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Reaching into response selection: stimulus and response similarity influence central operations

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REACHING INTO RESPONSE SELECTION: STIMULUS AND RESPONSE SIMILARITY INFLUENCE CENTRAL OPERATIONS

by

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph. D. thesis of

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To my Mom and Dad for all their love and support

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ABSTRACT

This dissertation examines the impact of stimulus and response similarity on response selection. Traditional models of response selection invoke a central processor that operates like a look-up table by matching the perceptually classified stimulus (e.g., green square) to the specified response (e.g., right button press). The look-up property of response selection affords the system the ability to map any stimulus onto any response, even if that stimulus-response has never been paired before. Under such an approach, the degree of perceptual similarity or dissimilarity that exists among stimuli in the environment should have little effect on central operations, the similarity or dissimilarity of the motor response executed in response to a stimulus should not influence response selection, and no interaction between stimulus and response features is permitted, given that stimulus features affect the encoding process, and response features affect the output process, but not response selection itself.

Eight studies examine the influence of stimulus and response similarity during response selection. The first two experiments establish the interaction across different task demands between stimulus and response similarity. The interaction was not the result of perceptual difficulty (Experiment 3) and was extended to a new set of stimuli (Experiment 4). A consequence of the design in Experiments 1 – 4 was that response condition was confounded with response configuration. In one of the response conditions the target location had three competitors on one side of it compared to the other condition where the target had one competitor on one side and two others on the other side. Experiments 5 and 6 examined the separate roles that response configuration and response metrics had on the interaction between stimulus and response similarity. The mechanism that produced the interaction was the result of competition between partially activated stimulus-response alternatives. Experiments 7 and 8 further explored the role of competition during response selection by turning to traditional response selection methodologies that introduce competition through either the presentation of irrelevant stimulus information or through presenting the stimulus along an irrelevant spatial dimension.

These data have broad implications for models of RS. To account for the ability to pair any stimulus modality with any response modality 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). Response selection works as a look-up table that receives a categorized stimulus as an input and returns an abstract response code as output. This type of model cannot produce an interaction between stimulus and response similarity and thus, the present data provide a serious challenge to these types of models. Finally, the data provide evidence that the metric relationship between stimuli and response matter and influence response selection. The co-activation of stimulus-response alternatives are at a level of representation that includes both stimulus and response properties. A framework is presented that captures key aspects of the data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

BACKGROUND AND SIGNIFICANCE

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 a situation in which you reach for your can of soda, which is situated on a table amongst many other soda cans that belong to other people. Successful completion of this task requires distinguishing between your soda can and other potentially distracting objects, such as similar (or perhaps even roughly identical) cans, and then selecting a motor program that avoids any obstacles on the way to the target object. A central component to this type of flexible, goal-based behavior is the ability to translate incoming sensory information into the appropriate action in the face of other competing possible actions, a process known as response selection (RS).

The human brain confronts multiple challenges when performing RS, including the vast array of sensory information available to the organism, the tremendous range of possible actions afforded by the environment, the dynamic internal state of the acting organism, and the fast timescale on which RS typically occurs. Although we have learned much about the processes needed to identify stimuli and to produce motor movements, the mechanisms by which humans are able to accurately map the stimulus to the response, even in the most simple experimental conditions (such as mapping simple stimuli to specific key presses), and to perform these mappings correctly on the first trial of an experiment, remain largely underspecified.

To explain the ability to map any detectable stimulus to any voluntary response, many theories of RS propose that it operates over abstract symbols that are detached from modality and metric influences suggesting stimulus and response do not directly interact. These theories hold that RS invokes a central processor that operates like a “look-up table” by matching the current classified stimulus (e.g., green square) to the specified response (e.g., left button press; Anderson & Leibre, 1998; Pashler, 1991, 1994). As discussed below, the “look-up” property of RS has been invoked because it allows for the system to map any stimulus with any response even if that stimulus-response has never been paired before. In this type of model RS is proposed to operate over abstract/amodal representations which allows for the ability to link any stimulus modality to any response modality. If this is true, that metric information is stripped away from RS then manipulating stimulus or response similarity should not affect RS.

One of the goals of this dissertation was to determine the influence that metric information plays in this translation process. One way to explore the role that metric information plays during RS is to determine if stimulus and response similarity interact. An interaction between stimulus and response properties indicates the engagement of central operations. In this way, determining how stimulus and response similarity affect performance and whether the two factors interact will have broad implications for models of RS. The traditional RS model does not predict an interaction between stimulus and response features as stimulus features affect the encoding process and response features affect the output process not RS.

Overview

As explained below, many stage-based theories of RS (Anderson & Leibre, 1998; Pashler, 1991, 1994) propose that it operates over abstract symbols that are detached from modality and metric (or, graded) influences in the input or output components of

RS. These theories hold that RS invokes a central processor that operates like a look-up table by matching the current perceptually classified stimulus (e.g., red triangle) to the specified response (e.g., left button press; Anderson & Leibre, 1998; Pashler, 1991, 1994). Under such an approach, the degree of perceptual similarity or dissimilarity that exists among stimuli in the environment should have little effect on central operations. The similarity or dissimilarity of the motor response executed in response to a stimulus should not influence RS. No interaction between stimulus and response features is permitted, given that stimulus features affect the encoding process, and response features affect the output process, but not RS itself. Although the present study does not resolve whether RS processes operate in a discrete or continuous fashion (see Miller, 1988), we aim to address key aspects of the debate by examining the degree to which metric manipulations of *both* stimulus and response features interact during RS.

If RS is a fundamental process of behavior, as argued here, then taking a principled approach to studying it is critical. The typical ways RS has been studied in the past has been through compatibility experiments (Fitts & Deininger, 1954; Fitts & Seeger, 1953; Kornblum, Hasbroucq, & Osman, 1990; Proctor, Wang, & Vu, 2002), the Simon task (de Jon, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Hommel, 1993; Lu & Proctor, 1995; Proctor, Lu, Wang, Dutta, 1995; Simon, 1969; Simon & Rudell, 1967), and dual-task experiments (Pashler 1994a, 1994b; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Ruthfuff, Pashler, Klassen, 2001). These different methodologies have been successful in demonstrating various aspects of RS processing.

I propose using mouse-tracking in this dissertation as a novel a way to study RS. This methodology is unique because along with capturing temporal measures (e.g., movement time) as do traditional button press experiments, mouse-tracking also captures the decision process (i.e., central operations) as the participant moves toward the target. Issues like the role of competition between S-R pairs, how the location of competitors affects movements, and role that stimulus and response similarity can be effectively studied using this technology.

Experiments 1 – 4 (Chapter 3) test the role that stimulus and response similarity play in RS. Similarity for both stimulus and response dimensions impacts the amount of competition between S-R alternatives. The competition between these representations is a critical factor in RS processes and plays a direct role in influencing participant's reaching behavior. One of the factors that influence reaching behavior is the location of the competitors in relation to the target. Thus, Experiments 5 and 6 (Chapter 4) attempts to determine the separate roles that the layout and similarity play in the interaction found in Experiments 1 and 2. Experiments 7 and 8 (Chapter 5) explore the role that different forms of irrelevant information play during RS. One traditional way to study RS has been to present irrelevant information and to observe how it affects behavior. In two experiments, irrelevant stimulus or response information is presented to determine how reaching movements are affected. The overarching goal of this dissertation is to provide principled and novel approach to understanding RS. Before the approach to these questions is introduced it is important to understand the history of RS models and how mouse tracking has been used.

Discrete vs continuous models of response selection

The goal of cognitive psychology is to understand how an organism acquires and uses knowledge about the world (Anderson, 1980). To help explain behavior across a wide range of tasks (e.g., perceptual discrimination, reading, problem solving, etc.) a plethora of models have been developed. The goal of each of these models is to explain performance by a set of component mental processes that represent a series of processes or operations that need to be performed to produce a response when a stimulus is presented. At a broad level, a stimulus needs to first be perceived (i.e. perception), then a decision needs to be made about which response to make based on the identity of the stimulus (i.e., decision), finally, the information needs to be passed to the motor system so the response can be executed (i.e., output). An issue that occurs when building a model is specifying the temporal relations between these various processes (perceptual, decision, output). In other words, *how* is the information transmitted from one process to the next? The information can be transmitted in a discrete fashion, such that information is only passed to the subsequent process once the preceding process has completed. Or the information can be transmitted in a continuous manner where output from one process is continuously available to the other processes. As Miller (1988) points out information can also be classified as discrete or continuous along two other dimensions: representation and transformation. Representation refers to whether the input and output codes for the processing stage are continuous or discrete. Transformation refers to whether the operation performed by the processing stage is continuous or discrete (e.g., spatial transformation done in a gradual or abrupt manner). A model can be both discrete and continuous, for example, Miller's (1988) asynchronous discrete coding model assumes that most stimuli are composed of features, and these features are identified separately. Discrete processing occurs for feature identification, but once a feature is identified, this information can be passed to RS while the other features are still being identified. Given the difficulty of differentiating between discrete and continuous models it is not the goal of this dissertation to resolve this issue but to use the debate as a way to frame the present methodological approach.

Discrete models of response selection

Response selection has traditionally been conceived of as an information processing stage that exists independent of either stimulus identification or response initiation (Donders, 1868; Sanders, 1967; Sternberg, 1969). Although there have been a variety of formulations of the exact number and nature of the stages through which information flows, early models of information processing held that these stages were discrete: one stage did not begin until the preceding stage has completed. In other words, the output of one stage served as input to the subsequent stage, and stage N + 1 cannot begin until stage N has finished. In a fully discrete model the total reaction time (RT) is the sum of the durations of component mental processes.

Discrete models continue to provide popular accounts of the performance of choice reaction time tasks. For example, the widely-cited Response-Selection Bottleneck model (Dux, Ivanoff, Asplund, & Marois, 2006; Pashler, 1994a; 1994b; Ruthruff, et al., 2003; Ruthfuff, et al., 2001) posits that certain mental operations, specifically, RS, can only occur one at a time. In this model, RS receives the output of stimulus classification processes and translates this into an abstract response code. Much of the evidence for this model comes from the psychological refectory period (PRP) procedure to examine dual-task costs (Pashler, 1984; Smith, 1969; Welford, 1959; Pashler & Johnston, 1989; Van Selst, Ruthruff, & Johnston, 1999). The key point to this model is that as with other discrete stage models, features of the stimulus and response do not directly interact and RS operates using abstract codes.

A variation of this perspective is a symbolic production system (adaptive control of thought-rational, ACT-R; Anderson et al., 2004; Anderson & Lebiere, 1998). Here, behavior emerges from the interaction of a number of modules. These modules perform their operations largely independent of other modules though a module can interact with the overall system by placing information in an associated buffer. A central production system responds to activity in these association buffers, which sends information or requests to various buffers. Response selection is thought to occur through the activation of production rules (typically, 'if-then' statements) that place representations of potential responses in working memory based on the identity of the stimulus. Here, RS operates over abstract symbols that are detached from modality and metrical influences. This model has been quite successful in accounting for behavior across a wide range of tasks, such as dual-task behavior (Anderson, Taatgen, & Byrne, 2005; Byrne & Anderson, 2001), categorization (Anderson & Betz, 2001), and general human performance (Anderson et al., 2004; Anderson, Qin, Sohn, Stenger, & Carter, 2003).

Because discrete stage models of RS assume that stimulus classification is complete before RS begins, they do not easily account for some interactions between stimulus features and responses features. For example, stimulus-response compatibility effects (e.g., Fitts & Seeger, 1953; Kornblum, et al., 1990) occur when the features of the stimulus matches those of the response, producing faster RTs and higher accuracy scores though these effects can be explained if it is assumed that some responses are more readily retrieved than others given a particular stimulus cue (Wuhr & Ansorge, 2007).

However, interactions between task-irrelevant stimulus features and the responses features on RT (Simon, 1969; Simon & Rudell, 1967) are less conveniently accommodated as are interactions between the features of stimuli of one task and the features of responses of a temporally overlapping second task (Hommel, 1998). To account for these interactive effects, dual-route models are often invoked in which stimulus information automatically activates representations of response options through a direct pathway that bypasses standard response selection stages (Eimer, Hommel, & Prinz, 1995; Hommel, 1998; Lien & Proctor, 2002). The indirect pathway identifies the correct response according to pre-specified rules typically learned through task instruction. In the Simon task for example, RTs are faster in congruent trials (when the stimulus appears on the same side as the response) because the activation from both direct and indirect pathways land on the same response, whereas in incongruent trials (when the stimulus appears on the opposite side as the response), the direct pathway (as triggered by the location of the stimulus) will activate one response and the indirect pathway will activate the other response. The direct pathway's activation decays over time and why the Simon effect has demonstrated to fade over time (i.e., the difference between incongruent and congruent trials becomes smaller as the RT increases).

In principle, these dual-route models can account for a broad array of empirical phenomena (De Jong, Liang, & Lauber, 1995; Lien & Proctor, 2002; Lu & Proctor, 1995;). However, they are difficult to test for multiple reasons: a single discrete stage processing pathway is capable of producing complex patterns of RTs in response to various experimental manipulations (see, Miller, 1988), the relative contributions of the two pathways are difficult to disentangle, and the “direct pathway” appears malleable (Lu & Proctor, 1995) and at least partially controlled (Chen & Melara, 2009).

Continuous models of response selection

An alternative approach to understanding interactions between stimulus features and response features abandons the requirement that stages must be completed before others begin and emphasizes the continuous dynamics of real-time action. These models stress the link between perceptual and motor processes as activation continuously cascades from one process to another. Such models propose that the output of any stage or processes is continuously available to subsequent or concurrent processes (Coles et al., 1985; Eriksen & Schultz, 1979; Gaskell & Marslen-Wilson, 2002; McClelland & Elman, 1986; McClelland, 1979); and information from an early process (e.g., stimulus classification) can serve as input to a later process (e.g., response selection) before the early process has completed. Continuous systems also differ from discrete models because processes are allowed to operate in parallel, even though the output of one process might serve as input to the next. Another general assumption of continuous models is that not only is partial information made available to subsequent processes but the subsequent processes use this information. Thus, total RT is not simply the sum of the durations of each of the component processes (as predicted by discrete models).

For instance, Ericksen and Schultz’s (1979) visual search model is based on the notion that response activation begins as soon as visual information is accumulated. Initially, incoming sensory information activates many of the possible response alternatives since the accumulating evidence is still consistent with many of the responses. As time progresses, evidence accumulates for the response alternatives that are supported by the ongoing stimulus processing. A response is made when the accumulated evidence satisfies a criterion. Therefore, the speed of making a response is determined in part by the amount of response competition where more competition leads to longer response latencies. There are longer RTs when the target and flanker stimuli are providing evidence for different responses, which can be attributed to competition between ongoing dynamic processes. Continuous models provide elegant explanations for increases in RT when the flankers indicate different responses than the target compared to when they indicate the same response.

Recently, Cisek (2006; 2007) developed a computation model of reaching decisions based on the principle of continuous flow of information from one process to the next, called the Affordance Competition Hypothesis. In this model, sensory information arriving from the world is continuously used to specify several currently available potential actions. These potential actions are represented by populations of neurons that represent a distribution of potential movement parameters (e.g., direction) and neurons with similar tuning excite each other, while neurons with dissimilar tuning inhibit each other. The strength of activation is the result of a variety of factors (e.g, salience of the stimulus, expected reward, probability, etc) but decisions are not made (e.g., moving on a ‘go’ trial) until the accumulated information has reached some threshold. Similarly, Welsh and Elliott (2004, 2005) have proposed a response activation model of reaching where each response ‘races’ independently however, the characteristic of the movement (e.g., the trajectory) are determined by the overall activity levels of the neurons in the motor system at the moment the ‘winning’ response reaches threshold and movement is initiated. Thus, if populations of neurons coding for the competing, target are active at the moment of movement initiation, then characteristics of that response will be incorporated into the target motor plan.

Thus, continuous models also provide a straightforward way to conceptualize and model differences in mouse trajectories between conditions as continuous action may have the ability to provide a continuous index of the cognitive processes that underlie RS (Buetti & Kerzel, 2008; Spivey, Grosjean, & Knoblich, 2005). As the decision unfolds over time evidence accrues for different response options and differences in the trajectories reflect the co-activation of these different response options. The use of mouse-tracking technology provides an innovative tool to do this as trajectories are sensitive to the co-activation of multiple representations. Therefore, novel aspects of RS (e.g., sensitive to metric properties of the stimulus and response) might be revealed as participants move their mouse to a target location.

Computer-Mouse Tracking and the Dynamics of Response Selection

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 reaction time (RT) are examined in order to make inferences about how perceptual and higher-level processes map onto one discrete motor response. One limitation of these dependent measures is that they only measure the final outcome of task operations, imposing discreteness on the underlying processes. Recently, behavioral testing methodologies have been developed that place a stronger emphasis on the dynamics of the action-based components of RS (Duran, Dale, & McNamara, 2010; Spivey, Grosjean, & Knoblich, 2005). As one example, by tracking the streaming 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 co-activation of stimulus-response (S-R) alternatives representations (Freeman, Dale, Farmer, 2011; Song & Nakayama, 2006; 2008; 2009; Spivey et al, 2005; Magnuson et al., 2007). The continuous nature of the movement trajectories can provide more direct evidence for competition between response options that cannot be easily detected when reaction time (RT) is the primary measure (Eriksen & Eriksen, 1974; Kornblum, 1965; 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; Paninski, Fellows, Hatsopoulos, & Donghue, 2004; Shen & Alexander, 1997; Tosoni, et al., 2008). Furthermore, there is growing evidence that motor regions are not just endpoints of cognitive decisions but actively integrate and potentially influence unfolding decision processes (Johnson, Ferraina, Bianchi, & Caiminit, 1996). Shen and Alexander (1997) demonstrated that primary motor cortex is not just a reflection of movement parameters in a reaching task. In fact, a proportion of neurons recruited in the task were active during an instructed movement. That is, these neurons fired when a spatial cue mismatched the limb required to move. Monkeys learned to respond during these trials, and the motor cortex appears to be involved in accomplishing this.

Behavioral evidence suggests reaching dynamics can be interpreted as revealing underlying cognitive dynamics. This comes from reaching movements that display both attraction and repulsion to distractors during flight, consistent with the emergence of the motor program as decision processes unfold (Song & Nakayama, 2006, 2008, 2009). In essence, when two motor commands are 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, or to a region between the 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). Thus, reaching movements may provide an online index of the activation of cognitive representations. As a result, 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, Grosjean and Knoblich (2005) exploited these properties of mouse tracking movements 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 (cohort condition; e.g., candy/candle) or dissimilar (control condition; e.g., candy/jacket) items and participants would hear the name of the object to which they should move the mouse. In the cohort condition, trajectories showed greater deviation towards 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 as well as direct evidence of competition between phonetically similar items. The authors summarized their results by asserting that the two response targets act as attractor points and the trajectory “…serves as a record of the mental trajectory traversed as a result of the continuously updated interpretation of the linguistic input.” (p. 10398).

However, it has been recently argued that the curvature in movement trajectory can be explained by a model in which perceptual and cognitive processing are discrete but the motor output operates in a continuous, parallel fashion (van der Wel, Eder, Mitchel, Walsh, & Ronsenbaum, 2009). In this model, two motor movements corresponding to an upward movement are asynchronously averaged (after a perceptual decision) to produce a smoothly cured output. This model does provide an existence proof in which a motor output maybe continuous, but the underlying cognitive decisions are serial. The implication for this type of model is that cognition and action are not dynamically coupled. However, in Spivey and colleagues’ reply (2010) the authors point out that it is somewhat unlikely that one neural system (cognition) would behave in a serial, discrete way and feed into a second system (action) that behaves in a qualitatively different way. The authors also used the same equations that van der Wel and colleagues (2009) did, but instead of having two separate movement parameters (one to move towards midline and the other to move towards the correction location) Spivey and colleagues computed two alternative movement commands (Cisek & Kalaksa, 2005). This was done at the outset and the resulting trajectory starts off towards the midpoint then smoothly curving towards one of the locations just like the behavioral data. The authors took this as evidence that both perceptual and motor decisions can be made in a continuous, parallel fashion.

Mouse tracking tasks have recently been used across a range of domains, including speech sound categorization (Farmer, Liu, Mehta, & Zevin, 2009), syntactic processing (Farmer, Anderson, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007), semantic categorization (Dale, Kehoe, & Spivey, 2007), attention-related processes (Hindy, Hamilton, Houghtling, Coslett, & Thompson-Schill, 2009), evaluative thinking (Dale & Duran, 2011; McKinstry, Dale, & Spivey, 2008), deceptive responding (Duran, Dale, & McNamara, 2010; Duran, Roche, Snyder, & McCall, 2008), and social perception and judgment (e. g. Freeman & Ambady, 2009; Freeman, Ambady, Rule, & Johnson, 2008; Wojnowicz, Ferguson, Dale, & Spivey, 2008). Stated broadly, experimental results have consistently demonstrated that arm movements (as measured by the movement 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).

