novel aspect to our findings was that response similarity increased difficulty, as the RC conditions produced the most curvature. We propose that competition among the S-R alternatives is sensitive to both stimulus and response features: When either the stimulus alternatives or response alternatives were "far" from each other, the overall competition is less strong, as evidenced by less error and less curvature in the trajectory. This finding is inconsistent with feed forward models of RS and underscores the role that the relationship between the stimulus and response properties plays in RS processes.

ITs and MTs. When appropriate, the analyses were performed two ways: data averaged across all locations (F_{all} or t_{all}) and data averaged across only the shared locations (F_{shared} or t_{shared}). We performed the shared-condition analyses because this provides a measure of how the different conditions affected the trajectory of the movement to the same spatial locations.

IT was submitted to a 2×2 (Stimulus Similarity \times Response Similarity) between-subjects ANOVA. There was a main effect of stimulus similarity, $F_{\text{all}}(1,76) = 5.58$, $\eta_p^2 = .068$, $f^2 = .073$, $p = .020$, $F_{\text{shared}}(1,76) = 6.21$, $\eta_p^2 = .076$, $f^2 = .082$, $p = .015$ as IT was faster for far stimuli than close for all locations ($M_{\text{far}} = 320$ ms, $M_{\text{close}} = 346$ ms) and shared locations ($M_{\text{far}} = 320$ ms, $M_{\text{close}} = 349$ ms), and a main effect of response similarity, $F_{\text{all}}(1,76) = 9.61$, $\eta_p^2 = .112$, $f^2 = .126$, $p = .003$, $F_{\text{shared}}(1,76) = 8.73$, $\eta_p^2 = .103$, $f^2 = .115$, $p = .004$, as far responses had a slower IT than close for all locations ($M_{\text{far}} = 350$ ms, $M_{\text{close}} = 316$ ms) and shared locations ($M_{\text{far}} = 352$ ms, $M_{\text{close}} = 318$ ms), but the interaction was not significant, $F_{\text{all}} < 1$, $F_{\text{shared}}(1,76) = 1.05$, $\eta_p^2 = .014$, $f^2 = .014$, $p = .309$ (Table 1 presents the means for the individual conditions). The similar pattern of data between shared and all locations indicates that IT to the shared locations was no different than when considering all the locations.

MT was submitted to an identical ANOVA. There was a main effect of stimulus similarity, $F_{\text{all}}(1,76) = 5.59$, $\eta_p^2 = .068$, $f^2 = .073$, $p = .021$, $F_{\text{shared}}(1,76) = 4.74$, $\eta_p^2 = .059$, $f^2 = .063$, $p = .033$, as MT was slower for the far stimuli compared with the close stimuli for all locations ($M_{\text{far}} = 529$ ms, $M_{\text{close}} = 505$ ms) and

Table 1
Mean Initial Times and Movement Times Across the
Four Conditions

Stimulus	Response	IT		MT (ms)	
		All (ms)	Shared (ms)	All (ms)	Shared (ms)
SC	RC	325 (10)	326 (11)	522 (11)	529 (12)
SC	RF	367 (14)	373 (15)	488 (13)	484 (14)
SF	RC	307 (10)	309 (11)	539 (9)	540 (9)
SF	RF	333 (11)	332 (11)	520 (10)	521 (10)

Note. IT = initial times; MT = movement times; SC = stimulus close; SF = stimulus far; RC = response close; RF = response far. Standard error of the mean is presented in parentheses.

shared locations ($M_{\text{far}} = 531$ ms, $M_{\text{close}} = 507$ ms), a main effect of response similarity, $F_{\text{all}}(1,76) = 6.50$, $\eta_p^2 = .079$, $f^2 = .086$, $p = .013$, $F_{\text{shared}}(1,76) = 8.56$, $\eta_p^2 = .101$, $f^2 = .112$, $p = .005$, as close responses had a slower MT compared with far responses for all locations ($M_{\text{far}} = 504$ ms, $M_{\text{close}} = 530$ ms) and shared locations ($M_{\text{far}} = 503$ ms, $M_{\text{close}} = 535$ ms) but the interaction was not significant, $F_i < 1$, $F_{\text{shared}}(1,76) = 1.36$, $\eta_p^2 = .018$, $f^2 = .018$, $p = .247$ (see Table 1 for values for individual conditions). Again, a similar pattern of data emerged for shared and all locations. The IT and MT data indicate a tradeoff such that a quicker IT resulted in a longer MT and vice versa, a pattern that is not surprising given the time pressure placed upon participants.

