

Keeping Simon simple: Examining the relationship between sequential modulations and feature repetitions with two stimuli, two locations and two responses

Eliot Hazeltine^{a,*}, Çağlar Akçay^b, J. Toby Mordkoff^a

^a Department of Psychology, University of Iowa, Iowa City, IA 52241, United States

^b Department of Psychology, University of Washington, Seattle, WA 98195, United States

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ABSTRACT

The present study examined performance across three two-choice tasks that used the same two stimuli, the same two stimulus locations, and the same two responses to determine how task demands can alter the Simon Effect, its distribution across reaction time, and its sequential modulation. In two of the tasks, repetitions of stimulus features were not confounded with sequences of congruent and incongruent trials. This attribute allowed us to investigate the sequential modulation of the Simon Effect in a two-choice task while equalizing the occurrence of feature repetitions. All tasks showed a similar sequential modulation, suggesting that it is not driven by feature repetitions. Moreover, distributional analyses revealed that the advantage for congruent trials decreased as reaction time increased similarly following congruent and incongruent trials. Finally, a large increase in RT was observed when repeated responses were made to novel stimuli and when novel responses were made to repeated stimuli. This effect also showed a sequential modulation regardless of whether the stimulus repeated. The findings suggest that, even in two-choice tasks, response selection is mediated by complex, dynamic representations that encode abstract properties of the task rather than just simple features.

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The Simon Effect is typically defined as a shortening of reaction time (RT) when the task-irrelevant location of a stimulus corresponds to the location of the response. That is, RT is shorter when the location of the stimulus corresponds to the location of the response than when the locations of the stimulus and response do not correspond. Although its magnitude is generally small, usually 20–25 ms, it is a robust effect that can be observed with small numbers of participants across a wide range of experimental conditions. The Simon Effect has received sustained interest since its discovery by J. Richard Simon in the mid 1960s (e.g., Simon & Rudell, 1967), in part because it exists at the nexus of stimulus and response processing. Thus, it provides important clues about diverse topics such as attention, response selection, conflict resolution, and embodied cognition. It may be the single most difficult phenomenon for the classic Discrete Stage Model to accommodate, and throughout the many transformations of cognitive psychology, the Simon Effect has remained highly relevant and mysterious.

Recently, two additional aspects of the Simon Effect have received attention for their implications with regard to control processes. First, the magnitude of the Simon Effect is larger after congruent trials (i.e., after trials in which the location of the stimulus corresponded with the location of the response) than after incongruent trials (i.e., after trials in

which the locations of the stimulus and response did not correspond) (e.g., Stürmer, Leuthold, Soetens, Schroeter, & Sommer, 2002). This phenomenon has been called “conflict adaptation” (Botvinick, Braver, Barch, Carter, & Cohen, 2001), but in the present paper we use the term *sequential modulation* to avoid theoretical assumptions about its source. Second, distributional analyses reveal that the Simon Effect typically “fades” as RT becomes longer. That is, when the RTs for congruent and incongruent trials are separated and divided into quantiles, the faster quantiles for the two sets show a larger Simon Effect than the slower quantiles (e.g., De Jong, Liang, & Lauber, 1994; Ridderinkoff, 2002; Rubichi, Nicoletti, Iani, & Umiltà, 1997). While sequential modulations are observed across a range of conflict tasks, such as the Stroop (e.g., Kerns, Cohen, MacDonald, Cho, Stenger, & Carter, 2004; Notebaert, Gevers, Verbruggen, & Liefoghe, 2006) and flanker tasks (e.g., Gratton, Coles, & Donchin, 1992), fading is generally not observed in these other tasks (see, Hommel, 1997).

The Simon Effect can be observed across a wide range of experiments and task demands, but here we focus on the most widely studied case: when there are two stimuli, two locations, and two responses. We examine fading and sequential modulations to gain insight into their underlying causes and what they can tell us about response selection. If sequential modulations and fading both stem from online adjustments in the gating of irrelevant spatial information, then one might expect the two to interact. According to this reasoning, after incongruent trials, the system may be less sensitive to location information and online control

* Corresponding author.

E-mail address: eliot-hazeltine@uiowa.edu (E. Hazeltine).

may play less of a role, which would lead to less fading than after congruent trials. Alternatively, one might posit that incongruency on the previous trial would ramp up the control system, leading to enhanced suppression on the subsequent trial, which would lead to more fading than after congruent trials (as reported by Ridderinkoff, 2002).