Response selection and Similarity

Much of the mouse-tracking work has used identification tasks, focusing on an examination of the curvature of mouse-movement trajectories when there is a competing item present in the display compared to when it is not. Often, these experiments have reported that perceptual similarity among a target stimulus and a competitor produces attraction to a distractor object as subjects ultimately move to the correct location in a multiple-object display (Farmer, Anderson, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009). This pattern of data is taken as evidence of co-activation between the possible responses as the selection processes unfold over time, and the magnitude of curvature toward a distractor can be taken 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. One exception (McDowell et al., 2002) reported that RTs were faster when reaching to response locations that were close together in space compared to 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.

Previous work has demonstrated the divergent effects that similarity has. Similarity among the stimuli, in general, hurts performance by making the discrimination more perceptually difficult and similarity among the responses facilitates performance by increasing the overlap among motor programs. Thus, these results suggest that similarity effects 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 interact, specifically, an overadditive interaction. Stimulus similarity should not just affect perceptual processes but also increase competition between response options (Farmer et al., 2007; Farmer et al., 2007; Freeman et al., 2011; Spivey et al., 2005). If stimulus similarity co-activates S-R alternatives then having close responses should increase competition because the overlap of motor programs will be partially activated and compete as well. In other words, having both similar stimuli and similar responses should elicit the most competition between the S-R alternatives.

In this way, determining how stimulus and response similarity affect performance, and whether the two factors interact, will have broad implications for models of RS. Although stage-based models could, in principle, be manipulated in order to account for interactions between stimulus and response features, continuous models provide a straightforward way to conceptualize and model differences in mouse trajectories that vary systematically as a function of metric influences of both stimulus and response similarity. Evidence accrues for different response options over time and differences in movement trajectories that are made during the decision process reflect the weighted co-activation or blending of multiple motor responses that correspond to different response options, removing the theoretical necessity of a discrete "stage" of RS.

The overarching goal of this dissertation is to explore how stimulus and response similarity impacted RS during a choice-RT task. Given the success of the mouse tracking tasks at revealing competition during central operations, I 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 co-activation of representations during RS. A critical indicator of RS processes is interactions between stimulus and response properties (Simon, 1969, Simon & Rudell, 1967). Thus, I 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.

CHAPTER 2: APPROACH

To examine how RS processes unfold in the face of metric manipulations of stimulus and response similarity, I modified the mouse tracking procedure so that it was more analogous to a choice-RT task. There were three key differences between the present approach and previous mouse tracking studies. The first, stimulus and response similarity were manipulated simultaneously. As argued above both stimulus and response properties should be important for RS processing.

Second, in typical mouse tracking experiments, mouse movements are made towards one of several simultaneously presented stimuli. Thus, the stimuli and possible responses are the same in such cases, and the critical measurement is deviation towards a particular irrelevant stimulus/incorrect response. However, in the present study, I employed a design that separates the stimulus that indicates to the subject which response should be made from the possible response locations, as in a typical choice reaction time task. That is, all possible response locations were displayed on every trial, but there was only a single cue indicating the correct target location, which was not presented at any of the response locations. There were a small number of possible cue stimuli (four), and participants had to remember the assignments of the cues to these unlabeled location boxes, just as in choice reaction times tasks in which participants must remember the S-R mapping. With this approach, all possible response locations were displayed on every trial so that it was necessary to decode the identity of the cue to determine which response to make. The cue was placed at the same location on every trial (except Experiments 4,5, and 8). This location was distinct from the response locations, such that deviations towards the cue always resulted in curvature towards the center of display regardless of the appropriate response or identity of the stimulus.

Finally, unlike previous mouse tracking studies where competitor stimuli were present on each trial in the present design only one cue stimulus was presented on each trial. Deviations from the target and towards competitors therefore, reflect effects of a non-displayed stimulus. In sum, the procedure was similar to typical mouse-tracking experiments in that participants were required to move the mouse from a starting point to a target location based on a presented cue stimulus. However, the procedure was similar to choice-RT experiments in that the cue stimulus was presented in a distinct location from the responses, whose locations are consistently mapped to stimuli throughout the experiment.

The overarching goal of this dissertation was to explore how stimulus and response similarity interact with one another and influence central operations. Using mouse trajectories Experiments 1 – 4 (Chapter 3) establishes the role that the metric properties of the input and output have on RS. Specifically, stimuli and responses interact such that there was increased competition between the S-R alternatives when both the stimulus and response codes were similar. Experiments 3 and 4 rule out perceptual difficulty and extend the finding to a new set of stimuli.

One of the consequences of how I manipulated response similarity was that the configuration of the response locations was confounded with response condition. In the close response condition, the critical target location had three competitors (response locations) on one side of it compared to the other condition that had one competitor on one side and two others on the other side of the target location. Experiments 5 and 6

(Chapter 4) examines the separate roles that response configuration and response metrics have on the stimulus x response interaction found in Experiments 1 and 2.

The mechanism that produced the stimulus x response interaction was the result of competition between the partially activated S-R alternatives. Experiments 7 and 8 (Chapter 5) further explores the role of competition during RS by turning to traditional RS methodologies that introduces competition through either the presentation of irrelevant stimulus information or through presenting the stimulus along an irrelevant spatial dimension (i.e., at various response locations).

General Method

In this dissertation eight experiments are conducted and six of them (Experiments 1-4, 7-8) follow the same general procedure described below.

Previous experiments have made participants start to make their movement before the stimulus appears (e.g., Huette & McMurray, 2010; Spivey et al., 2005), so that the decision was not complete before the initiation of the movement. However, this type of procedure is unlike most real-world tasks (and most experimental choice-RT tasks) in which movements are initiated after the stimulus is perceived. Therefore, we had participants initiate their movement once the stimulus was presented, as in a typical choice-RT task. One concern was that participants might not begin their movements until after completing the motor programming process. This, in turn, could prevent the effects from being evident in the trajectories because the conflict would be resolved before the movements were begun. Thus, in all but one of the experiments, there was a limited amount of time to respond to encourage participants to move while RS processes were still unfolding

For each experiment, two factors were manipulated: the similarity of the stimuli, and the similarity of the responses, resulting in a 2 x 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 used a between-subject design to ensure participants were not exposed to a variable mapping across conditions, which has been shown to be devastating to performance (Shiffrin & Schneider, 1977).

The stimuli were presented and responses collected using PC computers running Visual Basic software. The stimuli were presented as color patches (except Experiment 3) with the size of 100 x 100 pixels on a black background. The RGB values of the far stimuli were: 237, 28, 36 (red), 255, 242, 0 (yellow), 34, 177, 76 (green), 0, 0, 255 (blue); the RGB values of the close stimuli were: 74,128, 182 (blue), 35,134,167 (bluish green), 39, 137, 145 (greenish blue), 70,138, 120 (green). Participants sat 66 cm away from the screen resulting in a visual angle of 1.65 degrees.

The layout of the display can be seen in Figure 1. The start box was gray and had a size of 25 x 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 was: 485, 129; 579, 118; 661, 118; 755, 129; for the far condition, they were 230, 222; 485, 129; 755, 129; 1010, 222, 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 2nd left most response, green the 2nd 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 x 10), which were left on the screen for the entirety of the experiment.

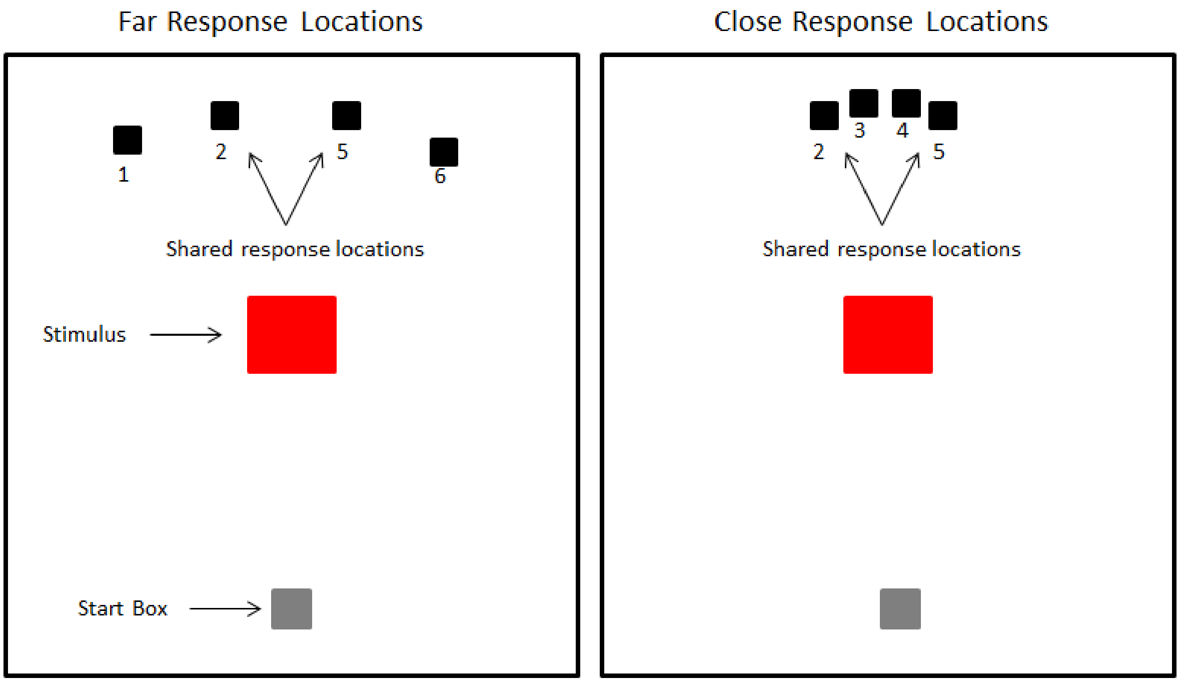

*Figure 1***.** The layout of the display seen by participants, including the start box and response locations. Locations 2 and 5 are in the same spatial locations across close and far response conditions. Note that this is not drawn to scale.

A trial proceeded as follows: a participant would move the cursor into the start box at the bottom of the screen. They were instructed to not move the cursor for 1,000 ms at which point the stimulus was displayed. Participants then moved the cursor to one of the four response locations that corresponded with the identity of the stimulus. 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 stimulus corresponds with which response location prior to the beginning of the experiment. We did this to emphasize the learning component of the task. To begin the next trial the participant had to move the cursor into the start box and not move the cursor for 1,000 ms at which point the stimulus was presented.

Each block consisted of 32 trials with each possible stimulus presented an equal number of times in a random order. Two randomly-selected warm-up trials were also added to the beginning of every block. There were a total of 20 identical blocks of which only the final 19 were included in the analysis.

CHAPTER 3:

ESTABLISHING THE ROLE OF STIMULUS AND RESPONSE SIMILARITY IN CENTRAL OPERATIONS

The purpose of Experiments 1 – 4 was to establish the role that stimulus and response similarity play in central operations. Both stimuli and responses can vary in similarity and little empirical work has addressed how these properties interact in a choice-RT task. Mouse movements were used because they provide a measure of co-activation between S-R alternatives, as indexed by deviations in the trajectory. If an interaction between stimulus and response similarity was the result of competition between the S-R alternatives, an analysis of the movement trajectories should provide evidence of this, and suggest that the competition was occurring at the level of central operations. Furthermore, an interaction between stimulus and response similarity would suggest that central operations were sensitive to the metric properties of the input and output, a finding not supported by traditional models of RS.

Experiment 1: Time Pressure

The purpose of Experiment 1 was to assess how stimulus and response similarity affected performance in a mouse-tracking task. Specifically, the experiment sought evidence for co-activation of representations as indexed by increased curvature as well as how this competition was affected by similarity amongst the stimulus and response alternatives.

Method

Participants

A total of eighty-five University of Iowa undergraduates participated for course credit. Five participants were dropped because of poor behavioral performance (see

Results section for criteria), which resulted in twenty in each condition. Ages ranged from 18 – 23.

Procedure

Experiment 1 followed the procedure presented in the General Method section (Chapter 2) with one addition. Participants were told that they had slightly less than 1 second (approximately 930 ms) to make their response. At the end of 930 ms the current location of their cursor was considered the final location.

This time limitation made the task fairly difficult and led to participants not moving the mouse near the correct location a substantial proportion of the time. I did not want to include incorrect trials in the trajectory analyses so this led to ambiguity regarding which trials to include as a response might be headed in the correct direction but still equidistant between two potential locations when the trial timed out. Therefore, I decided to adopt a conservative approach (participants final response location was closer to the correct location than any other location) but I also report similar findings when a more liberal criterion was used.

To alleviate the ambiguity of correct/incorrect responses a second experiment was conducted (Experiment 2) without the time pressure but with the added constraint that responses were made by clicking the mouse within a response box. Further, this design allowed me to consider how task demands (accuracy vs speed) influence the movements.

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 and movements that resulted in a final position more than 45 pixels away from the correct location were removed from the analyses. The nearest box was 95 pixels away in the near response condition so 45 were chosen as the cut off 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 till when their velocity dropped below 2 pixels/ms), but the movement was consider complete 930 ms after the presentation of the stimulus. These criteria ensured that participants were making movements toward the correct location and not ending their response in between two of the locations. This was a difficult task given the time pressure, and these criteria eliminated 42% of the data, but the same pattern of results was observed when more lenient criteria were used. I report the data derived using the strict criteria because these trials most clearly correspond to correct responses. Moreover, Experiment 2 imposed different constraints and produced very similar trajectories, so I am confident that the observed patterns do not stem from the liberal trimming procedure. When appropriate, the analyses were performed two ways: data averaged across all for locations (F_{all} or t_{all}) and data averaged across only the shared locations (F_{shared} or t_{shared}). The second analysis was performed because this provides a measure of how the different conditions affected the trajectory of the movement to the same spatial locations.

Initiation and Movement times

Initiation time was submitted to a 2 x 2 (stimulus similarity x response similarity) between subject ANOVA, a main effect of stimulus similarity emerged, $F_{all}(1,76) = 5.58$, $\eta_p^2 = .068$, $p < .05$, $F_{shared}(1,76) = 6.21$, $\eta_p^2 = .076$, $p < .05$, such that IT was faster for far stimuli than close for all locations ($M_{far} = 320$ ms, $M_{close} = 346$ ms) and shared ($M_{far} =$ 320 ms, $M_{close} =349$ ms). There was also a main effect of response similarity, $F_{all}(1,76) =$

9.61, $\eta_p^2 = .112$, $p < .01$, $F_{\text{shared}}(1,76) = 8.73$, $\eta_p^2 = .103$, $p < .01$, such that far responses had a slower IT than close for all locations ($M_{\text{far}} = 350$ ms, $M_{\text{close}} = 316$ ms) and shared ($M_{\text{far}} = 352$ ms, $M_{\text{close}} = 318$ ms). There was not a significant interaction, $F_{\text{all}} < 1$, $F_{\text{shared}}(1,76) = 1.05$, $\eta_p^2 = .014$, $p = .309$ (see Table 1 for 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.

Table 1. Mean initial times (IT) and movement times (MT) across the four conditions. SC = stimulus close; RF = response far.

Stimulus	**Response**	**IT (ms)**		**MT (ms)**	
		All	*Shared*	*All*	*Shared*
SC	*RC*	325	326	522	529
SC	*RF*	367	373	488	484
SF	*RC*	307	309	539	540
SF	*RF*	333	332	520	521

Movement time was submitted to an identical ANOVA. There was a main effect of stimulus similarity, $F_{all}(1,76) = 5.59$, $\eta_p^2 = .068$, $p < .05$, $F_{shared}(1,76) = 4.74$, $\eta_p^2 = .059$, $p < .05$, such that MT was slower for the far stimuli compared to the close stimuli for all locations (M_{far} = 529 ms, M_{close} = 505 ms) and shared (M_{far} = 531 ms, M_{close} = 507 ms). A main effect of response similarity also emerged, $F_{all}(1,76) = 6.50$, $\eta_p^2 = .079$, $p < .05$, $F_{shared}(1,76) = 8.56$, $\eta_p^2 = .101$, $p < .01$, such that close responses had a slower MT compared to far responses for all locations (M_{far} = 504 ms, M_{close} = 530 ms) and shared (M_{far} = 503 ms, M_{close} = 535 ms) but the interaction was not significant, $F_1 < 1$, $F_{shared}(1,76) = 1.36$, $\eta_p^2 = .018$, $p = .247$ (see Table 1 for values for individual conditions). 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. This tradeoff is not surprising though given the time pressure put on participants.

Movement trajectories

To evaluate the mouse trajectories, error along the X axis for the movement's endpoint (absolute distance from the final mouse position to the correct location) was first considered. This provides a coarse measure of how accurate or difficult each of the conditions were as the primary difference between response locations was along the x axis. Data were submitted to a 2 x 2 (stimulus x response) between-subject ANOVA. There was a main effect of stimulus, $F_{all}(1,76) = 5.27$, $\eta_p^2 = .065$, $p < .01$, $F_{shared}(1,76) = 9.89$, $\eta_p^2 = .115$, $p < .01$, as close stimuli had more error for all locations (M_{close} = 5.95 pixels, M_{far} = 4.90 pixels) and shared (M_{close} = 6.84 pixels, M_{far} = 5.26 pixels). There was a main effect of response, $F_{all}(1,76) = 18.02$, $\eta_p^2 = .192$, $p < .001$, $F_{shared}(1,76) = 34.92$, $\eta_p^2 = .215$, $p < .001$, as close responses had more error for all locations (M_{close} = 6.38 pixels, M_{far} = 4.47 pixels) and shared (M_{close} = 7.59 pixels, M_{far} = 4.51 pixels). The interaction was also significant, $F_{all}(1,76) = 4.75$, $\eta_p^2 = .059$, $p < .05$, $F_{shared}(1,76) = 8.18$, $\eta_p^2 = .097$, $p < .01$. The interaction was the result of the *SC-RC* condition having significantly more error along the X axis than any of the other conditions (see Figure 2). Note that the *SC-RC* condition, which had the largest endpoint error, was in the middle of the range, similar to the *SF-RF* condition, with regard to the temporal measures, IT and MT. In sum, performance was less accurate when both dimensions were close which suggests that the metrical relationship between the S-R mappings influences the trajectories.

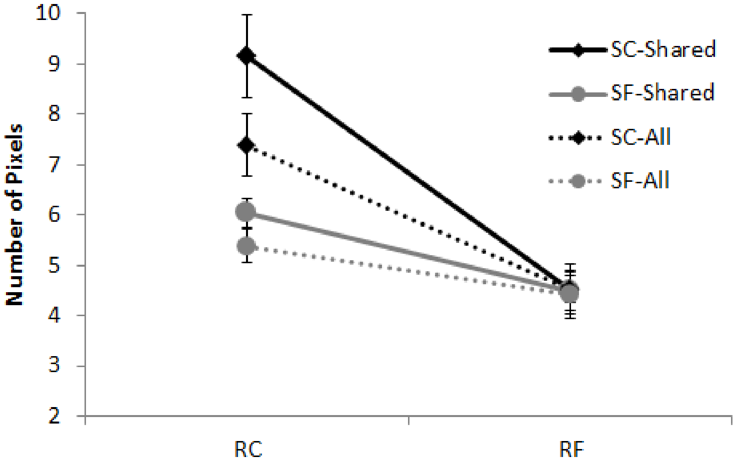

Figure 2. Error along the X-axis for all and shared locations.

To gain a more complete picture of the unfolding of competition, I analyzed the time-course of the trajectories. Each trajectory was first aligned to a common x, y starting position and then each trial was normalized by resampling at equal time-space 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 the analyses reported below were restricted to the shared locations (see Figure 3 for mean trajectories to the shared locations).

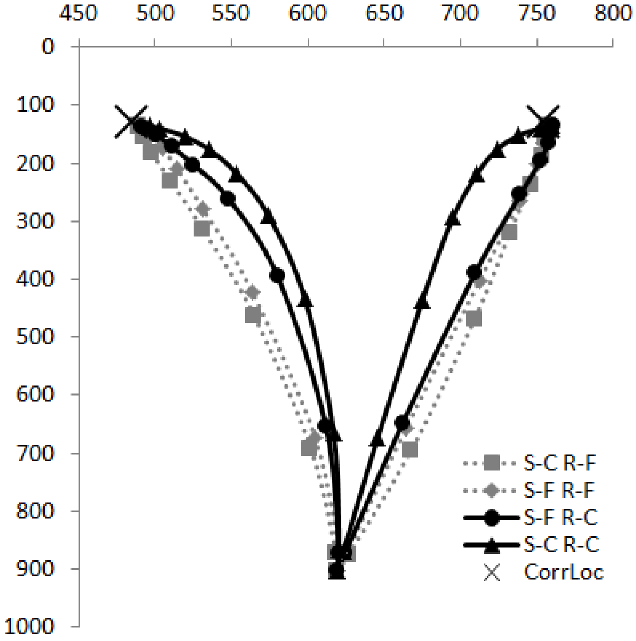

Figure 3. Mean trajectories across all for conditions for locations 2 & 5.