Experiment 1b: Accuracy

In Experiment 1a, we forced participants to make their responses within one second of the stimulus presentation to ensure that deviations in their trajectories reflected RS unfolding in real-time. That is, we discouraged participants from withholding their movements until they were completely planned. However, this instruction led to the need to reject a high proportion of movements because they were not clearly directed to one of the possible target locations (as discussed above). Therefore, to alleviate this issue, we required participants to respond by moving the mouse cursor to one of the response locations and “click” the mouse. Further, the time pressure was removed. This was done to ensure that the pattern of results found in Experiment 1a was not due to task demands. Thus, Experiment 1b sought to determine how task demands (speed vs. accuracy) affected performance, specifically with regard to the curvature of the trajectory.

Method

Participants. A total of 88 University of Iowa undergraduates participated for course credit. Eight participants were dropped due to poor behavioral performance or an inability to finish the experiment within the allotted time (60 mins). Ages ranged from 18–24 years old.

Procedure. The experiment followed the procedure presented in the General Method section with one addition. Participants were no longer under time pressure but were asked to make a response by pressing the left mouse button when the mouse cursor was over the appropriate response location. Responses outside of a response location were not accepted and the trial continued until a response

was made in one of the four response locations. Participants were instructed to respond as quickly and accurately as possible.

Results

Before the analysis, data were trimmed so that movements that had an IT less than 50 ms or greater than 1,000 ms (2%) and MT greater than 1,500 ms (7%) were removed. The percent correct was high for all of the conditions SC-RC (87%), SC-RF (86%), SF-RC (98%), SF-RF (98%). When accuracy was submitted to a 2×2 (Stimulus \times Response) between-subjects ANOVA, there was a main effect of stimulus, $F(1, 76) = 82.44$, $\eta_p^2 = .52$, $f^2 = 1.08$, $p < .001$, as close stimuli were more difficult to discriminate than far stimuli, but neither response, $F < 1$, nor the interaction, $F < 1$ were significant.

Movement trajectory. Trajectories were analyzed in the same fashion as in Experiment 1a. Overall curvature was first analyzed by submitting the data to a 2×2 (Stimulus \times Response) between-subjects ANOVA. There was a main effect of stimulus, $F_{\text{shared}}(1,76) = 20.67$, $\eta_p^2 = .214$, $f^2 = .272$, $p < .001$, of response, $F_{\text{shared}}(1,76) = 17.07$, $\eta_p^2 = .183$, $f^2 = .224$, $p < .001$, and critically, the interaction was significant, $F_{\text{shared}}(1,76) = 5.41$, $\eta_p^2 = .066$, $f^2 = .071$, $p = .023$, as the SC-RC condition had more curvature than the SF-RC condition (Figure 4A). The data suggest, as with Experiment 1a, that when both dimensions were similar there was more competition among the S-R alternatives.

We submitted every 10th time slice to a 2×2 (Stimulus \times Response) between-subjects ANOVA and to control for where the movement had been the previous time, slices were used as covariates. Time Slice 4 (approximately 40% into the movement), $F_{\text{shared}}(1,74) = 15.235$, $\eta_p^2 = .171$, $f^2 = .206$, $p < .001$, Time Slice 5, $F_{\text{shared}}(1,73) = 13.965$, $\eta_p^2 = .161$, $f^2 = .191$, $p < .001$, and Time Slice 6, $F_{\text{shared}}(1,72) = 4.816$, $\eta_p^2 = .063$, $f^2 = .067$, $p = .031$ were significant, suggesting that even during the middle of the movement there was significant competition in the SC-RC condition compared with the others.