An additional complication is that when standard versions of two-alternative forced-choice tasks are used, the relationship between current and previous congruency is confounded with feature repetitions. That is, congruent trials that follow congruent trials, and incongruent trials that follow incongruent trials, always involve either a complete repetition or a complete alternation of the stimulus' identity and location; the stimulus is either exactly the same (complete repetition) or composed of features none of which appeared on the previous trial (complete alternation). Conversely, congruent trials that follow incongruent trials, and incongruent trials that follow congruent trials, always involve partial repetitions of features; the stimulus' identity is either the same as the previous trial but appears at a different location or it's different from the previous trial but appears at the same location (partial repetition). This confounding of congruency sequence with feature repetition has plagued two-choice studies of sequential modulation (e.g., Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003).

To address this concern, many researchers have turned to forced-choice tasks with more than two stimulus–response pairings. With four or more pairings, the effects of feature repetitions can be cleanly dissociated from the sequence of compatible and incompatible trials, and researchers generally report sequential modulations within the subset of trials comprised completely of complete alternations (e.g., Akçay & Hazeltine, 2007; Kerns et al., 2004; Notebaert et al., 2006; Ullsperger, Bylsma, & Botvinick, 2005). Thus, there is reason to believe that the sequential modulations observed in two-choice tasks do not stem entirely from costs associated with partial repetitions of the stimulus and response features (but see, Chen & Melara, 2009).

However, changing the number of stimuli, locations, and responses may also change the nature of the Simon Effect. First, the magnitude of the effect is usually larger when larger numbers of S–R pairs are employed. For example, four-choice tasks generally produce Simon Effects that are about twice as large as those observed with two-choice tasks (e.g., Akçay & Hazeltine, 2007). Second, the additional stimuli and responses complicate the relationships among these items' locations. If all of the items are arranged along a horizontal axis, then an item's relative leftness or rightness compared to the previous trial may conflict or enhance the item's absolute leftness or rightness within the display (e.g., Hommel, 1993; Nicoletti & Umiltà, 1989; Stoffer, 1991). Alternatively, researchers may vary the stimuli and responses along the vertical dimension as well as the horizontal one, such that each stimulus location is an equal distance from fixation and placed along a unique direction from fixation. The concern with this configuration is that there is mounting evidence that the Simon Effect along the vertical dimension is qualitatively distinct from the Simon Effect along the horizontal dimension in that the vertical Simon Effect does not show fading (Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005; Wiegand & Wascher, 2005). Thus, using more than two S–R pairs and locations introduces a host of issues that make the evaluation of the Simon Effect more complex, especially when comparing across experiments with different numbers of S–R pairs.

In the present study, we take an alternative approach: rather than increasing the number of stimuli and responses, we hold these constant and change the task. By changing the task instead of the number of S–R pairs, we can manipulate the difficulty of S–R translation, break the confound between the congruency sequence and feature repetitions, hold the stimulus and response probabilities constant, and maintain the spatial relationships among stimuli and responses. Given the preponderance of research involving two-choice tasks, this approach should facilitate comparisons to previous studies.

1. The present study

We used three distinct two-choice tasks that all involved the same stimulus identities, stimulus locations, and responses to determine the role that stimulus and response repetitions play in the sequential modulation of the Simon Effect. The first task was a standard version of the Simon task, in which one stimulus (O) was mapped to the left key and the other stimulus (X) was mapped to the right key. We term this the *OLXR* (O-left, X-right) task. However, in the other tasks, specific stimuli were not strictly associated with particular keys. In the *OSXD* (O-same response, X-different response) task, participants pressed the same key as they pressed on the previous trial if an O was presented and the other (different) key if an X was presented. Finally, in the *SLDR* (same stimulus-left, different stimulus-right) task, participants pressed the left key if the stimulus was the same as the stimulus on the previous trial (e.g., O on trial *N*, after O on trial *N* – 1) and the right key if the stimulus was different (e.g., X on trial *N*, after O on trial *N* – 1). In the latter two tasks, participants were told to press whichever key they wished on the first trial of each block.

Manipulating task while keeping the number of stimuli, locations, and responses constant will provide useful data with regard to the mechanisms that underlie the Simon Effect and its sequential modulation. First, the three tasks vary in terms of difficulty, as indexed by both RT and the complexity of the instructions, so we can examine the effects of task difficulty on the Simon Effect. In this way, we can look at how the duration of central operations affects the magnitude of the Simon Effect without altering other aspects of the task that may also play a role, such as stimulus and response probability, the number of S–R mappings, etc. If the fading of the Simon Effect relates to the decay or suppression of automatic activation during central operations, the tasks with the longer RTs should show smaller Simon Effects, given that they have longer central operations.