First, I assessed the overall amount of curvature toward a distractor by calculating the area under the curve for each trajectory (Miles & Proctor, 2013). Curvature was submitted to a 2 x 2 (stimulus x response) between-subject ANOVA where stimulus, $F_{shared}(1,76) = 4.85$, $\eta_p^2 = .060$, $p < .05$, response, $F_{shared}(1,76) = 17.00$, $\eta_p^2 = .183$, $p < .001$, and the interaction were significant, $F_{shared}(1,76) = 4.73$, $\eta_p^2 = .058$, $p < .05$. The overall curvature data mirror the error data as the *SC-RC* condition resulted in more curvature toward a distractor than any of the other conditions (see Figure 4A) as revealed by paired-sample *t*-tests: *SC-RC* vs. *SC-RF* $t(38) = 3.93$, $p < .001$; *SC-RC* vs. *SF-RC* $t(38) = 2.77$, $p < .01$; *SC-RC* vs. *SF-RF* $t(38) = 3.79$, $p < .001$. Critically, the interaction suggests that when the stimulus and response dimensions were close, there was more competition between the S-R alternatives resulting in more error and more curvature.

The pattern becomes more apparent when looking at the deviation from a straight path (to the end location) over time (see Figure 4B). Data were submitted to a 2 x 2 x 9 (stimulus x response x time slice) mixed ANOVA. There was a main effect of time, $F_{shared}(8,608) = 143.81$, $\eta_p^2 = .654$, $p < .001$, indicating that the deviation changed over time. The time x stimulus, $F_{shared}(8,608) = 5.47$, $\eta_p^2 = .067$, $p < .001$, and time x response, $F_{shared}(8,608) = 11.98$, $\eta_p^2 = .136$, $p < .001$, and the three-way interaction of time x stimulus x response, $F_{shared}(8,608) = 3.70$, $\eta_p^2 = .046$, $p < .001$, were all significant as the *SC-RC* condition had more deviation from straight than the *SF-RC* condition over time. 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.

As a way to further explore the nature of this interaction it was of interest to determine when in time the interaction occurred. To identify the point within the movement at which the differences between conditions could be first detected, I 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 x 2 between-subject 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 5th and 6th time slices had a significant stimulus x response interaction, $F_{shared}(1,73) = 10.16$, $\eta_p^2 = .122$, $p < .01$, $F_{shared}(1,74) = 7.11$, $\eta_p^2 = .090$, $p < .01$, suggesting that the *SC-RC* condition was still resolving competition later on in the movement compared to the other conditions.

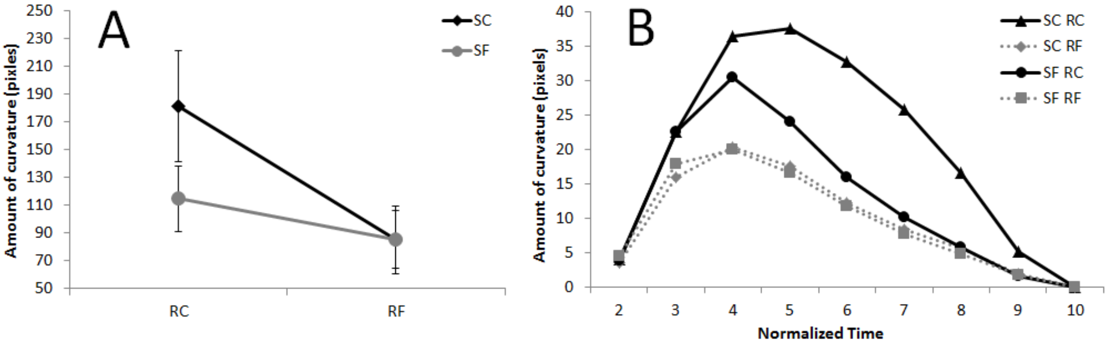

Figure 4. Total curvature across conditions (panel A) and deviation from a straight path x normalized time (panel B). S-C = stimulus close, R-F = response far.

Can these interactions 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 *SC-RC* condition (time slices 2-3; see Figure 4B). Therefore, it could be the case that when the responses were close participants adopted the strategy of starting the movement straight up towards the center and make their decision later on in the movement which response to make, causing more curvature in the mouse trajectory. The implication of such an account is that the angle of the initial movement should be no different for either one of the shared locations, because movements to either location begin by moving towards the center.

To test this, I identified the time point at which the angle of movement was statistically different for movements towards locations two and five. Each trial's trajectory was re-sampled 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 two and five. 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 a strategy. That is, the increased curvature in the *SC-RC* condition does not appear to stem from greater use of a strategy in which participants 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 further test whether the differences in curvature resulted from some participants in the *SC-RC* condition moving forward before deciding which target to go to, the same stimulus x response x time analysis above was re-ran but removed individuals who did not show significant differences in the angle of their movement to targets two and five in the first 10% of the normalized movement. This tested 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, 9 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 x stimulus x response interaction remained significant, $F_{\text{shared}}(8,472) = 4.77$, $\eta_p^2 = .078$, $p < .001$, and the stimulus x response interaction was significant for the total amount of curvature, $F_{\text{shared}}(1,59) = 6.22$, $\eta_p^2 = .095$, $p < .05$.

In sum, this experiment provides evidence that stimulus and response similarity affect response selection and in a surprising way: When both dimensions were close, there was more curvature and error in the trajectories. This suggests that the S-R representations were sensitive to the metric properties of both the stimuli and responses. That is, the interaction appeared to be driven by competition among the S-R alternatives at a level of processing that was sensitive to both stimulus and response features (response selection). When either the stimulus alternatives or response alternatives were ‘far’ from each other, the overall competition was less as evidenced by less error and less curvature in the trajectory.

Experiment 2: Accuracy

In Experiment 1 participants were forced to make their response within one second to ensure that deviations in their trajectories reflected decisions unfolding in real-time. That is, I attempted to discourage participants from withholding their movements until they were completely planned. However, this instruction led to rejecting a lot of movements that were not clearly directed to one of the possible target locations (as discussed above). Therefore, to alleviate the uncertainty of which trials to include in the analyses participants had to respond by moving the mouse cursor to one of the response locations and ‘click’ the mouse. This made it easier to determine if participants either made the correct or incorrect response. Further, the time pressure was removed. This was done to ensure that the pattern of results found in Experiment 1 was not due to task demands. Thus, Experiment 2 sought to determine how task demands (speed vs accuracy) affected performance, specifically with regard to the curvature of the trajectory, by having participants make very precise responses.

Method

Participants

A total of eighty-eight 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 forced to make a response by ‘clicking’ the mouse when the mouse cursor was in one of the response locations. 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 less than 1,500 ms (7%) were removed. Again, this was a fairly difficult task but 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 x 2 (stimulus x response) between-subject ANOVA, there was a main effect of stimulus, $F(1,76) = 82.44$, $\eta_p^2 = .52$, $p < .001$, as close stimuli were more difficult to discriminate than far stimuli, but neither response, $F < 1$, nor the interaction, $F < 1$ were significant.

Movement timing

Initiation time was submitted to a 2 x 2 (stimulus x response) between-subject ANOVA. There was an effect of stimulus, $F_{\mathrm{all}}(1,76) = 20.40$, $\eta_p^2 = .211$, $p < .001$, $F_{\mathrm{shared}}(1,76) = 21.32$, $\eta_p^2 = .219$, $p < .001$, as close stimuli produced longer ITs than far stimuli for all locations (M_{far}= 338 ms, M_{close}= 412 ms) and shared locations (M_{far}= 338 ms, M_{close}= 419 ms), and an effect of response, $F_{\mathrm{all}}(1,76) = 32.86$, $\eta_p^2 = .302$, $p < .001$, $F_{\mathrm{ahared}}(1,76) = 34.08$, $\eta_p^2 = .310$, $p < .001$, as far responses produced slower ITs than close responses for all locations ($M_{\mathrm{far=}}$ 404 ms, M_{close}= 346 ms) and shared locations (M_{far}= 411 ms, M_{close} = 346 ms), but the interaction was not significant, $F_{all} < 1$, $F_{\mathrm{shared}}(1,76) = 1.18$, $\eta_p^2 = .015$, $p = .28$ (see Table 2 for the individual values). Even with no time pressure and having participants make very precise movements, that data mirror that of Experiment 1.

As in the previous experiment MT was submitted to an identical ANOVA. Unlike IT there was no effect of stimulus, $F_{\mathrm{all}}(1,76) = 1.43$, $\eta_p^2 = .018$, $p = .24$, $F_{\mathrm{shared}}(1,76) = 3.35$, $\eta_p^2 = .042$, $p = .071$, no effect of response, $F_{\mathrm{all}}(1,76) = 1.70$, $\eta_p^2 = .022$, $p = .196$, $F_{\mathrm{shared}}(1,76) = 3.09$, $\eta_p^2 = .039$, $p = .083$, and the interaction was not significant, $F_{\mathrm{all}}(1,76) = 1.15$, $\eta_p^2 = .287$, $p = .29$, $F_{\mathrm{shared}}(1,76) = 1.18$, $\eta_p^2 = .022$, $p = .281$ (see Table 2 for individual values). The data suggests that the pattern observed in MT for Experiment 1 appears to result from the time-pressure demand.

Table 2. Mean initial times (IT) and movement times (MT) for all four conditions across all and shared locations.

Stimulus	**Response**	**IT**		**MT**	
		All (ms)	*Shared (ms)*	*All (ms)*	*Shared (ms)*
SC	*RC*	378	380	820	862
SC	*RF*	447	459	752	756
SF	*RC*	314	313	759	769
SF	*RF*	362	363	769	763

Movement trajectory

Trajectories were analyzed in the same fashion as in Experiment 1 however, unlike Experiment 1 I could not assess error along the X axis as participants had to respond within one of the response locations. Thus, the curvature data was the focus. Overall curvature was first analyzed by submitting the data to a 2 x 2 (stimulus x response) between-subject ANOVA. There was a main effect of stimulus, $F_{shared}(1,76) = 20.67$, $\eta_p^2 = .214$, $p < .001$, of response, $F_{shared}(1,76) = 17.07$, $\eta_p^2 = .183$, $p < .001$, and critically, the interaction was significant, $F_{shared}(1,76) = 5.41$, $\eta_p^2 = .066$, $p < .05$, as the *SC-RC* condition had more curvature than the *SF-RC* condition (see Figure 5a). The data suggest, as with Experiment 1, that when both dimensions were similar there was more competition among the S-R alternatives.

I also submitted the trajectories' deviation from a straight line to a 2 x 2 x 9 (stimulus x response x time slice) mixed ANOVA. There was a main effect of time, $F_{shared}(8,608) = 157.21$, $\eta_p^2 = .668$, $p < .001$, and a time x stimulus interaction, $F_{shared}(8,608) = 8.28$, $\eta_p^2 = .098$, $p < .001$, and a time x response interaction, $F_{shared}(8,608) = 7.07$, $\eta_p^2 = .085$, $p < .001$. Critically, the time x stimulus x response interaction was significant, $F_{shared}(8,608) = 5.13$, $\eta_p^2 = .063$, $p < .001$ (see Figure 5b). As with Experiment 1, I evaluated when in the movement the interaction occurred. Every 10th time slice was submitted to a 2 x 2 (stimulus x response) between-subject ANOVA and to control for where the movement had been the previous time slices were used as covariates. Time-slice four (approximately 40% into the movement), $F_{shared}(1,74) = 15.235$, $\eta_p^2 = .171$, $p < .001$, time-slice five, $F_{shared}(1,73) = 13.965$, $\eta_p^2 = .161$, $p < .001$, and time-slice six, $F_{shared}(1,72) = 4.816$, $\eta_p^2 = .063$, $p < .05$ were significant, suggesting that even during the middle of the movement there was significant competition in the *SC-RC* condition compared to the others.

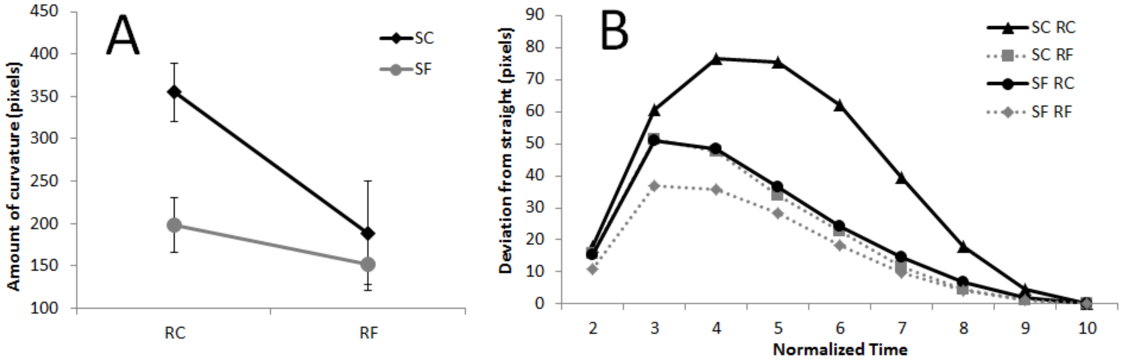

Figure 5. Total curvature for all four conditions and deviation from a straight line across normalized time.

As with the previous experiment I wanted to rule out that the increase in curvature for the *RC* conditions was not the result of a strategy of moving towards the center of the screen before making a decision. Thus, I identified the time point at which the angle of movement statistically differed for movements towards locations two and five. Again, 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 two and five 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 with the previous experiment, participants who displayed the ‘move first, decide later’ strategy were removed from the trajectory analyses. These participants were identified as ones who did not show a difference in the angle of their movement to targets two and five 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 x response curvature interaction was marginally significant, $F_{shared}(1,70) = 3.38$, $\eta_p^2 = .046$, $p = .07$, though the time x stimulus x response interaction remained highly significant, $F_{shared}(8,560) = 6.00$, $\eta_p^2 = .079$, $p < .001$. Thus, as with Experiment 1 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 this experiment compared to the previous experiment. 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 threshold for which response to make. Further, having no time pressure resulted in movements that took more time to make (initiation time + movement time). Requiring more evidence for a response to be made along with an increase in the movement's total time might have led to prolong competition, which led to the increase in curvature. However, this will have to be directly tested to determine if this was the case.

In general, the data from Experiment 2 replicate those from Experiment 1 well, particularly with regard to the ITs and trajectory curvatures. Specifically, curvature was driven by an interaction between stimulus and response. This suggests that even with different tasks demands (speed vs accuracy) the metrical properties of the task influence response selection. This finding is inconsistent with feed forward models of response selection and underscores the role that the relationship between the stimulus and response properties plays in RS processes.

Experiment 3: Visual Discrimination

Experiments 1 and 2 demonstrated that endpoint error and trajectory curvature were 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 discrimination was more difficult). Thus, it was an open question as to the cause of the interaction, which might have resulted from the similarity manipulation or an increase in the perceptual difficulty.

To test this possibility Experiment 2 replaces the similarity manipulation with another manipulation, stimulus size that also affects difficulty. While smaller stimuli may take longer to identify, they likely do not co-activate representations of competing S-

R alternatives as similar stimuli do. If the similarity leads to competing central codes but the size does not, then the size of the stimuli should not affect the shape of the trajectories. This is because the size manipulation taps into the perceptual processes, specifically encoding and classification, but not response selection (Pashler, 1991). However, 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.

The interaction in Experiments 1 and 2 was driven by the difference between the *SF-RC* and *SC-RC* conditions. Therefore, to test whether a size manipulation could produce changes in the amount of curvature a within-subject manipulation of size based on the *SF-RC* condition was utilized. The *RC* condition was used because those conditions previously produced the most curvature. The *SF* condition was used so that the stimuli were not similar in hue. If the stimulus x response interaction was driven by perceptual difficulty, then small stimuli should produce the most curvature (compared to the large stimuli) similar to the *SC-RC* condition.

Method

Participants

A total of seventeen 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 mins). Ages ranged from 18-24 years old.

Procedure

The experiment followed the same procedure as Experiment 1. In particular, participants ran in the *SF-RC* condition with the added component that the stimuli were either large (150 x 150 pixels) or small (15 x 15 pixels) in size, compared to 100 x 100 pixels in Experiments 1 and 2. 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 1 and 2. As in Experiment 1, participants had 930 ms to make their mouse movements. I 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 1.

Movement Timing

There was a small but statistically significant difference between the percentage of correct trials, $t(13) = 5.165$, $p < .001$, 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, $t_{\text{all}}(13) = 7.816$, $p < .001$, ($M_{\text{large}} = 276$ ms, $M_{\text{small}} = 287$ ms); $t_{\text{shared}}(13) = 8.335$, $p < .001$, ($M_{\text{large}} = 282$ ms, $M_{\text{small}} = 294$ ms). However, the large stimuli had a higher MT than the small stimuli, $t_{\text{all}}(13) = 8.064$, $p < .001$, ($M_{\text{large}} = 557$ ms, $M_{\text{small}} = 549$ ms); $t_{\text{shared}}(13) = 6.923$, $p < .001$, ($M_{\text{large}} = 552$ 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 to when the stimulus was large.

Movement trajectory

The trajectories were analyzed in the same manner as in Experiment 1. Error along the X-axis was first considered. There was no difference found between the large (6 pixels) and small stimuli (7 pixels), $t_{\text{all}}(13) < 1$; $t_2(13) = 1.167$, $p = .264$. Next, the total amount of curvature was analyzed. As with error along the X-axis there was no difference between large and small stimuli, $t_{\text{shared}}(13) = 1.10$, $p = .287$, ($M_{\text{large}} = 163$, $M_{\text{small}} = 153$). This holds for the other two locations as well, t's < 1 (see Figure 6). The data were also submitted to a 2 x 9 (size x time slice) within-subject ANOVA. There was a main effect of time, $F_{\text{shared}}\ (8,256) = 130.47$, $\eta_p^2 = .803$, $p < .001$, 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 response dimensions extends into response selection 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.

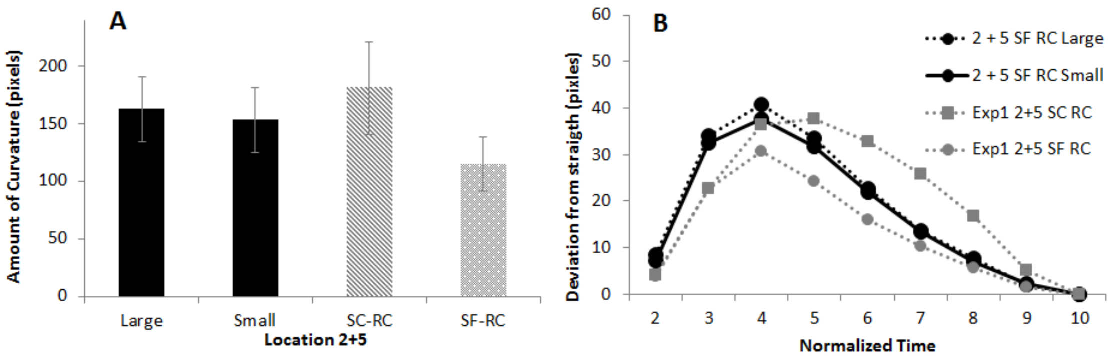

Figure 6. Panel A depicts the total amount of curvature for large and small stimuli as well as the SC-RC and SF-RC conditions from Experiment 1. Panel B depicts deviation from straight across normalized time for locations 2 and 5 along with conditions SC-RC and SF-RC from Experiment 1.

The results from Experiments 1 and 2 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 3 demonstrates that an alternative manipulation of the difficulty of the stimulus discrimination 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 1 and 2 were due to similarity increasing the competition among S-R representations that include metrical properties of both the stimuli and responses.

Experiment 4: Spatial Frequency

This experiment was designed to replicate the stimulus x response interaction found in the previous experiment using a different set of stimuli compared to color patches. There have been numerous studies (Liberman, Harris, Hoffman, & Griffith, 1957; Roberson, Hanley, & Pak, 2009; Winawer et al., 2007) demonstrating that participants were faster and more accurate discriminating between colors that belong to different categories than colors within the same category, even when colors were equally spaced across a perceptual metric, (e.g., CIE). This is known as categorical perception when a continuous dimension (e.g., color) is perceived as having discrete qualitative changes at category boundaries. Thus, the perception of a color might change depending on if it was close to a category boundary or not. This would suggest that the close colors (blue, bluish green, greenish blue, and green) might not have been perceived as equally similar and performance was affected because of it.