As with Experiment 1 we wanted to rule out that the location of the competitors was not the sole driver of the interaction. When the endpoints for the SF condition were considered, there was no difference between the SF-RF and SC-RF conditions, $t < 1$, again indicating that the increase in curvature for the RC conditions was not solely the result of all the competitors being located on one side of the shared location. We also attempted to rule out that the increase in curvature for the RC conditions was not the result of a strategy of moving toward the center of the screen before making a decision, as in Experiment 1. Again, we identified the time point at which the angle of movement statistically differed for movements toward Locations 2 and 5. The pattern was similar; differences in the trajectory occurred relatively early on, 325 ms for the SF-RC condition, 375 ms for the SF-RF condition, 425 ms for the SC-RC condition, and 450 ms for the SC-RF condition. In short, even though the RC conditions resulted in the most curvature, differences in the trajectories to Targets 2 and 5 did not appear to emerge later than the other conditions. This again suggests that the interaction found in the curvature data was not due to participants deferring their choice of target until later in the movement.

Also as in the previous experiment, we removed participants who displayed the “move first, decide later” strategy from the trajectory analyses. These participants were identified as those

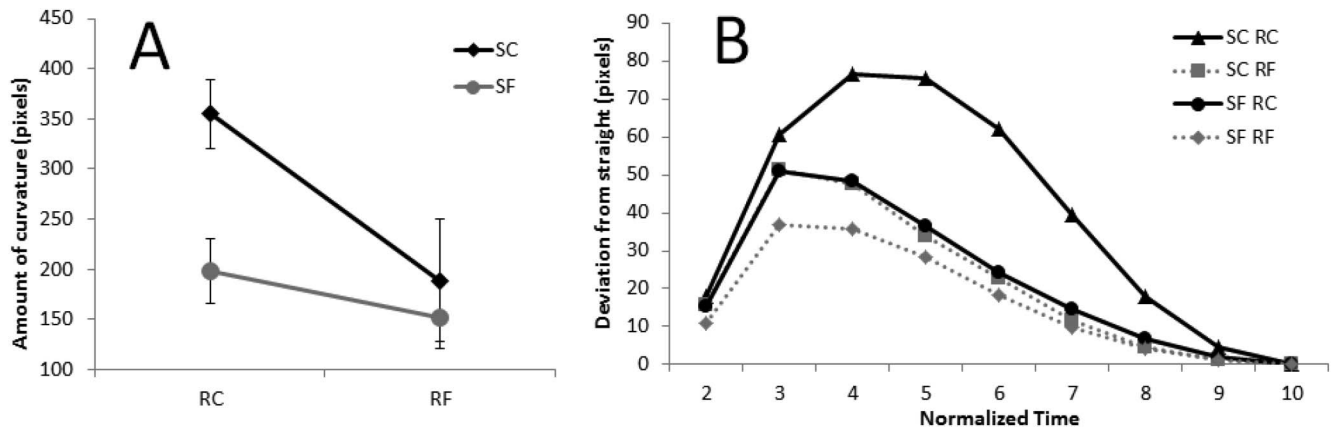


Figure 4. (A) Total curvature across conditions. (B) Deviation from a Straight Path \times Normalized Time. S-C = stimulus close, R-F = response far. Error bars are SEMs.

who did not show a difference in the angle of their movement to Targets 2 and 5 in the first 10% of the normalized movements. A total of six participants were removed from the analyses, one from the SF-RF condition and five from SC-RF condition. The Stimulus \times Response curvature interaction was marginally significant, $F_{\text{shared}}(1,70) = 3.38$, $\eta_p^2 = .046$, $f^2 = .048$, $p = .07$, though the Time \times Stimulus \times Response interaction remained highly significant, $F_{\text{shared}}(8,560) = 6.00$, $\eta_p^2 = .079$, $f^2 = .086$, $p < .001$. Thus, as with Experiment 1a, the interaction does not result from participants moving straight ahead and making their decision later.

It is worth noting that the overall magnitude of the curvature was higher in Experiment 1b than in Experiment 1a. This difference was unexpected, given the relaxation of the time pressure placed on participants. It was possible that forcing participants to be more precise might have increased the criterion threshold for which response to make. Further, having no time pressure resulted in movements that took more time to make (IT + MT). Requiring more evidence for a response to be made, along with an increase in the movement's total time might have led to prolonged competition, which led to the increase in curvature. However, this will have to be directly tested to determine if it was the case.