Second, the manipulation of task allows us to examine the role that the conceptualization of the responses plays in the Simon Effect. In the standard versions of the Simon task, such as the *OLXR* task, each stimulus is uniquely associated with a particular response, so a particular stimulus in a particular location is always congruent or incongruent. With the *OLXR* and *SLDR* tasks, we manipulate the coding of the responses, so that specific stimuli are no longer associated with particular responses. In this way, we can evaluate the role that standard S–R mappings (i.e., associating particular stimuli with particular keys) play in the Simon Effect. We note that in some cases, altering the S–R mapping has dramatic effects on the Simon Effect (e.g., Hedge & Marsh, 1975). Moreover, in the *OSXD* and *SLDR* tasks, a given display considered in isolation is neither congruent nor incongruent because the response is based on the relationship between the present and previous trial. Therefore, the congruency of a display depends on what occurred on the previous trial. Thus, the experiment will examine whether the fixed congruencies of the displays play a role in the Simon Effect. If the Simon Effect is driven, at least in part, by the static associations between stimuli and responses, then the Simon Effect should again be reduced for the *OSXD* and *SLDR* tasks.

Third, the manipulation of task will allow us to examine the source of the sequential modulation. Unlike typical two-choice tasks, the *OSXD* and *SLDR* tasks break the rule that repetitions of the stimulus necessarily require repetitions of the response and that alternations of the stimulus necessarily require alternations of the response. This change means that it will now be possible to look at sequential effects in a two-choice task while keeping feature repetitions constant across the conditions. For both of these tasks, the sequences of congruent and incongruent trials are entirely independent of whether the features repeated. Therefore, if sequential modulations in two-choice tasks stem, at least in a sizable proportion, from the confound between the congruency sequence and feature repetitions, then the *OSXD* and *SLDR* tasks should show a much smaller sequential modulation of the Simon Effect.

2. Experimental procedures

2.1. Method

2.1.1. Participants

Thirty-two participants (19 females) from the University of Iowa volunteered for a one-hour session of the experiment to meet a course requirement for an introductory psychology class. Two of the participants were eliminated from the analysis for having an overall error rate that was greater than 15% (one from the OSXD group and one from SLDR group).

2.1.2. Stimuli and apparatus

The experiment was conducted on PC computers with E-prime software. The stimuli were presented on a 17-inch monitor positioned about 70 cm from the participants' heads. A white fixation cross subtending approximately 1 degree of visual angle was presented throughout the experiment. The stimuli were white letters, either an X or an O, subtending 2 degrees of visual angle and presented 7.5 degrees to the left or right of the fixation cross. Participants responded with the index fingers of their left and right hands on the "z" and "m" keys, respectively.

2.1.3. Design

Each trial began with a 500-ms foreperiod followed by the presentation of the stimulus. The stimulus remained visible until the participant responded, after which there was a 1-s interval before the onset of the next trial. Thus, there was a 1500-ms interval between the response and the onset of the stimulus on the subsequent trial. No feedback was provided during the blocks, but after the block was complete, the mean RT and percent correct were displayed on the computer monitor. Participants were instructed to contact the experimenter if their accuracy fell below 90% on any block.

Participants performed 10 blocks, each consisting of 81 trials. The stimulus and location of the first trial was chosen randomly, but the remaining 80 trials were pseudorandomly chosen so that each combination of stimulus (O or X) and location (left or right) was equally probable. Participants were allowed to take short breaks between blocks.

3. Results

The first two blocks were treated as practice and were not analyzed. We also excluded any trial with an incorrect response or following an incorrect response, any trial with an RT less than 200 ms or greater than 2000 ms, and the first two trials of each block. This procedure eliminated 10% of the data, not including the first two blocks. To simplify the analyses, the data were coded in terms of congruency (i.e., whether the correct response corresponded with the stimulus location) rather than in terms of stimulus location and side of response. This allows for more straightforward comparisons across tasks, given that two of the tasks did not entail a strict correspondence between the stimulus identity and the correct response.