This was an intriguing possibility however; discrimination thresholds were fairly similar across categories and at the boundary between categories (e.g., blue/green; Roberson, Hanley, & Pak, 2009) suggesting even if perceived differently the colors were equally discriminable. Within a category participants show differences in mouse trajectories that are sensitive to the variations in hue (Huette & McMurray, 2010). This indicates that even within a category differences in performance can be found.

Given the concern of using colors and to extend the findings using another stimulus set spatial frequency patterns were used because they tap into early visual processing and avoid the use of category and verbal labels.

Method

Participants.

A total of 90 undergraduate students participated in this experiment for course credit. Ten participants were dropped from the analyses because of poor behavioral performance and failure to complete the experiment. Thus, there was a total of 80 participants, twenty in each group.

Procedure.

The experiment closely followed the procedures from Experiment 1 (including time pressure). This was done to aid in the comparison between the experiments. There were three changes to the procedure: first, the type of stimuli was spatial frequency patterns that were either similar to each other (close condition) or dissimilar (far condition), however, their discriminability was kept constant across the different patterns (see Figure 7). Second, the stimulus was only presented for 450 ms and finally, at the end of a trial a tone was played when the participant's final cursor position was not closer than 45 pixels from the correct location. This was to aid the participant in learning what stimulus went with which response location. The final position as well as the correct location was also marked at the end of each trial.

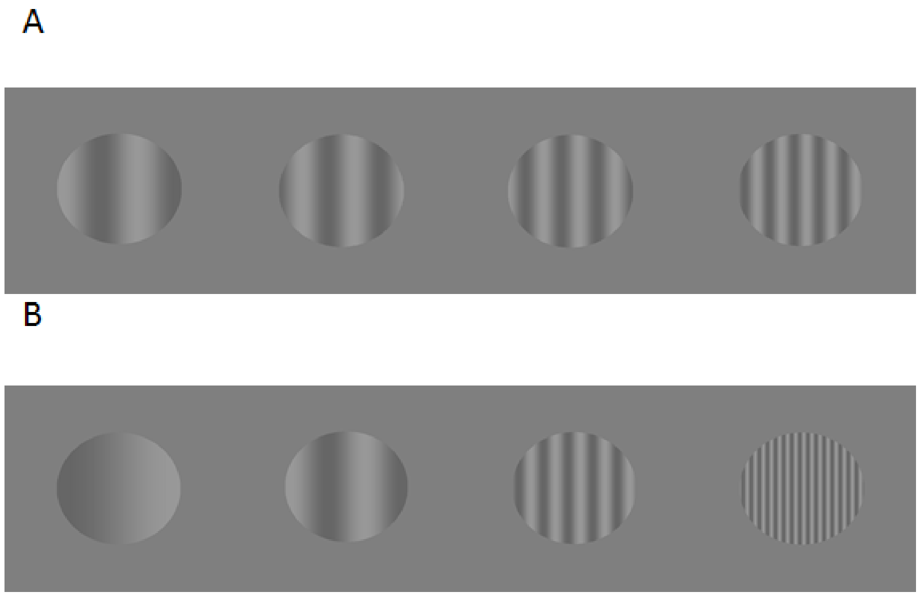

Figure 7. The spatial frequency images used in Experiment 4. Panel A depicts the close spatial frequency patterns and Panel B depicts the far spatial frequency patterns.

Results

Trials in which the IT was less than 50 ms (1%), movement times that were less than 1000 ms (1%), and movements that resulted in a final position more than 50 pixels away from the correct location were all removed from the analyses. As with Experiment 1, 45 pixels were chosen as the cut off to ensure the final position was closer to the correct location than to any other location. 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 and spatial frequency patterns, and these criteria eliminated 40% of the data.

For Experiments 1 and 2 there was no difference in the IT and MT for all or shared locations, as well as error along the X-axis (Experiment 1). Given the goal of this experiment was to replicate the critical findings from Experiment 1 and 2 and those data come from the shared locations only their data was analyzed and discussed below.

Movement timing

Initiation time was submitted to a 2 x 2 (stimulus x response) between subject ANOVA. There was a main effect of stimulus, $F(1,76) = 4.07$, $\eta_p^2 = .051$, $p < .05$, as close stimuli had a longer IT than far, ($M_{close} = 324$ ms, $M_{far} = 304$ ms) and a marginally significant effect of response, $F(1,76) = 3.37$, $\eta_p^2 = .042$, $p = .07$, as close response had a fast IT than far responses, ($M_{close} = 305$ ms, $M_{far} = 323$ ms). The interaction was not significant, $F<1$. The non-significant interaction replicates the findings from Experiments 1 and 2.

Movement time was submitted to the same analysis as IT. There was no effect of stimulus, $F(1,76) = 1.85$, $\eta_p^2 = .024$, $p = .177$, though response was marginally significant, $F(1,76) = 3.50$, $\eta_p^2 = .044$, $p = .065$, with close responses having a longer MT than far ($M_{close} = 547$ ms, $M_{far} = 532$ ms). The stimulus x response interaction was not significant, $F(1,76) = 1.42$, $\eta_p^2 = .018$, $p = .238$. The IT and MT data replicate those data found in Experiments 1 and 2. There was a slight tradeoff between IT and MT as faster IT’s lead to longer MT’s. The key measure was whether the stimulus x response interaction was replicated with using non-color stimuli.

Table 3. The IT's and MT's for the shared locations.

Stimulus	**Response**	**IT**	**MT**
SC	RC	291	558
SC	RF	337	521
SF	RC	295	552
SF	RF	301	548

Movement trajectories

The movement trajectories were processed and analyzed in a similar format as they were in Experiment 1. First the error along the X-axis was considered. The data was submitted to a 2 x 2 (stimulus x response) between-subject ANOVA. The effect of stimulus was marginally non-significant, $F(1,76) = 3.02$, $\eta_p^2 = .038$, $p = .086$, but neither response, $F < 1$, nor the interaction, $F(1,76) = 1.70$, $\eta_p^2 = .022$, $p = .196$, were significant. The amount of error along the X-axis was lower in this experiment than Experiment 1, less than 5 pixels in each condition.

Curvature data was submitted to a 2 x 2 (stimulus x response) between-subject ANOVA. There was a main effect of stimulus, $F(1,76) = 5.30$, $\eta_p^2 = .065$, $p < .05$, as close stimuli resulted in more curvature than far stimuli (M_{close} = 147 pixels, M_{far} = 120 pixels), a main effect of response, $F(1,76) = 48.89$, $\eta_p^2 = .391$, $p < .001$, as close responses resulted in more curvature than far, (M_{close} = 175 pixels, M_{far} = 92 pixels), and most importantly the interaction was significant, $F(1,76) = 7.97$, $\eta_p^2 = .095$, $p < .01$.

These data resemble those found in Experiments 1 and 2 as there was more curvature in the *SC-RC* condition (see Figure 8). When both dimensions were close there was more competition resulting in more curvature.

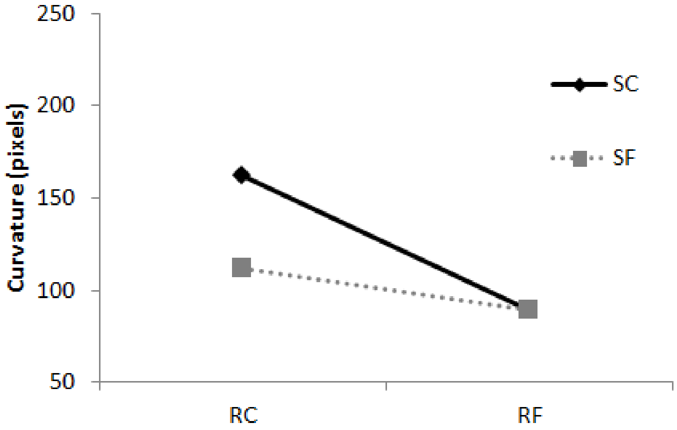

Figure 8. Curvature across all four conditions. SC = stimulus close; RF = response far.

The goal of this experiment was to replicate the stimulus x response interaction in the curvature data using a different set of stimuli. Previous research has suggested that participants perceive color as having discrete qualitative changes at category boundaries. Thus, the close colors from Experiments 1 and 2 might not have been perceived as equally similar and performance was altered because of it. The data were consistent with what was found in Experiments 1 and 2, indicating that this interaction generalizes with a different set of stimuli. It was not clear why the interaction previously found in the endpoint error data was not replicated here. The endpoint error was not that variable between conditions and in general, endpoint error was not seen as a measure of co-activation between S-R alternatives as curvature was.

Chapter Discussion

To investigate how stimulus and response similarity influence central operations, participants were asked to move a computer mouse to target locations depending on the identity of the cue. The two forms similarity interacted such that there was more end point error and curvature when both were similar, suggesting that RS processes were sensitive to the features of the stimuli and responses. The data were replicated when instructions emphasized speed and when instructions that emphasized accuracy, suggesting that this interaction does not stem from task demands. The curvature data was also replicated when the stimuli were spatial frequency patterns, demonstrating that the interaction generalizes not just color patches but other stimuli as well. Further, the interaction does not appear to result from participants deferring the selection of the appropriate response location. 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 perceptual difficulty, I ran an additional experiment in which the similarity manipulation was replaced with a stimulus size manipulation (that affected perceptual difficulty). Although size affected initiation time, it did impact the amount of curvature, indicating that perceptual difficulty per se does not increase in the curvature of the trajectories.

This interaction between stimulus and response similarity runs counter to theories of RS that propose central operations operate on abstract symbols that are devoid of metrical and modal information (Anderson et al., 2004; Pashler, 1994a). If RS receives categorized stimuli as inputs and returns abstract response codes as output, as predicted by traditional RS theories, then there should not have been an interaction between stimulus and response similarity. Instead, the interaction between stimulus similarity and response similarity on curvature appears to be driven by partial activation among the S-R alternatives.

What leads to this partial activation? Participants formed fast, flexible associations between stimuli and responses (Buss, Wifall, Hazeltine, & Spencer, 2013) that were sensitive to metrical information and, thus, influenced the competition between S-R representations. For example, in the *SC-RC* condition, the co-activation of the other similar colors and the overlap of response options lead to more competition and the largest curvature. The other S-R alternatives were metrically close along both the stimulus and response dimensions within central representations of the task. These central representations, then, overlap in activation on a given trial and pull the trajectory to other potential response locations leading to more curvature. Critically, competition was not the result of stimulus or response similarity alone but instead stems from overlap between central representations that are composed of both types of information.

Though the stimulus x response interaction of curvature was replicated across three different experiments there were methodological issues of the layout of the response locations that might have led to the increase in curvature for *SC-RC* condition. Chapter 4 addresses these issues.

CHAPTER 4

THE ROLE OF CONFIGURATION AND METRICS

Experiments 1, 2, and 4 revealed a stimulus by response interaction indicating that when both dimensions were close there was more curvature and error in the trajectories. I proposed this was due to increased competition between the S-R alternatives in the *SC-RC* condition compared to the other conditions. There were two factors that potentially influenced trajectories in Experiments 1, 2, and 4; metrics (i.e., the spatial distance between response locations) and configuration of the response locations (i.e., the layout). In Experiments 1, 2, and 4 when the responses were close and the target was one of the shared locations all of the competitors were on one side of the target (see Figure 1). In contrast, the shared locations in the far response condition had competitors on either side of the target (i.e., one competitor on one side and two competitors on the other side). For example, when a participant moved to location 2 in the *RF* condition, location 1 was to the left and locations 5 and 6 were to the right; compared to in the *RC* condition, when moving to location 2 there were only competitors to the right of the target. One of the goals of this chapter was to understand the role that configuration of targets and competitors played in the stimulus by response interaction found in Experiments 1, 2, and 4.

To do this, Experiment 5 (and 6) utilized an experiment in which a participant selected a target that was defined as being the ‘odd color’ (e.g., selecting the red square in the presence of two blue distractors). The location of the target was either flanked by competitors (the target was *inside* the competitors; this condition resembled the *far* response condition from Experiments 1, 2, and 4) or the competitors were to one side of the target (this condition resembles the *close* response condition from Experiments 1, 2, and 4; the target was *outside* the competitors; see Figure 9 panels A and B). With this design the metrics (i.e., the spatial distance between responses) did not change but the configuration did. Figure 9 (panels A and B) shows two different configurations (of the possible 3, see procedure). The target (the hashed square) was either to one side of the competitors (outside condition) or flanked by the competitors (inside condition). The critical comparison was to measure the curvature when the target was inside the competitors compared to when the target was outside the competitors. If the increase in curvature for the *SC-RC* condition was due in part to the configuration of the responses then there should be more curvature when the target was outside of the competitors compared to when the target was inside the competitors. To be clear this study was designed to better understand how the configuration of the responses impacted the interaction between stimulus and response similarity, not to rule out the role of competition between S-R alternatives.

The goal of Experiment 6 was to isolate the role that metrics play in the stimulus x response interaction while holding configuration constant. To do this, I used the same odd color task from Experiment 5; however, the response locations were ‘closer’ in space (see Figure 9 panels C and D). To make the metric manipulation clear Figure 9 (panels C and D) shows all of the possible response locations in Experiment 5 and 6, though on any trial only three locations appeared. To get a measure of the influence that metrics played in the interaction, the curvature in Experiments 5 and 6 were compared when participants moved to the same spatial location within the same configuration. The constraints of Experiment 6’s design (moving the response locations closer together) meant that the only comparison that could be made between experiments was for the conditions when the target was outside the competitors.

Finally, for both of the experiments color similarity was manipulated as well. The target color was either similar or dissimilar to the distractor. The previous experiments demonstrated the importance of stimulus similarity and this manipulation was intended to allow for the exploration of whether stimulus similarity interacts with configuration and metrics separately. It was expected that stimulus similarity would interact with both configuration and response metrics because similar stimuli should partially activate the other S-R alternatives.

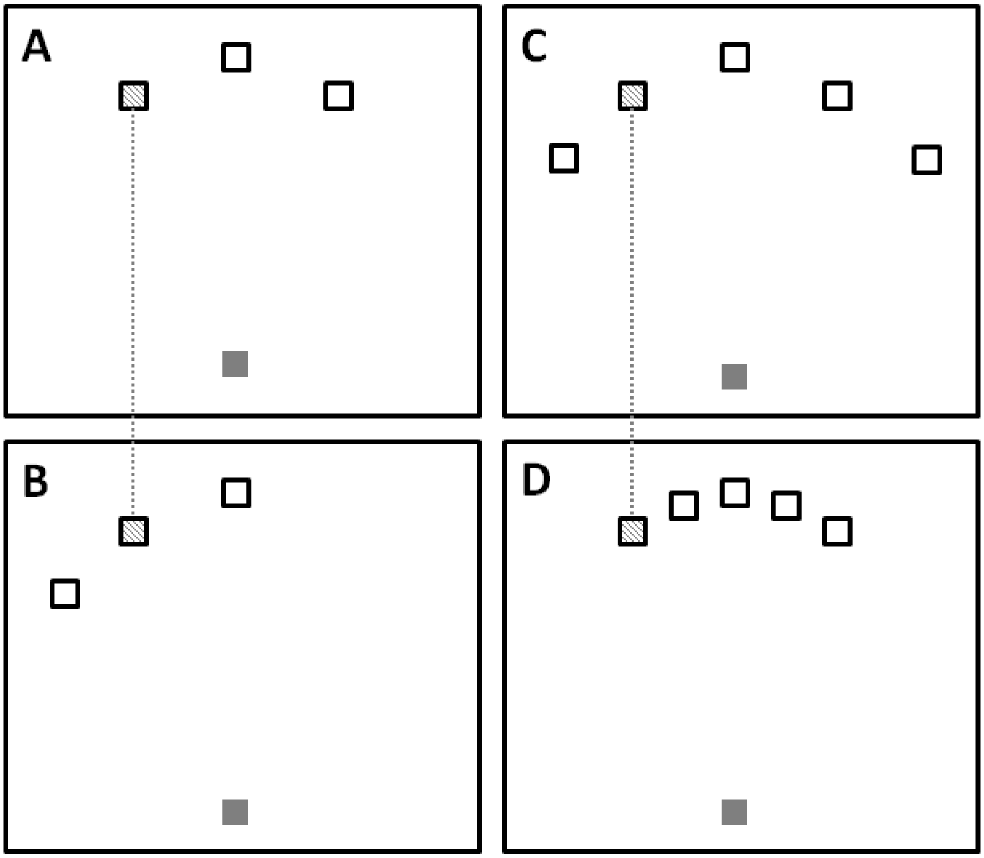

Figure 9. Panels A and B show the configuration manipulation in Experiment 5. The same target had either two competitors to one side or two competitors flanking it. Panels C and D show the metric manipulation between Experiments 5 and 6. Panel C represents the layout of all possible locations in Experiment 5 and Panel D represents the layout of all the possible locations in Experiment 6.

Experiment 5: The role of configuration

The goal of Experiment 5 was to determine how curvature was affected by configuration while holding response similarity constant.

Method

Participants

Forty-five participants ran in this experiment, with five participants not completing the experiment resulting in forty participants. Participants completed the experiment for course credit.

Procedure

The task was modified after the odd color task developed by Song and Nakayama (2006, 2007). Each trial required a participant to select the odd color amongst three color stimuli by making a mouse movement towards it. There were two types of trials: baseline and test trials. Baseline trials were trials in which only one stimulus was presented, whereas test trials were trials in which the odd color was presented with two distractors. There were four colors that were used (RGB value): blue (74,128, 182), blueish green (23, 136, 156), orange (211, 103, 44), and reddish orange (237, 82, 68) that allowed for the relationship between the target and distractors to be close or far.

There were a total of five different locations that stimuli could appear at. The x,y locations were 353, 164; 485, 129; 620, 117; 755, 129; and 887, 164 (see Figure 9, panel C). Locations 2 and 4 were at the same locations as the shared locations in Experiments 1-4. Three consecutive locations were used for each trial and they appeared in one of three configurations. Configuration 1 consisted of locations 1, 2, and 3, configuration 2 consisted of locations 2, 3, and 4, and configuration 3 consisted of locations 3, 4, and 5 (see Figure 9 panels A and B for configurations 1 and 2). For each configuration the target appeared in each of the locations equally. The target had the distractors to one side or the target was located in the middle of the distractors. Of primary interest was how a movement to one of the shared locations changed as a result of all the distractors being on one side (hereafter referred to as the outside condition) or when the distractors flanked the target (hereafter referred to as the inside condition) and was this change modulated the similarity between the target and distractor.

The stimuli were presented and responses collected using PC computers running Visual Basic software. A trial started with moving the mouse cursor to a start box at the bottom of the screen (like the previous experiments) and after 1,000 ms the three stimuli appeared in one of the configurations. Only the start box was visible between trials. Participants had 1469 ms to make a response by moving their mouse cursor to the odd color. If their final position was more than 35 pixels away they heard a 220 Hz tone for 250 ms and a white box (10 x 10 pixel) appeared over the correct location. To begin the next trial participants moved their cursor to the start box again. Participants sat 66 cm away from the screen resulting in a visual angle of 1.65 degrees.

Results

Before the analysis, data were trimmed so that movements that had an IT less than 100 ms or greater than 800 ms (1%) and MTs less than 1000 ms (10%) were removed. Only movements to the shared locations were considered for the analyses.

Movement timing

To determine the influence that the competitors had on the movement timing baseline versus test trials were first considered for initiation times. There was no difference in initiating a movement to one of the shared locations for baseline or test trials, $t<1$, ($M_{baseline}$ = 290 ms, M_{test} = 291 ms), which replicated Song and Nakayama (2007). Next, IT data was submitted to a 2 (target in vs target out) x 2 (stimulus close vs stimulus far) within-subject ANOVA to determine the influence that target/competitor location and target/competitor similarity had on performance. There was a main effect of target location (inside vs outside), $F(1,39) = 4.15$, $\eta_p^2 = .096$, $p < .05$, as IT was faster for an inside target location than outside location ($M_{inside} = 290$ ms, $M_{outside} = 296$ ms) and a main effect of stimulus similarity, $F(1,39) = 10.78$, $\eta_p^2 = .216$, $p < .01$, as close stimuli had a longer IT than far stimuli ($M_{close} = 297$ ms, $M_{far} = 289$ ms). The interaction failed to reach significance, $F<1$. These results were consistent with the previous Experiments 1-2 demonstrating that close stimuli leads to longer ITs.