In sum, the data from Experiment 1b replicate those from Experiment 1a, particularly with regard to ITs and trajectory curvature. Thus, Experiment 1b provides further evidence that the interaction between stimulus similarity and response similarity on curvature did not stem from participants moving toward the center of the configuration of responses when they were under time pressure to respond. Instead, the results suggest that response competition is greatest when stimuli and response are similar across a range of task demands.

Movement timing. IT was submitted to a 2×2 (Stimulus \times Response) between-subjects ANOVA. There was an effect of stimulus, $F_{\text{all}}(1,76) = 20.40$, $\eta_p^2 = .211$, $f^2 = .267$, $p < .001$, $F_{\text{shared}}(1,76) = 21.32$, $\eta_p^2 = .219$, $f^2 = .280$, $p < .001$, as close stimuli produced longer ITs than far stimuli for all locations ($M_{\text{far}} = 338$ ms, $M_{\text{close}} = 412$ ms) and shared locations ($M_{\text{far}} = 338$ ms, $M_{\text{close}} = 419$ ms), and an effect of response, $F_{\text{all}}(1,76) = 32.86$, $\eta_p^2 = .302$, $f^2 = .433$, $p < .001$, $F_{\text{shared}}(1,76) = 34.08$, $\eta_p^2 = .310$, $f^2 = .449$, $p < .001$, as far responses produced slower ITs than close responses for all locations ($M_{\text{far}} = 404$ ms, $M_{\text{close}} = 346$

ms) and shared locations ($M_{\text{far}} = 411$ ms, $M_{\text{close}} = 346$ ms), but the interaction was not significant, $F_{\text{all}} < 1$, $F_{\text{shared}}(1,76) = 1.18$, $\eta_p^2 = .015$, $f^2 = .015$, $p = .28$ (Table 2 presents the individual values). Despite the differences in the procedures, the data mirror those of Experiment 1a.

As in the previous experiment, MT was submitted to an identical ANOVA. Unlike IT there was no effect of stimulus, $F_{\text{all}}(1,76) = 1.43$, $\eta_p^2 = .018$, $f^2 = .018$, $p = .24$, $F_{\text{shared}}(1,76) = 3.35$, $\eta_p^2 = .042$, $f^2 = .044$, $p = .071$, no effect of response, $F_{\text{all}}(1,76) = 1.70$, $\eta_p^2 = .022$, $f^2 = .022$, $p = .196$, $F_{\text{shared}}(1,76) = 3.09$, $\eta_p^2 = .039$, $f^2 = .041$, $p = .083$, and no interaction, $F_{\text{all}}(1,76) = 1.15$, $\eta_p^2 = .0287$, $f^2 = .403$, $p = .29$, $F_{\text{shared}}(1,76) = 1.18$, $\eta_p^2 = .022$, $f^2 = .022$, $p = .281$ (see Table 2 for individual values). The data suggest that the pattern observed in MT for Experiment 1a appears to result from the time-pressure demand.

Experiment 2: Size Discrimination

Experiments 1a and 1b demonstrated that endpoint error and trajectory curvature are greater when both the stimuli and responses are similar. However, one consequence of the stimulus similarity manipulation was that conditions with similar stimuli were more difficult (because perceptual discrimination was more difficult). Thus, it is an open question as to the cause of the interaction, which might have resulted from the similarity manip-

Table 2
Mean Initial Times and Movement Times for All Four Conditions Across All and Shared Locations

Stimulus	Response	IT		MT	
		All (ms)	Shared (ms)	All (ms)	Shared (ms)
SC	RC	378 (9)	380 (9)	820 (29)	862 (36)
SC	RF	447 (21)	459 (19)	752 (42)	756 (48)
SF	RC	314 (12)	313 (12)	759 (24)	769 (24)
SF	RF	362 (12)	363 (12)	769 (25)	763 (25)

Note. IT = initial times; MT = movement times; SC = stimulus close; SF = stimulus far; RC = response close; RF = response far. Standard error of the mean is presented in parentheses.

ulation or an increase in the time to complete perceptual processing.