3.1. Congruency and sequential modulation

The first analysis focused on the established Simon Effect and its dependence on the congruency of the previous trial. Thus, the data were submitted to a three-way ANOVA, with congruency of the current trial and congruency of the previous trial as within-subjects factors and task as a between-subjects factor. The results are shown in Fig. 1.

The main effect of task was significant, $F(2,27) = 19.54$, $p < .0001$, indicating that the OLXR task was performed more quickly than the OSXD task, $t(18) = 3.85$, $p < .05$, which was performed more quickly than the SLDR task, $t(18) = 2.48$, $p < .05$. Neither the main effect of

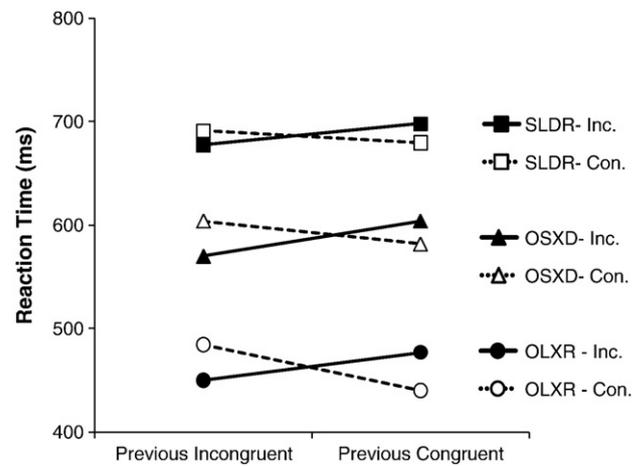


Fig. 1. Reaction times across the three tasks as a function of congruency and previous congruency. Congruent (Con.) and incongruent (Inc.) trials are plotted separately. Previous congruency is depicted on the x-axis.

congruency nor the main effect of previous congruency approached significance, $F_s < 1$.

There was a significant interaction between congruency and previous congruency, $F(1,27) = 68.82$, $p < .0001$, and this interaction showed a marginal dependence on task, $F(2,27) = 2.99$, $p = .07$. The two-way interaction reflects the standard sequential modulation; congruent trials were performed faster after congruent trials, whereas incongruent trials were performed faster after incongruent trials. The trend toward a three-way interaction between congruency, previous congruency, and task suggests that the sequential modulation is not the same for all tasks. Although the sequential modulation was reliable for each task considered separately (OLXR: I-C after I: -27 ms, I-C after C: 44 ms, $F(1,9) = 58.08$, $p < .0001$; OSXD: I-C after I: -34 ms, I-C after C: 21 ms, $F(1,9) = 20.47$, $p < .005$; SLDR: I-C after I: -14 ms, I-C after C: 18 ms, $F(1,9) = 6.50$, $p < .05$), its magnitude was largest for the OLXR task and smallest for the SLDR task. Given that these tasks differed in terms of mean RT and that the Simon Effect can fade as RT increases, the source of this finding is unclear; it may be that the marginal three-way interaction directly results from the differences in the task demands or only indirectly via the differences in RT. To further examine this issue, we turn to distributional analyses, which can distinguish between these two possibilities by evaluating the Simon Effect across a range of RTs for each task.

3.2. Distributional analyses

The data for each subject and each congruency \times previous congruency condition were binned into quintiles, with the fastest 20% of the trials in the first bin, the next fastest 20% in the next bin, etc. The mean bin RTs were then converted to congruency scores (by subtracting the congruent RT from the incongruent RT) for each quintile, task, and previous congruency. The results are shown in Fig. 2. Finally, the data were submitted to a mixed three-way ANOVA, with quintile and previous congruency as within-subjects factors, and task as a between-subjects factor. There were significant main effects of previous congruency, $F(1,27) = 64.88$, $p < .0001$, and quintile, $F(4,108) = 23.60$, $p < .0001$, and a significant interaction between quintile and task, $F(8,108) = 4.09$, $p < .0001$. No other main effects or interactions were significant.

¹ It was unexpected that there was no main effect of congruency—that is, no Simon Effect. The absence of a Simon Effect stems from a complete crossover of the congruency effect after incongruent trials. This pattern has been observed in other experiments examining the Simon Effect (Valle-Inclan, Hackley & de Labra, 2002). Given the robustness of the sequential modulation, even when unconfounded with feature repetitions, it appears that participants were sensitive to spatial congruency.