Movement times were analyzed in the same manner as the ITs. Movement times were significant faster in baseline trials than test trials, $t(39) = 6.26$, $p < .001$, ($M_{baseline} = 705$ ms, $M_{test} = 730$ ms). The influence of the target location and target/distractor color similarity was determined by submitting MTs to a 2 (target in vs target out) x 2 (stimulus close vs stimulus far) within-subject ANOVA. There was a main effect of stimulus similarity, $F(1,39) = 70.67$, $\eta_p^2 = .644$, $p < .001$, as close stimuli had a longer MT than far stimuli ($M_{\mathrm{close}} = 759$ ms, $M_{\mathrm{far}} = 719$ ms), however, there was no effect of target location, $F(1,39) = 2.74$, $\eta_p^2 = .066$, $p = .11$, and the interaction failed to reach significance, $F<1$.

Table 4. Initiation time and movement time for close and far colors across in and out target locations.

Color	**IT**		**MT**	
	In (ms)	*Out (ms)*	*In (ms)*	*Out (ms)*
Close	295	300	757	761
Far	285	292	715	722

Movement trajectories

Trajectories were analyzed in the same manner as in Experiment 1. To assess the influence of the competitors' presence on the screen baseline and test trials were compared. There was more curvature in test trials than in baseline trials (M_{test} = 97 pixels, $M_{baseline}$ = 89 pixels), though the difference did not reach statistical significance, $t(39) = 1.56$, $p = .15$. However, the difference in curvature was significantly different for location 2, $t(39) = 7.20$, $p < .001$ (M_{test} = 134 pixels, $M_{baseline}$ = 85 pixels) and location 4, $t(39) = 4.16$, $p < .001$, (M_{test} = 53 pixels, $M_{baseline}$ = 93 pixels). These data replicate the results from Song & Nakayama (2007) where there was more curvature in the trajectory during test trials than in the baseline trials.

Curvature data was then submitted to a 2 (target in vs target out) x 2 (stimulus close vs stimulus far) within-subject ANOVA. There was a main effect of target location, $F(1,39) = 49.81$, $\eta_p^2 = .561$, $p < .001$, as out locations had more curvature than in locations, (M_{out} = 168 pixels, M_{in} = 103 pixels) and a main effect of stimulus similarity, $F(1,39) = 119.28$, $\eta_p^2 = .754$, $p < .001$, as close stimuli lead to more curvature than far stimuli, (M_{close} = 170 pixels, M_{out} = 100 pixels). The target location x stimulus similarity was also significant, $F(1,39) = 29.51$, $\eta_p^2 = .431$, $p < .001$, as there was more curvature when the target location was out and the colors was close (see Figure 10). These results indicate that when the competitors were located to one side of the target the amount of veer towards the competitors increased when there was more competition between the target and competitors. When the stimuli were far and the target was out there was less competition and thus, less pull towards the competitors resulting in less curvature.

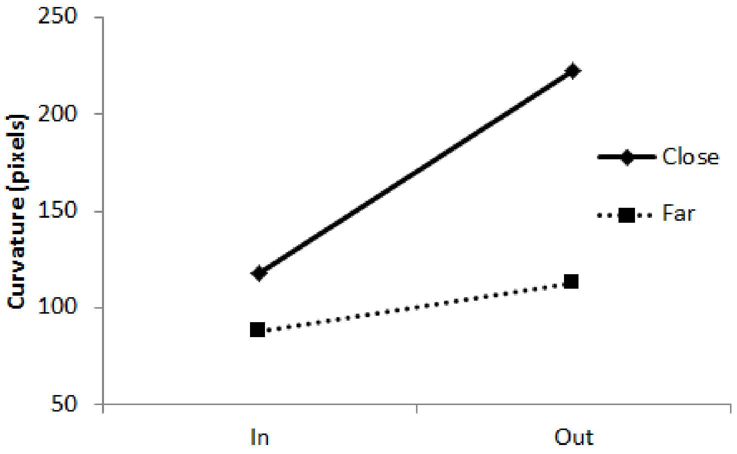

Figure 10. Curvature when the target was in or outside of the competitors across close and far stimuli.

The close stimuli also had the longest IT and MT, which suggests that this was the most difficult condition. Therefore, the increase in difficult might have led to the more curvature as participants moved towards the center of the configuration. To rule out this possibility participants who did not have a difference in their initial angle moving towards one of the shared locations in configuration 2 for close stimuli were removed from the analysis, which resulted in the removal of 35 participants. Then the same 2 (target in vs target out) x 2 (stimulus close vs stimulus far) within-subject ANOVA was performed. The pattern of the data was the same as before and the interaction was marginally significant, $F(1,39) = 6.49$, $\eta_p^2 = .619$, $p = .06$.

The goal of this experiment was to determine the role that the configuration of the response locations had on mouse movements while holding response similarity constant. The results clearly indicate that the trajectories were affected by the location of the competitors in relation to the target. These results were also consistent with the notion that close stimuli led to more competition between the S-R alternatives as there was an interaction between stimulus similarity and configuration. There was more curvature when the target was outside the competitors than when the target was inside when the target and competitor were similar colors. In other words, if the target was on the outside there was a greater pull by the competitors when the stimuli were close.

The purpose of the Experiment 6 was to further explore the role that response similarity plays in the interaction found in Experiments 1, 2, and 4. It was argued at the end of the last chapter that both stimulus and response properties were important in producing the interaction. Given that the configuration of the response locations influences RS processing, it remains an open question of what role does response similarity play in influencing mouse movements. In other words, if the configuration was held constant but the spatial relationship between response locations were changed, how would that affect the curvature of the trajectory?

Experiment 6: Configuration and metrics

The purpose of Experiment 6 was to determine the role of response metrics while holding configuration constant. To do this, curvature to the same spatial location and within the same response configuration was compared across experiments (Experiment 6 to Experiment 5). Experiment 6 followed the same procedures as Experiment 5 and to manipulate metrics, Experiment 6 had response locations that were closer together in space than Experiment 5 (see Figure 8 panels C and D). The purpose of Figure 8 (panels C and D) was to provide a visual representation of the metric relationship between all the response locations though on any trial only three locations appeared. Because of the layout of the response locations for Experiment 6, the only configuration that allowed for a comparison between Experiments 5 and 6 was when the target was in an outside condition. As with Experiment 5, the target appeared both inside and outside the competitors in Experiment 6 however, because the primary goal was to hold configuration constant and to assess the role that response metrics play only the data for the outside condition were reported.

As with Experiment 5 color similarity between target and competitors was also manipulated in this experiment. Thus, it could be determined if there was interaction between stimulus and response similarity, within the same configuration.

Method

Participants

A total of 44 participants ran in this experiment for course credit. Four participants were thrown out because of failure to complete the experiment.

Procedure

The procedure was the exact same as laid out in Experiment 5. The only difference was the location of the response locations: location 1 was (485, 129), location two (552, 120), location three (620, 117), location four (689, 120), and location 5 (755, 129). Location 1 and 4 were in the same spatial location as the shared location in the previous experiments.

Results

The data was trimmed as in the previous odd color experiment so that movements that had an IT less than 100 ms or greater than 800 ms (1%) and MTs less than 1000 ms (11%) were removed.

The primary analysis was to compare how performance to the shared locations changed based on the distance from the target to the competitor. To do this analysis it was necessary to compare performance across experiments, specifically, the endpoints in this experiment (locations 1 and 6) and the locations 2 and 4 in the Experiment 5 in the out condition. Thus, performance was measured as a basis of metrics (the distance of the target to the competitor) within the same configuration and determined if response distance interacts with close or far colors.

Movement timing

The data for the endpoints in this experiment was first considered. There was no difference in IT for close or far colors at the endpoint locations, $t(39) = 1.21$, $p = .24$, ($M_{close} = 294$ ms, $M_{far} = 288$ ms). To determine if IT changed as a function of target/distractor distance IT data was submitted to a 2 x 2 (stimulus similarity x experiment) mixed ANOVA. There was a main effect of color similarity, $F(1,78) = 4.44$,

$\eta_p^2 = .054$, $p < .05$, close colors had a longer IT than far colors ($M_{close} = 297$ ms, $M_{far} = 290$ ms) but no effect of experiment, $F<1$, nor was the interaction significant, $F<1$.

Movement time data was analyzed in the same manner as the IT data. There was a significant difference between close and far colors, $t(39) = 2.21$, $p < .05$, as close colors had a longer MT than far colors ($M_{close} = 760$ ms, $M_{far} = 748$ ms). Next, MT data was submitted to a 2 x 2 (stimulus similarity x experiment) mixed ANOVA to determine how target/distractor distance affected MT. There was no effect of experiment, $F(1,78) = 1.29$, $\eta_p^2 = .016$, $p = .26$, but there was a main effect of color, $F(1,78) = 40.13$, $\eta_p^2 = .340$, $p < .001$, as close colors had a longer MT than far colors ($M_{close} = 761$ ms, $M_{far} = 735$ ms). The interaction was also significant, $F(1,78) = 11.29$, $\eta_p^2 = .126$, $p < .01$, as the difference between close and far stimuli was larger when the distance between the target and distractor was further apart (see Figure 11). These data were similar to the MT data found in Experiments 1 and 2 where the close response conditions lead to longer MT as well. It was somewhat surprising that color similarity had such a small effect with the close responses (Experiment 6) however, with the response locations so close in space the movement to one location was very similar to movement to another location.

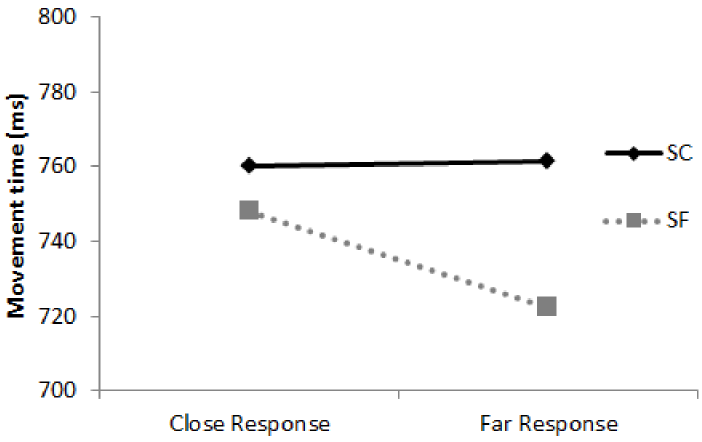

Figure 11. Movement time across experiments for close and far colors. Close Response refers to Experiment 6 and Far Response refers to Experiment 5.

Movement trajectories

Trajectories were analyzed in the same manner as in Experiments 1 – 5. First, the difference in curvature for close and far colors towards the endpoint locations (for this experiment) was considered. There was a marginally significant difference between close and far colors, $t(39) = 1.78$, $p = .083$, as there was more curvature with close colors than far colors (M_{close} = 115 pixels, M_{far} = 101 pixels). The curvature data was next submitted to a 2 x 2 (stimulus similarity x experiment) mixed ANOVA to determine if target/distractor distance interacted with color/target similarity. There was a main effect of experiment, $F(1,78) = 25.26$, $\eta_p^2 = .245$, $p < .001$, as there was more curvature when the response locations were further apart (M_{close} = 108 pixels, M_{far} = 167 pixels) and a main effect of color similarity, $F(1,78) = 74.41$, $\eta_p^2 = .488$, $p < .001$, as there was more curvature for close colors than far colors (M_{close} = 169 pixels, M_{far} = 107 pixels. The interaction was also significant, $F(1,78) = 44.34$, $\eta_p^2 = .362$, $p < .001$, as the difference between close and far colors was much larger when the target and distractor were further apart than when they were closer together (see Figure 12).

This experiment demonstrated that within the same configuration there was interaction between stimulus and response similarity. These data indicate that it was not just the configuration of the response locations that led to more curvature in the *RC* conditions but the similarity of the responses as well (along with stimulus similarity). The trajectory data mirrored the MT data as there was less of a difference for close and far colors when the responses were close. Again, this was not too surprising given that the trajectory of movement to one location was very similar to the trajectory of moving to another location.

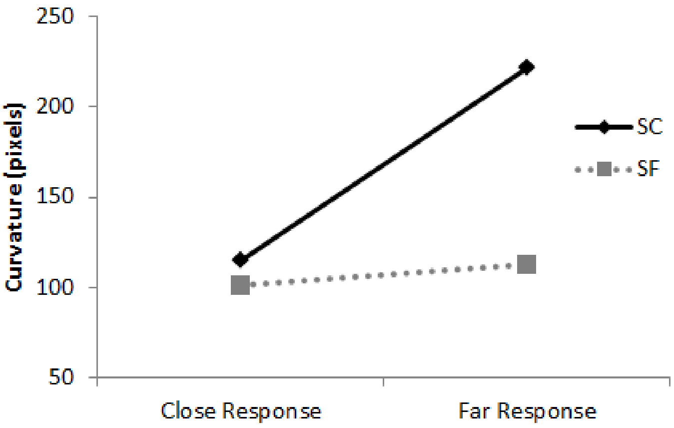

Figure 12. The amount of curvature across close and far colors and target/distractor distances. Close response refers to Experiment 6 and Far response refers to Experiment 5.

There were two intriguing aspects to Figure 12, first, was the small difference between close and far stimuli for Experiment 6 (the close response). As mentioned above, the responses were close enough to diminish the effect of stimulus similarity. Second, when comparing the curvature data across Experiments 5 and 6 it was intriguing that the close stimuli in the far response condition (Experiment 5) resulted in more curvature than the close stimuli in the close response condition (Experiment 6). The data from Experiments 1, 2, and 4 suggest that when both the stimuli and responses were close this led to the most competition between the S-R alternatives resulting in the most curvature. So, how can these disparate results be reconciled? The distance endpoint to endpoint for the present experiment (Experiment 6) was much smaller than it was for the RC condition in Experiments 1 and 2. When the responses were so close in Experiment 6 the movement parameters needed to move to one location was very similar to moving to another location. This suggests that at some point as the response locations become closer in space their overlap will diminish differences between close and far stimuli. Given that when the response were far apart (e.g., Experiments 1 and 2) the difference in curvature between close and far stimuli was also smaller, this suggest an inverted-U relationship between the distance of the responses and the effect of stimulus similarity.

How does the difference in curvature for close and far stimuli change as a result of response distance in Experiments 1, 2, 5, and 6? To evaluate this I first needed the same configuration across all the experiments, specifically, I used only movements to endpoints. In the close condition for Experiments 1 and 2 this includes the shared locations (locations 2 and 5) and for the far condition in Experiments 1 and 2 this includes locations (1 and 6), which is data that was not analyzed in Experiments 1 and 2.

Next, the distance from the endpoint to the nearest competitor was determined. Experiments 1 and 2 had two response configuration, close and far and the distance between the endpoint and nearest competitor was 94 and 271 pixels. For Experiment 5 the distance between the endpoint and the nearest competitor was 135 pixels and in Experiment 6 the distance between the target and nearest endpoint was 67 pixels. The five different distances were ranked order from closest to farthest. Then for each experiment the curvature to the endpoints was determined for both close and far stimuli and the difference was taken (close stimuli – far stimuli). If there was more than one point for a given distance the mean was taken.

Figure 13 shows how the influence of stimulus metrics changes as a function of response metrics. When the distance from the target to the competitor was very close there was little effect of close and far stimuli. This was the result of a great deal of overlap between the possible motor programs, which lead to the movements being very similar for any of the locations, regardless if it was a target or competitor. There was little difference when the distance between the target and competitor was far. This was potentially the result of the competitor being far enough away where the participant paid less attention to the competitor. It might not be the case that stimulus metrics has no effect at close or far distances but this was just the result of task demands. The inverted U pattern also indicates that in a "mid" range of response distances that close stimuli leads to more curvature than far stimuli. In general, the results from the first set of experiments (Experiments 1 – 6) indicate that the stimulus x response interaction was the result of metric differences and that those differences can be modulated based on the configuration of the responses.

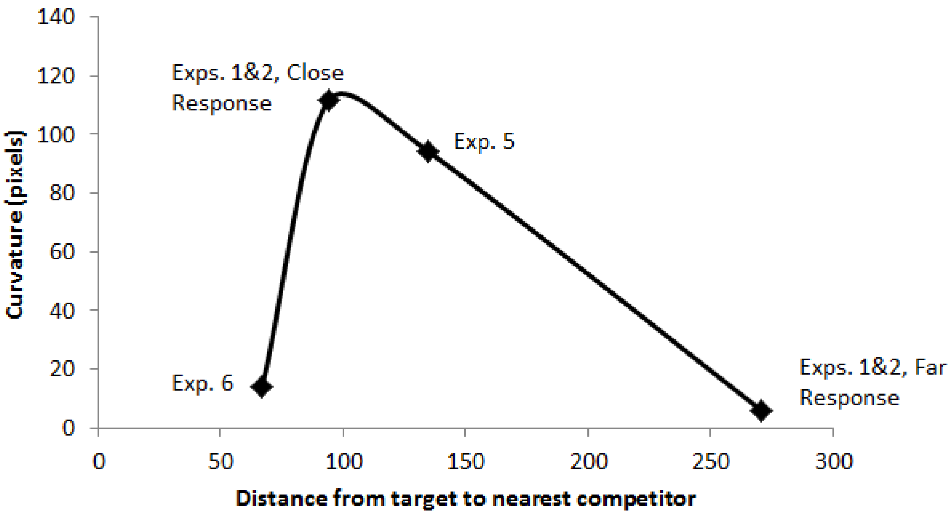

Figure 13. Difference in curvature for close and far stimuli (close – far) as a function of distance from the endpoint target to the nearest competitor.

Chapter Discussion

The goal of this chapter was to explore the influence that metrics and configurations had on the stimulus x response interaction found in Experiments 1 and 2. Experiment 5 demonstrated how the configuration of the target and distractors influences curvature. There was more curvature when the distractors were to one side of the target than if the target is in the middle of the distractors. Configuration also interacted with stimulus similarity as close stimuli with an outside target had the most curvature. The between experiment analysis, Experiment 6, indicated that metrics matter as well. As in Experiments 1 and 2 there was a stimulus x response interaction when configuration was held constant.

The comparison between Experiments 5 and 6 revealed that the difference in curvature between close and far stimuli was smaller for the spatially closer locations in

Experiment 6 compared to Experiment 5. This was in contrast to what was found in Experiments 1 and 2. These findings were reconciled when looking at the difference in curvature for close and far stimuli as a function of the distance between the target and nearest competitor (for the same configuration). An inverted-U appears, as the difference between close and far stimuli was minimized when the responses were very close and when the responses were far apart. Excluding the end points there was a clear interaction between the similarity of the stimuli and responses. In general, when the responses were close they heavily influence the curvature but when the responses became too close the difference between close and far was less because of the increase overlap between the responses.

Overall, these data suggest that the design used in Experiments 1 – 4 was effective in measuring how response metrics influenced performance. This becomes clear when the endpoint data (locations 1 and 6) from Experiments 1 and 2 was considered as I did in the above analysis (see Figure 13).

CHAPTER 5:

EXPLORING THE NATURE OF COMPETITION DURING REACHING MOVEMENTS

The purpose of Experiments 7 and 8 was to use traditional RS methods to further probe the interaction between stimulus and response similarity found in Experiments 1, 2, and 4. The increase in curvature for the *SC-RC* condition found in Experiments 1, 2, and 4 was the result of overlap along the stimulus and response dimension such that the presentation of a stimulus partially activated the S-R alternatives. This co-activation resulted in competition between the alternatives. One way to probe RS processes has been to introduce competition via irrelevant information and I wanted to use other tasks that introduce competition during RS to determine if that competition interacts with the interaction between stimulus and response similarity. For example, the experiments in this chapter elicited response competition by either the presentation of irrelevant stimuli (i.e., Flanker task; Experiment 7) or presenting the stimulus along an irrelevant spatial dimension (i.e., Simon task; Experiment 8). Further, the use of mouse trajectories provides a continuous measure of the source of the competition from the Flanker/Simon tasks. If these methodologies introduce competition through S-R alternatives then there should be an interaction between the competition elicited from the irrelevant information and the interaction between stimulus and response similarity.

The goals of these two experiments were fairly similar. First, was to determine how these classic response competition manipulations interacted with the stimulus x response similarity effect reported above. Next, was to find direct evidence of the irrelevant information causing conflict during central operations as indexed by deviation in the trajectory or initial angle of movement. The third goal was to compare and contrast across experiments as each experiment induces competition in different ways but typically thought to involve RS processing. Finally, although these manipulations (i.e., Flanker, Simon) have been thought to cause response competition (Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004; Lamers & Roelofs, 2011), it was unclear how the task demands of mouse movements relate to previous button-press studies that have investigated these effects, different task demands might result in different types of competition emerging during performance.