To test this possibility, we needed a manipulation that increases the time to identify the stimulus without making possible stimuli more similar to each other. Stimulus intensity is known to affect early perceptual processes and not interact with factors known to affect RS (see, e.g., Lien & Proctor, 2002; Pashler & Johnston, 1989; Sanders, 1980). We were concerned that making the stimuli less intense by simply reducing their brightness might have the unintended consequence of making them more similar, because we would, in effect, be adding black or gray to the four colors, and thus, this manipulation might not be sufficiently distinct from the stimulus manipulations used in the previous two experiments. Therefore, we opted to manipulate stimulus size instead, which also affects the stimulus energy but does lead to greater overlap among the features of the stimuli. That is, we assume that like similar stimuli, small stimuli take more time to identify (Lingnau & Vorberg, 2005), but unlike similar stimuli, small (dissimilar) stimuli do not activate competing S-R alternatives. If similarity leads to competing central codes, but size does not, then the size of the stimuli should not affect the shape of the trajectories. On the contrary, if the similarity manipulation affected curvature primarily by increasing the difficulty of the task—by making the stimulus more difficult to classify—then the size manipulation should produce the same effects; increasing the difficulty of encoding and classifying the stimulus by making the stimulus smaller should lead to more curvature in the trajectories.

To test between these alternative possibilities, we used a within-subject manipulation of size based on the SF-RC condition. We used the SF condition so that the stimuli were not similar in hue, and we used the RC condition because that condition produced the most curvature. The difference between SF-RC and SC-RC drove the interaction, so we examined whether the same differences occurred between stimulus large-RC and stimulus small-RC. If the Stimulus \times Response interaction was driven by perceptual difficulty, then small stimuli should produce the most curvature (compared with the large stimuli), similar to the SC-RC condition.

Method

Participants. Twenty University of Iowa undergraduates participated for course credit. Three participants were dropped due to poor behavioral performance or an inability to finish the experiment within the allotted time (60 min). Ages ranged from 18–24 years old.

Procedure. The experiment followed the same procedure as Experiment 1a. In particular, participants ran in the SF-RC condition with the added factor that the filled-circle stimuli used to cue the movements were either large (150×150 pixels) or small (15×15 pixels) in size, compared with 100×100 pixels in Experiments 1a and 1b. Unlike the previous two experiments, this was a within-subject design. The size was varied randomly from trial to trial and was irrelevant for the correct response, which was based only on the stimulus color as in Experiments 1a and 1b. As in Experiment 1a, participants had 930 ms to make their mouse movements. We returned to the time-pressure requirement to ensure participants did not make their decision before starting their movement.

Results

Before the analyses, the data were trimmed in the same manner as Experiment 1a.

Movement trajectory. The trajectories were analyzed in the same manner as in Experiment 1a. We first considered error along the X axis. There was no difference in error between the large (6 pixels) and small stimuli ($t_{\text{all}}(13) < 1$; $t_2(13) = 1.167$, $d = .64$, $p = .264$). Next, the total amount of curvature was analyzed. Again, there was no difference between large and small stimuli, $t_{\text{shared}}(13) = 1.10$, $d = .18$, $p = .287$, ($M_{\text{large}} = 163$, $M_{\text{small}} = 153$). This holds for the other two locations as well, $t_s < 1$ (see Figure 5). The data were also submitted to a 2×9 (Size \times Time Slice) within-subject ANOVA. There was a main effect of time, $F_{\text{shared}}(8,256) = 130.47$, $\eta_p^2 = .803$, $f^2 = 4.08$, $p < .001$, but the interaction was not significant, $F_{\text{shared}} < 1$. These data suggest that the interaction found in the previous two experiments was not the result of a difficult discrimination. Instead, the pattern of results indicate that manipulations of similarity along both stimulus and

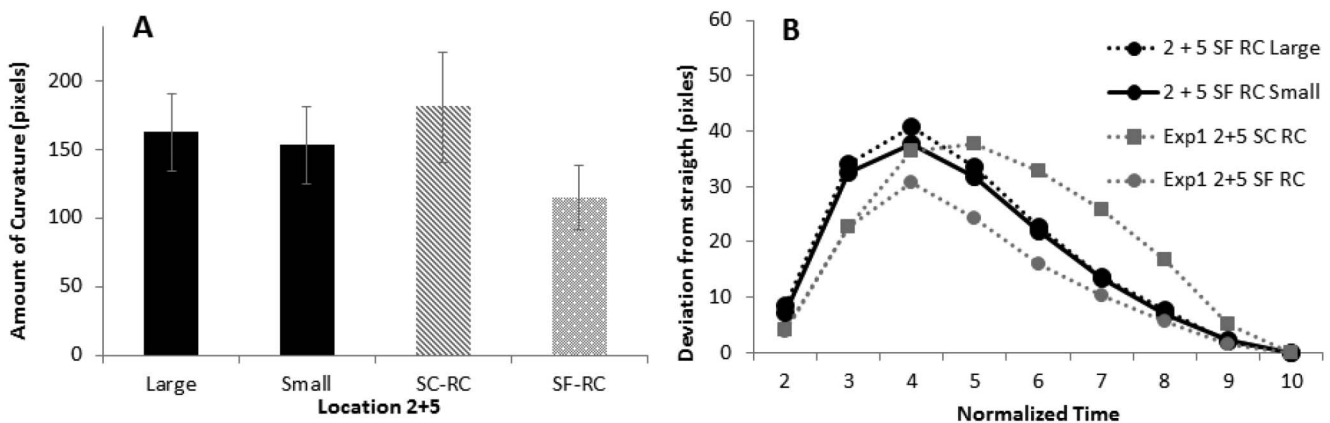


Figure 5. (A) Total amount of curvature. The gray bars represent the SC-RC and SF-RC conditions from Experiment 1. (B) Deviation from straight across normalized time for Locations 2 and 5. Error bars are SEMs.

response dimensions extends into RS processing. Moreover, the metrical properties of a task matter and support the notion that perception and action are not isolated events, but are fundamentally integrated in the process of RS.

Movement timing. There was a small but statistically significant difference between the percentage of correct trials, $t(13) = 5.165$, $d = .23$, $p < .001$, with large stimuli resulting in more correct trials than small stimuli ($M_{\text{large}} = 0.85$, $M_{\text{small}} = 0.83$). Next we analyzed the temporal components of the movement. There was a significant difference in IT as large stimuli had a lower IT than small stimuli, $t_{\text{all}}(13) = 7.816$, $d = .37$, $p < .001$, ($M_{\text{large}} = 276$ ms, $M_{\text{small}} = 287$ ms); $t_{\text{shared}}(13) = 8.335$, $d = .39$, $p < .001$, ($M_{\text{large}} = 282$ ms, $M_{\text{small}} = 294$ ms). However, the large stimuli had a higher MT than the small stimuli, $t_{\text{all}}(13) = 8.064$, $d = .30$, $p < .001$, ($M_{\text{large}} = 557$ ms, $M_{\text{small}} = 549$ ms); $t_{\text{shared}}(13) = 6.923$, $d = .31$, $p < .001$, ($M_{\text{large}} = 552$ ms, $M_{\text{small}} = 544$ ms). These results confirm that the size manipulation did affect difficulty in that it took longer to initiate a movement when the stimulus was small compared with when the stimulus was large.

Both Experiments 1a and 1b revealed an interaction between stimulus and response similarity, but it remained an open question as to whether or not the interaction was due to similarity causing competition among central codes. Experiment 2 demonstrates that an alternative manipulation of the time to process the stimulus that was designed to avoid increased competition among codes produced very different patterns of results: The size manipulation clearly affected the temporal aspects of the movement but resulted in no differences in the end-point error or the amount of curvature. Taken together, these results suggest that the interactions found in Experiments 1a and 1b were due to similarity increasing the competition among S-R representations that include metrical properties of both the stimuli and responses.