Experiment 7: Flanker task

The interaction reported in Experiments 1 and 2 suggest that the S-R alternatives were competing at the level of RS. The purpose of this experiment was to further explore the stimulus x response interaction within traditional RS effects, such as the flanker effect. In a typical flanker task (Eriksen & Eriksen, 1974) a target stimulus is surrounded by non-target flankers. Choice-RT is typically slower when the identity of the flankers do not match the identity of the target (incongruent trial) compared to when the identity of the target and flankers do match (congruent trial). This pattern of data has been taken as support that information flows continuously through the system activating in parallel targets and flankers (McClelland, 1979; Miller, 1988, 1993). The subsequent activation of the corresponding response representations leads to competition among them and slower RT for incongruent trials.

The magnitude of the flanker effect (incongruent trials – congruent trials) can be modulated by the degree of the similarity between the target and the flankers (Cohen & Shoup, 1997; Cohen, Fuchs, Bar-Sela, Brumber, & Magen, 1999; Lamberts, 1994; Lachman & van Leeuwen, 2004). Bernard & Chung (2011) manipulated target-flanker similarity in a letter identification task. They found an increase in error rates as the target and flanker became more similar, suggesting that the features of the flanker competed with features of the target to be integrated into the target item. In the present experiment it was expected that the close stimuli should result in a larger flanker effect than the far stimuli.

One of the goals of this experiment was to explore the relationship between the established stimulus x response similarity interaction and response competition induced by incongruent flankers. One way to evaluate this was to look at the difference in curvature between congruent and incongruent trials to assess the amount of competition caused by incongruent trials. Incongruent trials were not predicted to have that much of an effect for either the *SC-RC* or *SF-RF* conditions. This was because there was already overlap between the stimulus and response dimensions and added competition should not have a large effect in the *SC-RC* condition and the opposite should be true for the *SF-RF* condition. Given the little overlap between the S-R alternatives along either dimension any added competition from the incongruent flankers should have little effect. The key comparison was between the *SC-RF* and the *SF-RC* conditions. If the incongruent flankers only activated response options then it would be expected that the *SC-RF* condition would show large interference effects. The *SC-RF* condition has overlap along the stimulus dimension and if the incongruent flankers partially activated other response options, leading to overlap along the response dimension, then the condition should look similar to the *SC-RC* condition. However, if competition occurs at the RS level then the representation should include not just response properties but stimulus properties as well and the largest flanker effect should be seen in the *SF-RC* condition. This would occur because the incongruent flankers were not just partially activating response options but an S-R alternative that contain both stimulus and response information. Thus, the flankers might lead to different patterns of interference than expected.

The analyses reported below attempt to characterize how response competition as induced by the incongruent flankers interacts with stimulus and response similarity.

Method

Participants

A total of 90 participants received course credit for running in this experiment. Ten participants were dropped from the analyses due to poor behavioral performance, resulting in 20 participants per group.

Procedure

The procedure followed the same procedure in Experiment 1 with one addition. Along with a central stimulus two flanking stimuli were also presented. They were the same size as the central stimulus and were 22 pixels adjacent to the target on either side. Participants were instructed only to attend to the central stimulus and to ignore the flanking stimuli. Half of the trials were congruent (the flankers and central stimuli were the same identity) and the other half were incongruent (the flankers identity was not the same as the central stimulus).

As before there were four between-subjects groups, *SC-RC, SC-RF, SF-RC, SF-RF*, with the stimuli and response locations matching those used in Experiment 1.

Results

Before the analysis, data were trimmed so that movements that had an IT less than 100 ms or greater than 900 ms (1%) and MTs less than 900 ms (1%) were removed.

Only movements to the shared locations were considered for the analyses. To capture the impact that the incongruent flankers had two separate analyses were completed. The first analysis included all of the flankers and the second analysis only included flankers that corresponded to the shared locations. This second analysis provides a more fine grain perspective of the influence that an irrelevant stimulus has on participant's behavior.

Movement timing

The traditional way to characterize a flanker's impact on performance has been to separate trials into congruent (the identity of the target and flanker were the same) and incongruent (the identity of the target and flanker were not the same) trials. This was done and initiation times were submitted to a 2 x 2 x 2 (Congruency x Stimulus x Response) mixed ANOVA. There was a main effect of response, $F(1,76) = 17.29$, $\eta_p^2 = .185$, $p < .001$, as close responses had a faster IT than far responses ($M_{\text{close}} = 312$ ms, $M_{\text{far}} = 358$ ms), but neither congruency, $F(1,76) = 2.35$, $\eta_p^2 = .03$, $p = .129$, nor stimulus, $F < 1$ were significant. The congruency x response interaction was significant, $F(1,76) = 5.43$, $\eta_p^2 = .067$, $p < .05$, as the flanker effect (Incongruent IT – Congruent IT) was larger for the response far conditions than the response close conditions ($M_{\text{far}} = 6$ ms, $M_{\text{close}} = -1$ ms). The interactions of congruency x stimulus, stimulus x response, *F's* < 1, and the congruency x stimulus x response, $F(1,76) = 2.46$, $\eta_p^2 = .03$, $p = .121$, were all not significant (see Table 5 for individual values).

The lack of a stimulus x response interaction was not surprising as one was not found in Experiments 1 and 2. The main effect of the response and the interaction of congruency with response were consistent with the irrelevant flankers causing response conflict. In general, there was a small flanker effect across each of the four conditions

($M_{SC\text{-}RC}$ = 0 ms, $M_{SC\text{-}RF}$ = 2 ms, $M_{SF\text{-}RC}$ = -2 ms, $M_{SF\text{-}RF}$ = 9 ms) and only the SF-RF condition reached significance, $t(19) = 3.24$, $p < .01$. It was not clear the reason for the small magnitude of the flanker effect other than the possibility that given the current design IT did not provide a good measure of the flanker effect.

The data were also analyzed by limiting the incongruent flankers to those of the shared locations. For the most part the pattern of the data and statistical results were the same as the analysis above. There was no effect of congruency or stimulus, F<1, but there was a main effect of response, $F(1,76) = 16.67$, $\eta_p^2 = .18$, $p < .01$, as close responses had a faster IT (M_{far} = 358 ms, M_{close} = 311 ms). The congruency x stimulus, the stimulus x response, and the congruency x stimulus x response, interaction were all non-significant, *F's*<1. The congruency x response interaction was significant, $F(1,76) = 3.87$, $\eta_p^2 = .048$, $p = .05$, with a larger flanker effect for far responses than close responses (M_{far} = 6 ms, M_{close} = -2 ms). The data were consistent with the previous analysis and suggests that even with limiting the flankers the incongruent stimuli had little effect on initiation time.

Movement times were sorted in the same manner as the IT data (inclusion of all the flankers for incongruent trials) and submitted to the same 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA. There was a main effect of response, $F(1,76) = 20.03$, $\eta_p^2 = .209$, $p < .001$, as far responses had a faster movement time than close responses (M_{far} = 499 ms, M_{close} = 542 ms). The effect of stimulus and congruency were not significant, F<1. The stimulus x response and congruency x stimulus interactions were not significant, *F's*<1. The congruency x response interaction was significant, *F*(1,76) = 6.17, η_p^2 = .075, $p < .05$, along with the congruency x stimulus x response interaction, *F*(1,76) = 7.61, η_p^2 = .091, $p < .05$ (see Table 5 for individual values).

Table 5. Congruent and incongruent IT and MT for all four conditions. (IT = initiation time; MT = movement time)

Stimulus	**Response**	**IT**		**MT**	
		Congruent (ms)	*Incongruent (ms)*	*Congruent (ms)*	*Incongruent (ms)*
SC	*RC*	312	312	544	544
SC	*RF*	350	352	503	504
SF	*RC*	313	311	535	543
SF	*RF*	361	371	499	489

The interaction was the result of the flankers having a larger effect in the *SF* condition than the *SC* condition (see Figure 14). In particular, the *SF-RC* condition revealed the largest flanker effect, suggesting that the irrelevant flankers led to the addition of irrelevant stimulus information and combined with the close responses produced more conflict, as indexed by the flanker effect for MT. It was somewhat surprising that there was a negative flanker effect in the *SF-RF* condition, indicating that MT was faster in the incongruent condition than the congruent condition.

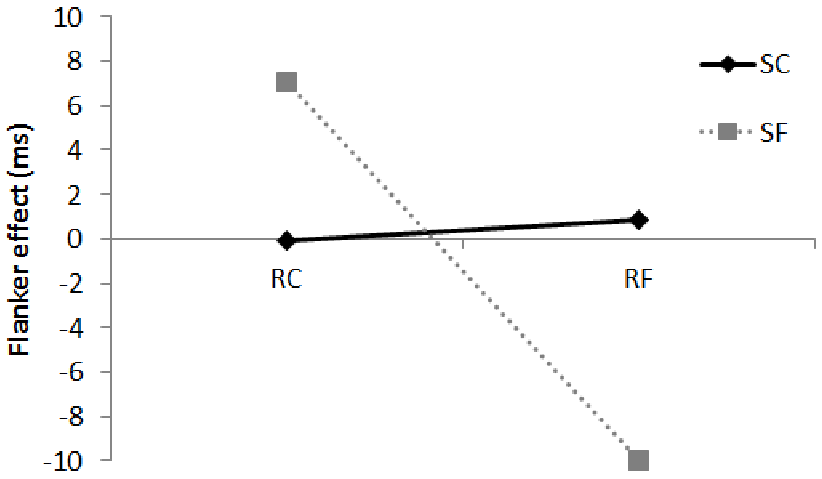

Figure 14. Flanker effect across all four conditions for movement time (MT).

As with IT the MT data was also analyzed when the incongruent flankers indicated one of the shared locations. As before there was a main effect of response, $F(1,76) = 18.17$, $\eta_p^2 = .193$, $p < .001$, as far responses had a shorter MT than did long close responses ($M_{\text{far}} = 499$ ms, $M_{\text{close}} = 541$ ms). There was no effect of stimulus or congruency, F's < 1. The congruency x stimulus interaction, $F<1$, the congruency x response interaction, $F(1,76) = 1.95$, $\eta_p^2 = .025$, $p = .167$, or congruency x stimulus x response interaction, $F(1,76) = 2.52$, $\eta_p^2 = .032$, $p = .116$, all failed to reach significance. The three way interaction failed to reach significance in this analysis though the pattern and direction of the interaction were the same with the above analysis, suggesting the data were nosier in this analysis then the prior one. Nonetheless, the *SF-RC* condition once again displayed the largest flanker effect. This indicates that when there was overlap along the response dimension the irrelevant stimulus information had a much larger effect when the stimuli were dissimilar than when the stimuli were similar.

Considering both IT and MT together there was an overall tradeoff between IT and MT as the conditions that started sooner (close responses) then took a longer time to move to the target. This was not too surprising as a similar pattern emerged in Experiment 1.

Movement trajectories

Trajectories were analyzed in the same fashion as in Experiment 1. First, error along the X-axis was analyzed as it provides a coarse measure of the accuracy of the trajectory. As with the temporal measures the first analysis includes trials in which the target was one of the shared locations and all the flankers. Data was submitted to a 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA. There was a main effect of stimulus, $F(1,76) = 8.36$, $\eta_p^2 = .099$, $p < .01$, as there was more error for close stimuli than far stimuli ($M_{\text{close}} = 6.7$ pixels, $M_{\text{far}} = 4.9$ pixels), an effect of response, $F(1,76) = 18.51$, $\eta_p^2 = .196$, $p < .001$, as close responses showed more error than far responses ($M_{\text{close}} = 7.1$ pixels, $M_{\text{far}} = 4.5$ pixels), though congruency was not significant, $F(1,76) = 1.10$, $\eta_p^2 = .014$, $p = .297$. The stimulus x response interaction was significant, $F(1,76) = 25.18$, $\eta_p^2 = .249$, $p < .001$, as the *SC-RC* condition had more error than any of the other conditions, replicating Experiment 1. The congruency x response, $F < 1$, congruency x stimulus, $F(1,76) = 1.06$, $\eta_p^2 = .014$, $p = .31$, and the congruency x stimulus x response, $F(1,76) = 2.80$, $\eta_p^2 = .035$, $p = .10$, were all non-significant. These data replicated the findings in Experiment 1 that the most error was found in the *SC-RC* condition but do suggest that irrelevant flankers had little effect on endpoint error.

Error along the X-axis was also analyzed by including only trials in which the target and flankers indicated one of the shared locations (see Figure 15, panel A). As with the above analysis there was a main effect of stimulus, $F(1,76) = 9.97$, $\eta_p^2 = .116$, $p < .01$, with more error for the close stimuli than the far stimuli ($M_{\text{close}} = 7.8$ pixels, $M_{\text{far}} = 5.3$ pixels). There was a main effect of response, $F(1,76) = 18.54$, $\eta_p^2 = .196$, $p < .001$, as close responses had more error than the far responses ($M_{\text{close}} = 8.2$ pixels, $M_{\text{far}} = 4.9$ pixels). There was also a main effect of congruency, $F(1,76) = 12.68$, $\eta_p^2 = .143$, $p < .01$, as incongruent trials resulted in more error than congruent trials ($M_{\text{incongruent}} = 7.5$ pixels, $M_{\text{congruent}} = 5.6$ pixels). The stimulus x response interaction was significant, $F(1,76) = 13.95$, $\eta_p^2 = .155$, $p < .001$, with more error in the *SC-RC* condition than any of the other conditions ($M_{\text{SC-RC}} = 10.9$ pixels, $M_{\text{SC-RF}} = 4.6$ pixels, $M_{\text{SF-RC}} = 5.5$ pixels, $M_{\text{SF-RF}} = 5.1$ pixels; see Figure 15, panel B). These data replicate the finding from Experiment 1, when both of the dimensions were close there was more competition among the S-R alternatives leading to more error. The congruency x stimulus interaction, $F(1,76) = 4.69$, $\eta_p^2 = .058$, $p < .05$, and the congruency x response interaction, $F(1,76) = 4.28$, $\eta_p^2 = .053$, $p < .05$, were both significant. These interactions were driven by more error during the close (stimulus or response), incongruent trials ($M_{\text{SC-Cong}} = 6.3$ pixels, $M_{\text{SF-Cong}} = 5.0$ pixels, $M_{\text{SC-InCong}} = 9.3$ pixels, $M_{\text{SF-InCong}} = 5.7$ pixels; $M_{\text{RC-Cong}} = 6.8$ pixels, $M_{\text{RF-Cong}} = 4.5$ pixels, $M_{\text{RC-InCong}} = 9.7$ pixels, $M_{\text{RF-InCong}} = 5.2$ pixels). Finally, the three way, congruency x stimulus x response interaction, $F(1,76) = 1.06$, $\eta_p^2 = .014$, $p = .31$, was not significant.

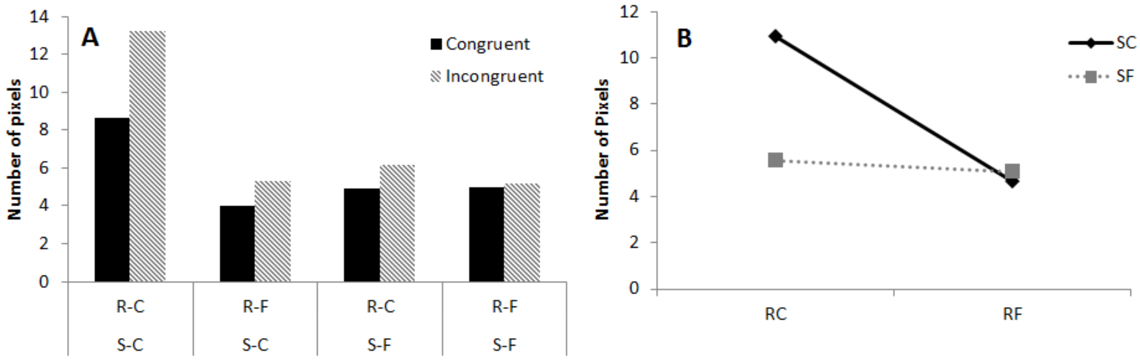

Figure 15. Panel A depicts Error along the X-axis for congruent and incongruent trials across all four conditions. Panel B depicts the stimulus x response interaction.

The curvature data were submitted to the same 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA analyses as the other measures with the inclusion of all the flankers. There was a main effect of stimulus, $F(1,76) = 5.973$, $\eta_p^2 = .073$, $p < .05$, as there was more curvature for the *SC* conditions than the *SF* conditions ($M_{\text{close}} = 161$ pixels, $M_{\text{far}} = 110$ pixels), a main effect of response, $F(1,76) = 30.51$, $\eta_p^2 = .286$, as close responses displayed more curvature than far responses ($M_{\text{close}} = 175$ pixels, $M_{\text{far}} = 96$ pixels), and a main effect of congruency, $F(1,76) = 7.87$, $\eta_p^2 = .094$, $p < .01$, as there was more curvature during incongruent than congruent trials ($M_{\text{incongruent}} = 151$ pixels, $M_{\text{congruent}} = 135$. The stimulus x response interaction was significant, $F(1,76) = 4.72$, $\eta_p^2 = .059$, $p < .05$, driven by more curvature in the *SC-RC* condition than any of the other conditions (see Figure 16, panel A). This replicates the interaction found in Experiments 1 and 2. The congruency x response interaction, $F(1,76) = 3.11$, $\eta_p^2 = .039$, $p = .08$, was not significant, but the congruency x stimulus interaction, $F(1,76) = 4.44$, $\eta_p^2 = .055$, $p < .05$, and the congruency x stimulus x response interaction were significant, $F(1,76) =$

5.22, $\eta_p^2 = .064$, $p < .05$, as *SF-RC* condition had the largest flanker effect compared to the other conditions (see Figure 16).

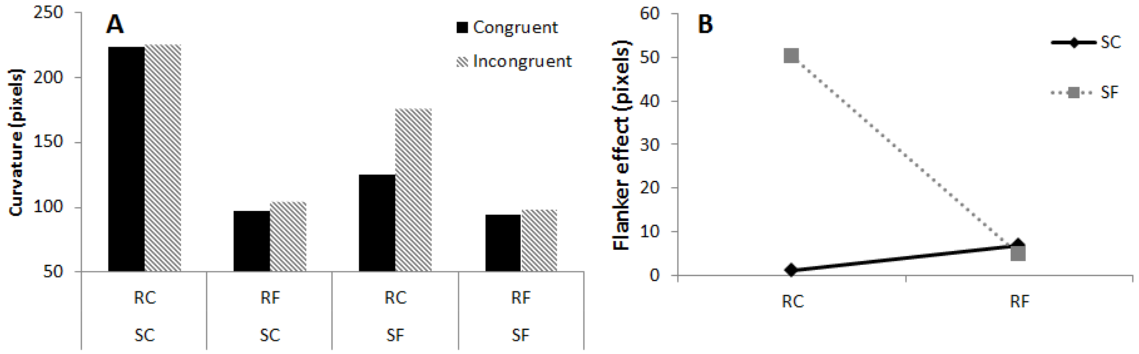

Figure 16. Panel A depicts curvature across all four conditions for Congruent and Incongruent. Panel B depicts the Flanker effect (Incongruent – Congruent) for all four conditions.

Just as in the MT data the *SF-RC* condition displayed the largest flanker effect (see Figure 16). The data suggest that the flankers activated irrelevant stimulus information. When the stimuli were already close this has little effect because the responses were activated by the similar stimuli. However, in the *SF-RC* condition the flankers activated irrelevant stimulus information and combined with the similar responses lead to more competition between the S-R alternatives. This result motivates thinking more seriously about the relationship between the stimuli and responses. The competition was not just at the level of response options but the S-R alternative, which links the features of the stimulus to the features of the response.

Unlike Experiment 1 the curvature data somewhat differ from that of the analysis of error along the X-axis. The endpoint error displayed the largest flanker effect in the *SC-RC* condition not the *SF-RC* condition. The difference might have resulted from congruent and incongruent trials taking the same path towards the target (similar curvature) but the end of the movement was less accurate for incongruent trials (endpoint error). In addition, error along the X-axis was used as a coarse measure and curvature was a more fine grain analysis. Future work will have to be done to determine if these differences are meaningful.

As with the other measures the curvature data was submitted to the same analyses as above though only trials in which flankers that corresponded to one of the shared locations were included. The pattern of the data was very similar to the analyses above (see Figure 17 and Figure 16) however, many of the interactions failed to reach significance. For instance, congruence x stimulus, $F(1,76) = 2.25$, $\eta_p^2 = .029$, $p = .138$, congruency x response, and congruency x stimulus x response, *F’s* < 1, all failed to reach significance, suggesting that the data were nosier than in the previous experiment. The *SC-RF* and *SF-RF* conditions did have larger flanker effects in this analysis than in the one that included all the flankers, though the *SF-RC* condition still displayed the largest flanker effect.