General Discussion

To investigate how stimulus and response similarity affect central operations, we asked participants to move a computer mouse to target locations depending on the identity of the cue. The two forms of similarity produced an interaction, such that there was more end point error and curvature when both stimulus and response were similar, indicating that RS processes are sensitive to the features of the stimuli and responses. These findings were replicated when instructions emphasized accuracy, making it unlikely that this interaction stems from task demands. Further, the interaction does not appear to result from participants deferring the selection of the appropriate response location or the configuration of the responses. Not only were there observable differences early in the trajectory, but these differences were apparent when “late deciders” were removed from the analysis. Moreover, to rule out the possibility that the interaction resulted from differences in the time to complete perceptual processing, we ran a third experiment in which the similarity manipulation was replaced with a stimulus size manipulation (Sanders, 1980). Although size affected IT, it did not impact the amount of curvature, indicating that slowing perceptual processing per se does not increase in the curvature of the trajectories.

These data have broad implications for theories of RS. To account for the ability to pair any stimulus modality with any

response modality, the dominant accounts of RS assume that central operations are performed by a generic set of processes that operate over representations that are stripped of metric information (amodal representations; Anderson et al., 2004; Pashler, 1994). In these models, RS processes essentially operate as a look-up table (MacKay, Holley, Friedin, & Cohen, 1973) that receives a categorized stimulus as an input and returns an abstract response code as output. This type of model, in which RS operates on representations only of the task relevant stimulus features, cannot produce an interaction between stimulus and response similarity. Attempts to reconcile these types of models with other S-R phenomena, such as the Simon effect, have relied on direct activation of the response codes based on a correspondence between particular stimuli and responses (Lien & Proctor, 2002). Because there is no correspondence between the stimuli and responses in the present experiment, it is difficult to see how the direct pathway could be driving the pattern of results. Furthermore, the present data underscore that RS operates over representations that contain both stimulus and response information.

The overadditive interaction suggests that competition was driven by partial activation among the S-R alternatives and that the partial activation was dependent on both stimulus and response similarity (Wifall et al., 2014). One account of RS that is consistent with this finding is the dynamic field account of Buss, Wifall, Hazeltine, and Spencer (2014). Building on findings in the developmental literature that children have the ability to successfully switch tasks depends on metrical properties of both the stimuli and responses (Buss & Spencer, 2014; Fisher, 2011), the researchers modeled RS as the activation of peaks within two-dimensional S-R fields (Figure 6). One dimension was tuned to a continuous stimulus dimension (e.g., color) and the other dimension tuned to a continuous response dimension (e.g., space). S-R alternatives com-

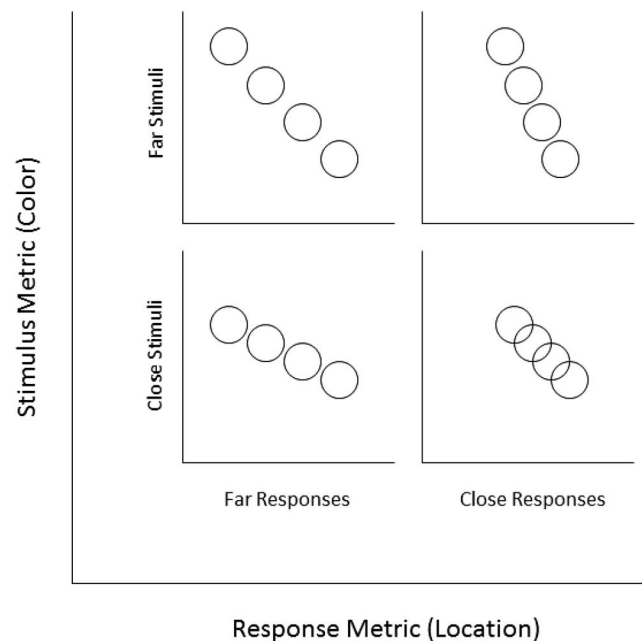


Figure 6. Conceptual framework of the relationship between stimuli and responses.

pete in the process of forming a stable peak of activation, which is the basis for a response. Thus, RS in this model is represented by the binding of stimulus and response information as peaks of activation.

In the Buss et al. (2014) model, S-R alternatives are represented in terms of both their stimulus and response properties, so the degree to which a given stimulus activates a competitor depends on the similarity between both the two stimuli and the two responses. As depicted in Figure 7, overlap among the representations of the S-R alternatives depends on both stimulus and response similarity. The SC-RC condition led to the most curvature because when a close stimulus was presented it coactivated the other S-R mappings, creating more competition between the S-R alternatives and thus, more curvature. The other conditions only overlapped along one dimension, thus leading to less competition and indicating that both stimulus and response information were critical for RS.

A strength of dynamic field theory (DFT) is the ability to link to the rich structure inherent in mouse-trajectory data. DFT simulations capture the moment-to-moment unfolding of a decision through real-time neural dynamics. These decision dynamics can be reciprocally coupled to a motor system (see, e.g., Sandamirskaya & Schöner, 2010; Sandamirskaya, Zibner, Schneegans, & Schöner, 2013; Steinhage & Schöner, 1997) that, for instance, moves a virtual mouse cursor as the model engages in the task in real-time. In this way, the explanation offered by the model can be constrained by multiple aspects of behavior—the qualitative accuracy of the response, the quantitative details of the response timing, and the qualitative measure of curvature at each moment during the execution of the response.

Relation to Other Paradigms

We were not the first to investigate how moving a mouse cursor or making a reaching motion is impacted by competitor items. In selective reaching tasks (Howard & Tipper, 1997; Welsh & Elliott, 2004; Welsh, Elliott, & Weeks, 1999), participants make reaching movements to a target in the presence of a nontarget stimulus. The results from mouse-tracking studies and selective-reaching tasks demonstrate how competitors or irrelevant information affect performance as trajectories can veer toward or away from competitors depending on the similarity and location of the competitor compared with the target. The present results are consistent with the notion that competitors are partially activated to the degree that they match the stimulus with similar competitors, affecting the mouse trajectory to a greater degree than dissimilar competitors.

Although the current data are consistent with previous mouse-tracking studies and selective-reaching tasks in demonstrating the influence of competitors, there are three key differences between these paradigms and the present one. First, the current paradigm contains manipulations of both stimulus and response similarity. By contrast, in previous mouse-tracking studies, only stimulus similarity was manipulated (e.g., see a piece of candy and a candle vs. see a piece of candy and a jacket) but not response similarity. And, in some of the previous selective reaching studies, response similarity was manipulated (e.g., manipulating the distance between the nontarget stimulus and target) but not stimulus similarity. Second, the stimulus was separate from the response location, forcing participants to remember the S-R mappings. Finally, pre-

vious studies have also had the competitor displayed on each trial. This was not explicitly the case here as the response locations were marked, but only one stimulus was presented on a given trial. Thus, the competitive interaction was the result of nondisplayed stimuli coupled with displayed response locations. We note here, however, that the interaction was not entirely driven by the displayed response locations, but instead by the coactivation of S-R alternatives by similar stimuli. In this way, the results suggest that the competitor does not necessarily need to be present to introduce competition.

Finally, the present data do not resolve the issue of whether RS operates in a discrete or continuous manner. As noted in the introduction, Miller (1988) points out there are a variety of ways a representational system can be continuous or discrete. Information can be represented, transformed (abruptly or gradually), and/or transmitted in a continuous or discrete manner. This debate has typically focused on how information is transmitted from process to process, and in this sense, a strictly feedforward discrete mechanism cannot account for the present data because it does not permit an interaction between stimulus and response information. Recall that in such models, stimulus similarity is only hypothesized to affect encoding and response similarity is only hypothesized to affect motor output. A model that transmits information continuously can more readily account for these data in that coactivation of multiple representations and competitive effects extend to postperceptual motor processing.

The goal of this paper was to explore how stimulus and response similarity affected RS. We manipulated stimulus and response similarity as participants moved a computer mouse to the same spatial locations. We found an interaction between stimulus and response similarity indicating that RS operates over representations that contain both types of information, which run counter to many theories of RS. Thus, the data here provide further evidence that even “simple” behaviors like moving a mouse cursor to a target location is a complex dynamic process that is sensitive to both stimulus and response properties.

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