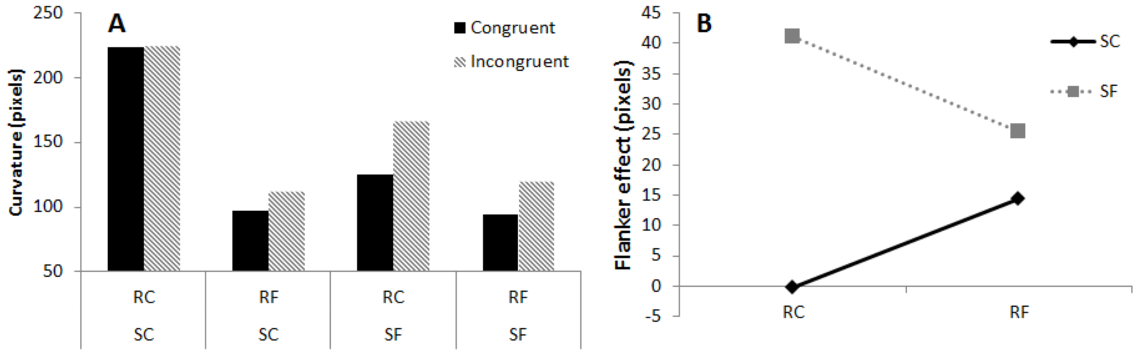

Figure 17. Curvature for congruent and incongruent trials across all four conditions. Only flankers that corresponded to one of the shared locations were included.

The curvature data was also analyzed by plotting curvature as a function of the distance from the target to the identity of the flanker (see Figure 18). In other words, was there a difference in curvature when an incongruent flanker corresponded to a location that was right next to the target or further away? In Figure 17, 0 refers to a congruent trial (to a shared location) and each data point represents the distance from that location (the incongruent flanker corresponded to) to the target location. Curvature did not change as a result of the distance from the target that identity of the flanker corresponded to in the *SC-RC* condition, $F(2,38) = 1.22$, $\eta_p^2 = .060$, $p = .308$, in the *SF-RC* condition, $F(2,38) = 1.27$, $\eta_p^2 = .063$, $p = .293$, the *SF-RF* condition, $F<1$, and there was a marginally significant effect of flanker distance for the *SC-RF* condition, $F(2,38) = 3.01$, $\eta_p^2 = .137$, $p = .06$, as there was a slight trend for curvature to increase as the flanker corresponded with a location further away from the target.

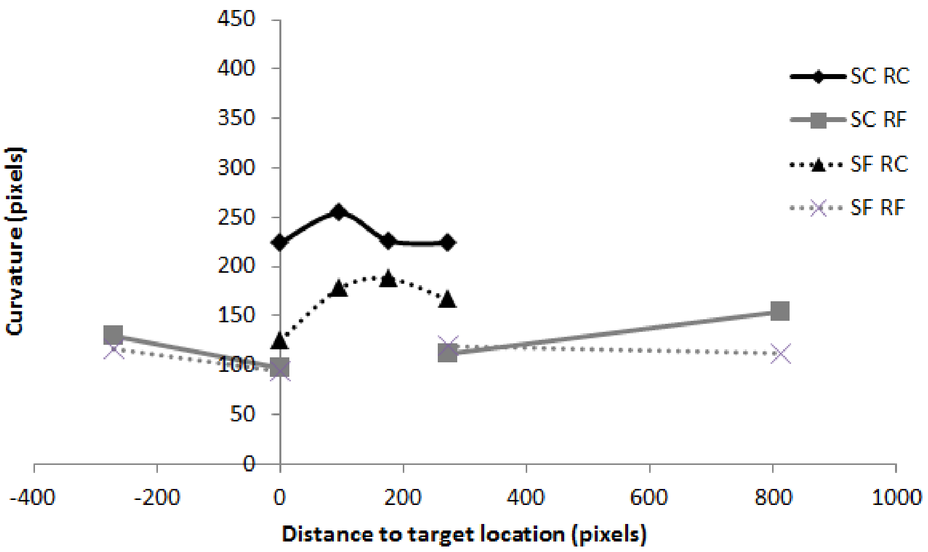

Figure 18. Curvature across distance from the flanker identity to the target location.

Next, the data for the close response locations were submitted to a 2 x 3 (experiment x distance) mixed ANOVA to determine if there were differences between close and far stimuli within the same response condition. There was no effect of distance, $F(2,76) = 1.35$, $\eta_p^2 = .034$, $p = .27$, a main effect of experiment, $F(1,38) = 4.45$, $\eta_p^2 = .105$, $p < .05$, as there was more curvature in the *SC-RC* experiment than the *SF-RC* experiment. The interaction was not significant, $F(2,76) = 1.12$, $\eta_p^2 = .028$, $p = .333$. The data for the far conditions were submitted to a 2 x 3 (experiment x distance) mixed ANOVA as well. There was no effect of experiment, $F<1$, no effect of distance, $F(2,76) = 1.30$, $\eta_p^2 = .033$, $p = .28$. The interaction was non-significant, $F(2,76) = 2.57$, $\eta_p^2 = .063$, $p = .08$, though there was a trend for curvature to increase as distance increased for the *SC-RF* condition but not the *SF-RF* condition.

The goal of the experiment was to further explore the interaction found in Experiments 1 and 2 using a traditional RS methodology, the flanker task. In general, the curvature flanker effects were small in the *SC-RC, SC-RF*, and *SF-RF* conditions (as well as in IT and MT). The largest flanker effect was found in the *SF-RC* condition. This was the result of the flankers activating irrelevant stimulus information and when combined with the overlap along the response dimension results in more competition between the S-R alternatives. In essence, the *SF-RC* condition during incongruent trials was similar to the *SC-RC* condition as there was overlap along both the stimulus and response dimensions. This potentially explains why the flanker effects were smaller for the other conditions, especially the *SC* conditions. In the *SC-RC* condition there was already overlap along both dimensions so irrelevant information had little effect. In the *SC-RF* condition the stimuli were already overlapping so irrelevant the stimulus information had little effect. For the *SF-RF* condition there was no overlap along either dimension so the irrelevant stimulus information did had less of an overall effect compared to the *SF-RC* condition.

These results also suggest that the flankers did not just activate response options but its effects were at the level of RS, which contains information about both the stimulus and response. If the incongruent flankers just activated response information the largest interference effects would have been in the *SC-RF* condition. However, the largest interference effects were in the *SF-RC* condition, suggesting the competition between the S-R alternatives occurs during RS and the representations contain properties of both the stimulus and response.

Experiment 8: Spatial Stroop Simon

The purpose of this experiment was similar to the flanker experiment – to create conflict and observe its effect while participants make reaching movements. Unlike the flanker task where the stimulus was centrally presented in this experiment the stimulus appeared in one of the four response locations. The identity of the stimulus either indicated a response to that target location (congruent trial) or to one of the other three locations (incongruent trial). Thus, the design of the experiment allows the identity of the target to be compatible or incompatible (Stroop) with the response or spatially compatible or incompatible (Simon) with the response.

There have been several studies that have investigated how the Simon effect affects reaching movements (Buetti & Kerzel, 2008; Miles & Proctor, 2011; Rubichi & Pellicano, 2004; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010). Initial movement angle has been used to explore response programming in the Simon effect (Buetti & Kerzel, 2008). When the task was done without out temporal constraints initial movement angles correspond with RTs. That is, initial movement angles were larger for incongruent trials than congruent trials, indicating the pointing movement was initially attracted to the source of the stimulus. If the Simon effect is broken down into fast and slow RTS, the initial movement angle was larger for fast RTs than slow RTs, suggesting that the less a response was prepared the more the motor movement was biased towards the wrong side. Intriguingly, when a time limit was imposed for movement initiation the Simon effect was eliminated in RT but not in movement parameters (e.g., initial angle). This reflects that initial movement angles capture some response conflict that was not noticeable in RT. This motivates looking beyond measures independently (e.g., end point error, curvature, etc) but to evaluate how these measures are related and influence each other.

As with the flanker experiment there were several goals: first, to see how the Simon and Stroop effects interacted with the stimulus and response similarity effect. As discussed in the chapter introduction the data from Experiments 1, 2, and 4 were the result of competition between the S-R alternatives that were sensitive to the metric properties of the stimulus and response. I wanted to determine how other forms of RS competition potentially interact with the interaction between stimulus and response similarity. Next, to find direct evidence off irrelevant features causing conflict and finally, to compare the conflict created in this experiment to the flanker experiment.

Method

Participants

A total of 86 undergraduate students participated in this experiment for course credit. Six of the participants were dropped from the analyses because of the poor behavioral performance or failure to complete the experiment. Thus, there was a total of 80 participants, 20 in each group.

Procedure

The experiment followed the procedures presented in the General method section with several additions. The most notably addition was that the stimulus no longer was presented in a central location but presented at one of the four response locations. The size of the stimulus was slightly larger than the response locations (15 x 15 pixels). In addition, to visual feedback of marking where the participant had ended their response and the correct location, participants heard a tone if their end point location was further than 50 pixels from the correct location. Half of the trials were congruent (the location of the presented stimulus matches the correct response location) and the other half (the location of the presented stimulus indicates another response location).

Results

Before the analysis, data were trimmed so that movements that had an IT less than 100 ms or greater than 900 ms (1%) and MTs less than 1000 ms (7%) were removed. Only movements to the shared locations were considered for the analyses. To capture the impact that the incongruent locations had two separate analyses were completed. The first analysis included trials in which the stimulus appeared at any location but the target location was one of the shared locations. The second analysis only included locations that corresponded to the shared locations. This second analysis provides a more fine grain perspective of the influence that an irrelevant response location has on participant's behavior.

Movement timing

The first analysis included trials in which the stimulus was presented at any one of the four locations but the target location was one of the shared locations. This provides a coarse measure of how incongruent response locations affect performance. Initiation time was submitted to a 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA (see Table 4 for individual values). There was a main effect of stimulus, $F(1,76) = 5.70$, $\eta_p^2 = .070$, $p < .05$, as close stimuli had a slower IT than far stimuli ($M_{\text{close}} = 435$ ms, $M_{\text{far}} = 393$ ms), there was a main effect of response, $F(1,76) = 22.17$, $\eta_p^2 = .226$, $p < .001$, as close responses had faster IT than far responses ($M_{\text{close}} = 372$ ms, $M_{\text{far}} = 456$ ms), and a main effect of congruency, $F(1,76) = 36.43$, $\eta_p^2 = .324$, $p < .001$, as congruent trials had a faster IT than incongruent trials ($M_{\text{congruent}}$ = 406 ms, $M_{\text{incongruent}}$ = 422 ms). The congruency x stimulus interaction and stimulus x response interaction were not significant, *F's*<1. The congruency x response interaction was significant, *F*(1,76) = 40.40, $\eta_p^2 = .347$, $p < .001$, as there was a larger congruency effect (incongruent – congruent) for far responses than close responses (M_{far} = 32 ms, M_{close} = -1 ms). The three-way interaction of congruency x stimulus x response, *F*<1, was not significant.

Table 6. Initiation time and movement time across all four conditions.

Stimulus	**Response**	**IT**		**MT**	
		Congruent (ms)	*Incongruent (ms)*	*Congruent (ms)*	*Incongruent (ms)*
SC	*RC*	391	390	735	806
SC	*RF*	464	495	751	826
SF	*RC*	355	354	719	767
SF	*RF*	415	448	691	734

The IT data follow the same general pattern as the other experiments. For instances, close responses resulted in faster ITs but close stimuli resulted in slower ITs. The influence of congruency on IT only affected the far locations ($M_{\text{SC-RC}}$ = -1 ms, $M_{\text{SC-RF}}$

= 31 ms, $M_{\text{SF-RC}}$ = -1 ms, $M_{\text{SF-RF}}$ = 33 ms). These data suggest that in the close response condition that starting a movement was unaffected by stimulus location whereas, starting a movement in the far condition was affected by stimulus location.

Initiation time was also analyzed when the stimulus appeared in only one of the shared locations. This provides a fine grain analysis of the effect of a particular incongruent location on performance. As before data was submitted to a 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA. There was a main effect of stimulus, $F(1,76) = 6.56$, $\eta_p^2 = .079$, $p < .05$, with close stimuli having a slower IT than far stimuli (M_{close} = 433 ms, M_{far} = 389 ms), a main effect of response, $F(1,76) = 16.95$, $\eta_p^2 = .182$, $p < .001$, with close responses slower than far responses (M_{close} = 375 ms, M_{far} = 447 ms), and a main effect of congruency, $F(1,76) = 10.11$, $\eta_p^2 = .117$, $p < .01$, as congruent trials were faster than incongruent trials ($M_{\text{congruent}}$ = 406 ms, $M_{\text{incongruent}}$ = 416 ms). The congruency x stimulus, stimulus x response, and congruency x stimulus x response interactions all failed to reach significance, *F's*<1. The congruency x response interaction was also non-significant though trending in the correct direction, $F(1,76) = 2.67$, $\eta_p^2 = .034$, $p = .106$. Unlike the previous analysis (inclusion of all incongruent locations) there was a smaller congruency effect for each of the four conditions ($M_{\text{SC-RC}}$ = 9 ms, $M_{\text{SC-RF}}$ = 14 ms, $M_{\text{SF-RC}}$ = 0 ms, $M_{\text{SF-RF}}$ = 15 ms).

The MT data followed the same processing steps as did the IT data. Movement time data was first submitted to a 2 x 2 x 2 mixed ANOVA (see Table 4). There was a main effect of stimulus, $F(1,76) = 4.78$, $\eta_p^2 = .059$, $p < .05$, as close stimuli had a longer MT than far stimuli, (M_{close} = 779 ms, M_{far} = 728 ms), there was a main effect of congruency, $F(1,76) = 166.06$, $\eta_p^2 = .686$, $p < .001$, as congruent trials were faster than incongruent trials ($M_{\text{congruent}}$ = 724 ms, $M_{\text{incongruent}}$ = 783 ms). The effect of response was non-significant, F<1. The stimulus x response, congruency x response, and congruency x stimulus x response interactions were all non-significant, F<1. The congruency x stimulus interaction was significant, $F(1,76) = 8.66$, $\eta_p^2 = .102$, $p < .01$, as the congruency effect was larger for close stimuli than far, (M_{close} = 73 ms, M_{far} = 46 ms). Finally, the MT data was also analyzed only using trials in which the stimulus appeared in one of the shared locations and the target was one of the shared locations. This analysis yielded the same statistical and pattern of data as with the first analysis.

Unlike some of the previous experiments there was no systematic tradeoff between IT and MT as *SF-RC* condition had the fastest IT but *SC-RF* had the slowest MT. It was somewhat intriguing that congruency as measured by IT was more sensitive to the response condition however, congruency as measured by MT was more sensitive to the stimulus condition. This indicates that in this type of task where the participant was responding to the source of the stimulus on half of the trials the start of a movement was more sensitive to the layout of the response locations but once the movement had started the discrimination of the stimulus influenced the movement more.

Movement trajectories

Trajectories were analyzed in the same manner as Experiment 1. Error along the X-axis was first considered (see Figure 19, panel A). Data was submitted to a 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA. There was a main effect of congruency, $F(1,76) = 225.12$, $\eta_p^2 = .748$, $p < .001$, as congruent trials had more endpoint error than incongruent trials, ($M_{Congruent}$ = 8.4 pixels, $M_{Incongruent}$ = 4.7 pixels), neither stimulus, F<1, nor response, $F(1,76) = 1.24$, $\eta_p^2 = .016$, $p = .268$, were significant. The stimulus x response interaction was not significant, $F(1,76) = 1.35$, $\eta_p^2 = .017$, $p = .249$, the congruency x stimulus interaction was not significant, $F(1,76) = 3.05$, $\eta_p^2 = .039$, $p = .09$, and the congruency x response interaction was not significant as well, $F(1,76) = 1.41$, $\eta_p^2 = .018$, $p = .238$. The three-way interaction of congruency x stimulus x response was significant, $F(1,76) = 11.47$, $\eta_p^2 = .131$, $p < .01$ (see Figure 19 panel B), as the difference between incongruent and congruent trials was the smallest in the *SC-RC* condition compared to the other conditions. These data were a fairly surprising result, especially given the curvature analysis (see below). It really was not clear as to why the incongruent trials led to *less* endpoint error than congruent trials. The flanker task (Experiment 7) did report a similar result of differences between the curvature and endpoint data, suggesting that these measures might be sensitive to different effects.

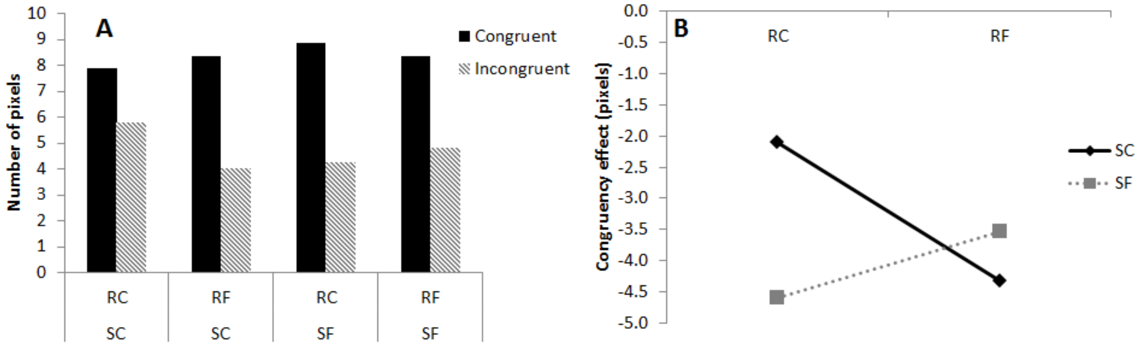

Figure 19. Panel A refers to endpoint error for congruent and incongruent trials across all four conditions. Panel B refers the congruency effect (Incongruent – Congruent) for all four conditions.

Next, curvature data was submitted to a 2 x 2 x 2 (congruency x stimulus x response) mixed ANOVA. There was a main effect of response, $F(1,76) = 12.94$, $\eta_p^2 =$

.146, $p < .01$, as there was more curvature for the close responses than the far responses (M_{close} = 180 pixels, M_{far} = 126 pixels), there was a main effect of congruency, $F(1,76)$ = 156.21, $\eta_p^2 = .673$, $p < .001$, as there was more curvature for incongruent trials than congruent trials, ($M_{\text{congruent}}$ = 89 pixels, $M_{\text{incongruent}}$ = 217 pixels) and the effect of stimulus failed to reach significance, $F<1$. The stimulus x response interaction was significant, $F(1,76) = 5.15$, $\eta_p^2 = .063$, $p < .05$, with more curvature in the *SC-RC* condition than any of the others replicating the effect from Experiments 1 and 2 (see Figure 20, panel A). The congruency x stimulus interaction was not significant, $F(1,76) = 1.73$, $\eta_p^2 = .022$, p = .193, but the congruency x response, $F(1,76) = 16.52$, $\eta_p^2 = .179$, $p < .001$, and congruency x stimulus x response, $F(1,76) = 5.27$, $\eta_p^2 = .065$, $p < .05$, were both significant (see Figure 20, panel B) as the *SC-RC* condition had the largest congruency effect. The congruent trials were largely unaffected by the different stimulus and response conditions, which was not too surprising given the nature of these trials, to respond to the source of the stimulus. However, the incongruent trials were.

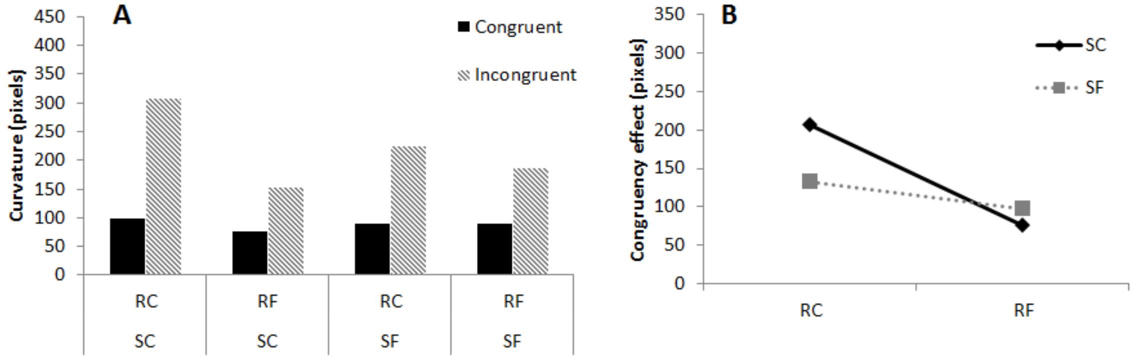

Figure 20. Panel A depicts curvature for congruent and incongruent trials across all four conditions. Panel B depicts the congruency effect (Incongruent – Congruent) across all four conditions.

The curvature data was also analyzed by limiting trials to only when the stimulus appeared at one of the shared locations and the target was one of the shared locations. There was no effect of stimulus, $F(1,76) = 2.63$, $\eta_p^2 = .033$, $p = .109$, though there was a main effect of response, $F(1,76) = 6.25$, $\eta_p^2 = .076$, $p < .05$, as there was more curvature for close response than far responses, ($M_{close} = 225$ pixels, $M_{far} = 172$ pixels), and a main effect of congruency, $F(1,76) = 161.18$, $\eta_p^2 = .680$, $p < .001$, as there was less curvature for congruent trials than in incongruent trials, ($M_{congruent} = 89$ pixels, $M_{incongruent} = 308$ pixels). The congruency x stimulus interaction was significant, $F(1,76) = 4.52$, $\eta_p^2 = .056$, $p < .05$, as there was a larger congruency effect for close stimuli than far stimuli, ($M_{close} = 256$ pixels, $M_{far} = 183$ pixels). There was a significant congruency x response interaction, $F(1,76) = 5.80$, $\eta_p^2 = .071$, $p < .05$, as there was a larger congruency effect for close responses than far response ($M_{close} = 261$ pixels, $M_{far} = 178$ pixels). The stimulus x response interaction was not significant, $F(1,76) = 1.78$, $\eta_p^2 = .023$, $p = .186$, nor was the three-way interaction of congruency x stimulus x response, $F(1,76) = 1.12$, $\eta_p^2 = .014$, p

= .294. The three way interaction of congruency x stimulus x response, failed to reach significance because the data was more variable as well as there being a larger congruency effect for the other conditions (*SC-RF*, *SF-RC*, *SF-RF*) not just the *SC-RC* condition (see Figure 21). However, the pattern of the data was very similar across both types of analyses (see Figure 20 vs Figure 21).

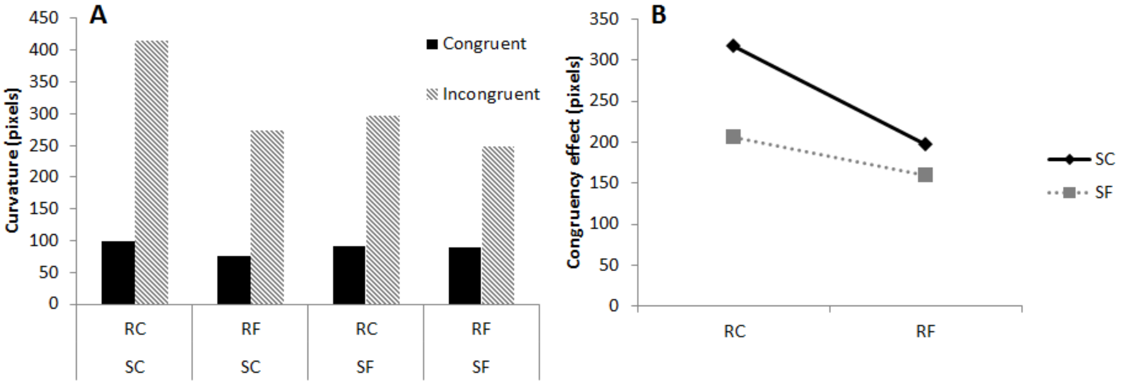

Figure 21. Curvature and congruency effects when the source of the stimulus appeared in one of the shared locations. Panel A depicts curvature for congruent and incongruent trials across all four conditions. Panel B depicts the congruency effect (Incongruent – Congruent) for all four conditions.

As with the previous experiment the curvature data was also analyzed as a function of the distance from where to the stimulus appeared to the correct location (see Figure 22). As with the previous analysis, 0 represented a congruent trial and each data point represents the distance that from where the stimulus appeared to the target location. The data were analyzed in two ways, first, each condition was analyzed separately to determine within a condition if distance to target affected curvature, and secondly, within the same response condition to determine if the change in curvature across distance interacted with stimulus similarity. As can be gleamed form Figure 21, all four conditions had a main effect of distance, as the distance from the stimulus location to the target grew so did the curvature (*SC-RC*, $F(2,38) = 35.59$, $\eta_p^2 = .652$, $p < .001$; *SC-RF*, $F(2,38) = 10.41$, $\eta_p^2 = .354$, $p < .001$; *SF-RF*, $F(2,38) = 10.81$, $\eta_p^2 = .363$, $p < .001$; *SF-RC*, $F(2,38) = 16.14$, $\eta_p^2 = .459$, $p < .001$). To see if there was a difference between conditions, data was submitted to a 2 x 3 (experiment x distance) mixed ANOVA. For the *RC* conditions, there was a main effect of distance, $F(2,76) = 50.60$, $\eta_p^2 = .571$, $p < .001$, a main effect of experiment, $F(1,38) = 5.42$, $\eta_p^2 = .125$, $p < .05$, as there was more curvature in the *SC* than the *SF* condition, and the distance x experiment interaction was also significant, $F(2,76) = 3.01$, $\eta_p^2 = .073$, $p = .055$, as there was more of an increase in curvature as the distance increased for the *SC* condition than the *SF* condition. For the *RF* conditions, there was a main effect of distance, $F(2,76) = 20.08$, $\eta_p^2 = .346$, $p < .001$, but there was no effect of experiment, $F<1$, nor was the distance x interaction significant, $F(2,76) = 1.21$, $\eta_p^2 = .031$, $p = .31$, as there was no difference in curvature for close and far stimuli as the distance to the target increased.

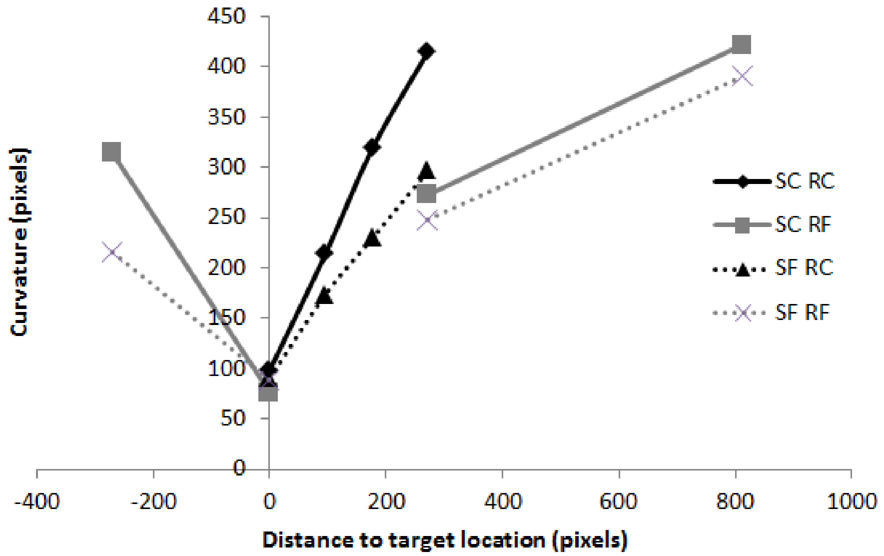

Figure 22. Curvature as a function of the distance from where the stimulus appeared to the correct location.

In general, there was little difference in curvature between conditions for congruent trials however, curvature was greatly affected by the incongruent trials. This occurred because of the nature of the task. Half of the trials participants were required to make a mouse movement towards the source of the stimulus (congruent trials). When a stimulus was presented there was a tendency to move towards that location, at least initially, regardless of congruent and incongruent trials (Buetti & Kerzel, 2008; see Figure 23). The initial angles when the correct location was location 2 but the stimulus appeared at location 5 (Incongruent 2), was very similar to the initial angle when the stimulus appeared at location 5 and the correct location was location 5 (congruent 5). If the identity of the stimulus corresponded with that location then there was very little activation of the other S-R alternatives so the metric dimensions did not matter as much during RS. On the other hand, if the identity of the stimulus did not correspond with the location as the stimulus information accrues it co-activated additional S-R alternatives. Given that these S-R alternatives were sensitive to the metric properties when both dimensions were close (*SC-RC*) there was more competition between the alternatives, leading to more curvature, during the incongruent trials. Altogether, these data indicate that irrelevant information along the response dimension has a large impact on performance.

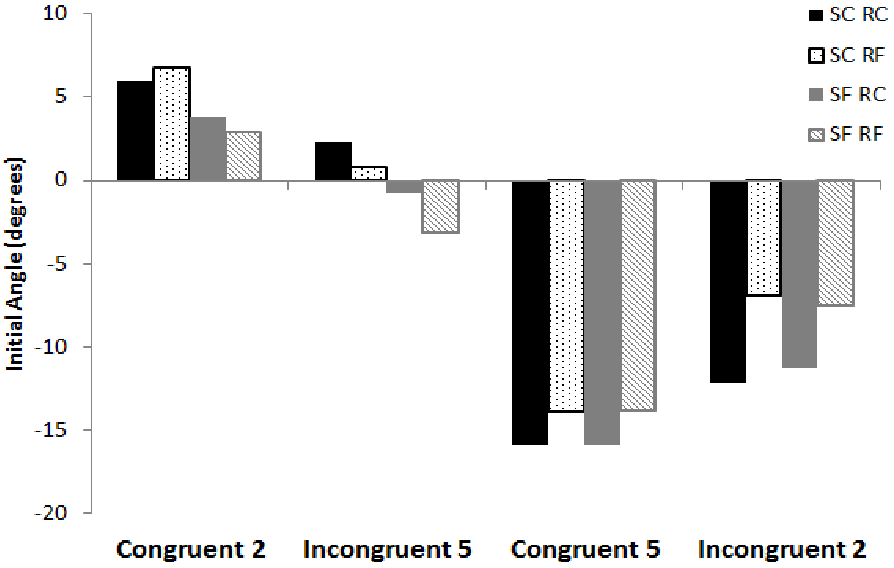

Figure 23. Initial angle to location 2 or location 5 for congruent and incongruent trials. Incongruent 2 refers to when the stimulus appeared at location 5 but the correct location was location 2.

Chapter Discussion

The purpose of this chapter was to further explore the nature of the competitive interaction found in Experiments 1 and 2. It was my interpretation that the interaction occurred at the level of RS. Therefore, to further explore this interaction I used traditional RS methods that elicited competition via irrelevant stimulus information (Flanker task, Experiment 7) or irrelevant spatial dimension (Simon task, Experiment 8). Even with the different types of irrelevant information presented a stimulus x response interaction was found in both tasks, providing additional replications of Experiment 1, as well indicating RS involvement during these tasks.

Though the stimulus x response interaction was found the pattern of data was different across these two tasks. For instances, congruency had a much smaller effect in the Flanker task than in the Simon task. Further, the condition with the largest congruency effect was different across these two tasks. In the Flanker task, the *SF-RC* condition had the largest congruency effect as the irrelevant flankers co-activated other stimuli and because the response were already overlapping this led to more competition between the S-R alternatives. In contrast, the *SC-RC* had the largest congruency effect in the Simon task. Here, after the initial movement towards the source of the stimulus the overlap along both dimensions leads to more competition.

This distinction between the two tasks was also apparent when curvature was plotted as a function of how far away the location of the stimulus was or what location the identity of the flankers corresponded to. For the Simon task as the distance to the target increased so did curvature. This distinction was not as drastic in the Flanker experiment. Part of this difference was due to the type of irrelevant information introduced during incongruent trials. For the Simon task if the initial movement was towards the source of the stimulus it follows that as the distance between where the stimulus was presented and the target increased so did the curvature, whereas, for the

Flanker task the irrelevant information led to the co-activation of additional S-R alternatives. In general, regardless of how competition was introduced these data were consistent with previous reaching tasks that demonstrated the presence of a non-target impacts the trajectory of a goal-directed movement (Howard & Tipper, 1997; Tipper, Howard, & Houghton, 1998; Welsh & Weeks, 1999; Welsh & Elliott, 2004). Though the present studies go beyond how movement was affected by the mere presence of a non-target but how the metric properties of S-R alternatives matter as well.

CHAPTER 6: GENERAL DISCUSSION

This dissertation explored how stimulus and response similarity affected RS by having participants move a computer mouse to a target location. There was an interaction between stimulus and response similarity as the *SC-RC* condition resulted in more curvature than any of the other conditions. The interaction was replicated across different task demands (speed or accuracy), as well as non-color stimuli. The interaction was not the result of perceptual difficulty as the size manipulation affected initiation time and not the amount of curvature. The interaction was influenced by the location of the responses and he influence of stimulus similarity changed as response distance changed. Finally, the interaction was replicated across two traditional RS tasks. The Flanker and Simon tasks also revealed that the stimulus x response interaction was affected by irrelevant information but in different ways.

These data have broad implications for models of RS. To account for the ability to pair any stimulus modality with any response modality 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). Response selection works as a look-up table that receives a categorized stimulus as an input and returns an abstract response code as output. This type of model cannot produce an interaction between stimulus and response similarity and thus, the present data provide a serious challenge to these types of models.

Instead, this interaction was driven by partial activation among the S-R alternatives. As discussed in Chapter 4 I propose that participants form fast, flexible associations between stimuli and responses (Buss et al., 2013). Stimulus-response alternatives were modeled as peaks of activation within two-dimensional stimulus-response fields. 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). Stimulus-response alternatives compete 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.

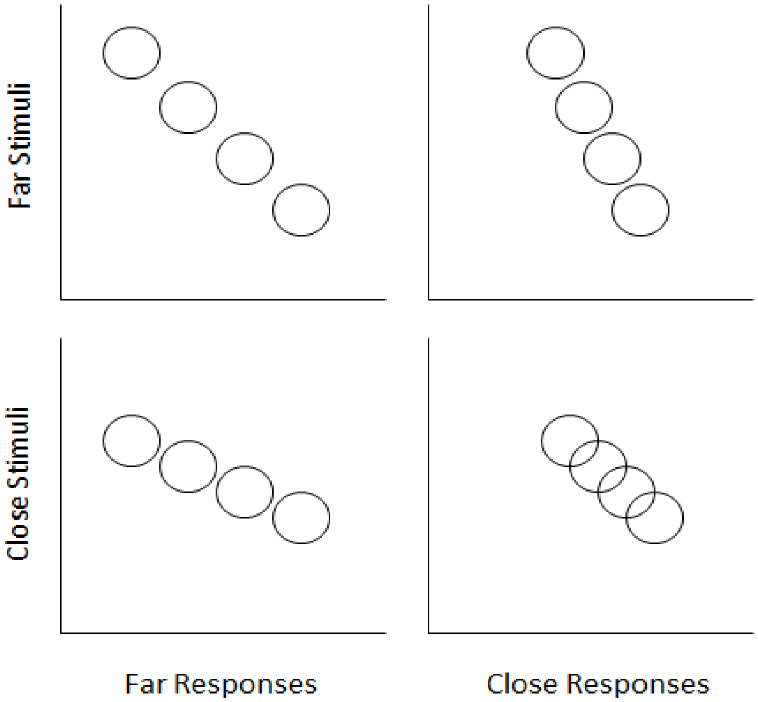

Figure 24. The relationship between the S-R alternatives across the four conditions.

Why did the *SC-RC* condition lead to the most curvature? The answer is that this situation creates overlap among the S-R alternatives across both dimensions. When a close stimulus was presented it co-activated the other stimulus-response mappings, creating more competition between the S-R alternatives and 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.

The results from Chapter 4 were also consistent with this general framework; the metric relationship between stimuli and responses mattered and as there was more overlap along a dimension there was more competition. Furthermore, there was little effect of curvature with stimuli that were dissimilar. When the three items were presented there was little overlap along the stimulus dimension leading to less competition (and less curvature. When the identity of the target and competitors were similar there was more overlap along the stimulus dimension leading to more competition. The configuration of the responses interacted with stimulus similarity such that when the location of the competitors was to one side of the target there was a greater pull and this pull canceled out when the target was inside the competitors.

This framework is consistent with the data from Chapter 5 as well. In the Flanker task for instance, when a stimulus was presented during the *SF-RC* condition (the condition that lead to the largest congruency effect during the Flanker task) the stimulus co-activates other S-R alternatives. There is already overlap along the response dimension and with the irrelevant stimulus information there is overlap along both dimensions resulting in a condition that looks similar to the *SC-RC* condition. An incongruent trial had little effect in the *SC-RC* condition because there was already overlap along both dimensions so the irrelevant information had little effect. For the Simon task, the data for incongruent trials were also consistent with the present framework. The most curvature was found in *SC-RC* condition because of the overlap of the S-R alternatives along both dimensions.

Previous research has typically demonstrated that stimulus similarity impairs performance (Farmer et al., 2007; Freeman et al., 2011; Song & Nakayama, 2009) and response similarity facilitates performance (McDowell et al., 2002). A feed-forward, discrete stage model would predict that *SF-RC* condition should have been the "easiest", or the condition with the least amount of curvature. However, this did not happen. This condition along with the *SC-RC* drove the stimulus x response interaction and suggests a more continuous interaction between stimuli and responses. This underscores the takeaway message from this dissertation: both the properties of the stimulus and the response *matter* and influence RS. Response selection here was not a simple look-up table (Anderson et al., 2004) that matches the classified stimulus to the response, or abstract translation stage but the active binding of stimulus and response information. Response selection was influenced by the configuration of the response locations, the source of the stimulus, irrelevant stimuli, as well as the metric relationship between the stimuli and the responses. Thus, RS is not some passive processes that just receives an input and outputs information isolated from all other processing but is actively influenced by a variety of factors.

Finally, these results have real-world implications. The data suggest the configuration of icons on a website, for example, matter and influence the efficieny that a person is able to navigate a computer mouse to a particular icon. Further, this procedure might reveal a participant's interest in another item even though they never clicked on it. This fact could have a major impact for marketers and website designers. By tracking where the mouse cursor is and to the extent a person is considering another item (and to the degree) marketers could use this information to better understand a person's likes and dislikes.

Relationship to other paradigms

I am not the first person to investigate how moving a mouse cursor or making reaching motion is impacted by competitor items. As reviewed in the introduction previous mouse tracking studies in the language literature have participants move a computer mouse to a target on the screen in the presence of a competitor that was phonologically related or not. In selective reaching tasks (Howard & Tipper, 1997; Welsh et al., 1999; Welsh & Elliot, 2004) participants are expected to make a reaching movement to a target in the presence of a non-target stimulus. The results from mouse tracking studies and selective reaching tasks have been widely successful in demonstrating how competitors or irrelevant information affect performance. The results present in this dissertation are consistent with the notion that competitors are partially activated to the degree they match the stimulus with similar competitors affecting the mouse trajectory to a greater degree than dissimilar competitors.

Though the current paradigm is 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 manipulated both stimulus and response similarity whereas, 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 non-target stimulus and target) but not stimulus similarity was manipulated. Second, for all of the experiments (except Experiments 5, 6, and 8) the stimulus was separate from the response location, forcing participants to remember the S-R mappings. Finally, previous studies have also had the competitor displayed on each trial. This was not explicitly the case in Experiments 1-4 as the response locations were marked but only one stimulus was presented on a given trail. Thus, the competitive interaction was the result of non-displayed stimuli but displayed response locations however, the interaction was not entirely driven by the displayed response locations but by the co-activation of S-R alternatives by similar stimuli. In this way, the interaction was not a complete non-displayed competitor effect though the results hint that the competitor does not necessarily need to be present on introduce competition.

Information flow through the system

Finally, the present data does not resolve the issue of whether RS operates in a discrete or continuous manner. As discussed in Chapter 1 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 that sense a strictly feed-forward discrete mechanism cannot account for the present data. The data are much more easily accounted for with a continuous/dynamic system that allows for co-activation of multiple representations and the competitive effects to extend to post perceptual motor processing. A feed-forward system cannot account for these data because it does not predict an interaction between stimulus and response information as stimulus similarity only affects encoding and response similarity affects motor output. A model that transmits information continuously can account for this data as it more readily allows for partial activation of S-R alternatives.

Conclusions

Reaching out to grab an item like a beverage or moving a mouse cursor to click an icon on a webpage is virtually constant occurrences in daily life. A process that is critical to accomplish these types of tasks is RS. In a series of experiments presented here RS was demonstrated to be sensitive to metric relations between the stimuli and responses, the configuration of the responses, as well as if irrelevant information was presented. These results suggest that when designing environments a person would interact with (e.g., webpages, touch screens, etc) that issues of similarity, configuration, irrelevant information are kept in mind to aid in building environments that we can more readily use. The results 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 its environment.

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