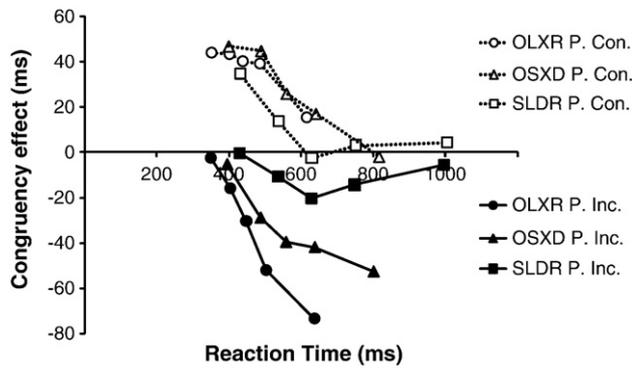


Fig. 2. Magnitude of the Simon Effect across the RT quintiles plotted for the three tasks. Trials following congruent trials (Con., unfilled) and trials following incongruent trials (Inc., filled) are plotted separately.

The main effect of previous congruency was expected and reflects the standard form of sequential modulation: the congruency effect was more positive after congruent trials than after incongruent trials. The main effect of quintile indicates that, overall, the advantage for congruent trials became less positive as the RT increased. As can be seen in Fig. 2, there is little indication that the previous congruency of the trials interacted with the effect of quintile, $F < 1$. That is, all tasks show the same two trends: congruency effects are larger (i.e., more positive) after congruent trials than after incongruent trials, and congruency effects become smaller with longer RTs. Previous congruency modulated the effect congruency on the current trial, but it did not systematically change the shape of the distribution across the three tasks. Following congruent trials, the fastest trials show the congruency effect, with responses on the same side as the stimulus being performed faster than responses on the opposite side of the stimulus. This Simon Effect diminishes as RT increases, so that the slowest trials show no Simon Effect whatsoever. Following incongruent trials, the fastest trials show no Simon Effect, and the slower response show a reversed Simon Effect, with responses on the opposite side of the stimulus being performed faster than responses on the same side of the stimulus.

This overall pattern suggests two distinct processes, one dependent on the congruency of the previous trial but independent of RT and one dependent on RT but independent of the previous trial. That is, the effect of current congruency fades as RT increases, but the effect of previous congruency does not. These findings are generally consistent with the claims of Hommel (1994), who manipulated stimulus intensity and stimulus onset and found that these factors did not interact with the frequency of incongruent trials in determining the magnitude of the Simon Effect. However, the current findings contrast with those of Ridderinkoff (2002), who reported more fading (i.e., larger effects of RT) after incompatible trials. Given the limited power of our design and that our statistics are sided with the null result, we can make no strong claims except to note that, for both the OLXR and OSXD tasks, the slopes of the quintile functions were significantly negative after both congruent and incongruent trials (all t 's > 2.7 , p 's $< .05$). This finding indicates that fading is not restricted to trials after congruent or trials after incongruent trials.

Nonetheless, the interaction between quintile and task does indicate that the rate at which congruency advantage became less positive differed across the experiments. The Simon Effect for the OLXR and OSXD tasks are largely overlapping where the mean RTs are the same, suggesting that the small, nonsignificant difference in the sequential modulation can be explained by the differences in the mean RTs for these two tasks. Wiegand and Wascher (2007) reported that varying the S–R mapping from trial to trial led to fading with a vertical version of the Simon Effect, which usually does not show fading, but did not affect fading in a horizontal version. In the present tasks, the S–R rules remain constant, but the associations between stimuli and response change. The

observed pattern of fading is largely consistent with their findings in that the OSXD task showed robust fading.

With regard to the SLDR task, the distributional analysis is unclear. There is some evidence that fading was observed in the SLDR task, but these effects were not statistically significant (both after congruent and after incongruent trials, t 's < 1). There is also preliminary evidence that the reduced congruency effect observed with the SLDR task is not exclusively caused by the longer RTs associated with that task. For example, the Simon Effect of the third quintile of the SLDR task after incongruent trials (-20 ms) is significantly less negative than the Simon Effect of the fifth quintile of the OLXR task after incongruent trials (-73 ms), even though the mean RTs are nearly identical (629 ms vs. 636 ms). However, the design is not sufficiently powerful to make strong conclusions about the role of task in the magnitude of the Simon Effect or its time-course.

3.3. Sequential modulations and feature repetitions

A notable attribute of the OSXD and SLDR tasks is that they do not possess a confound between feature repetitions and the conditions that are used to estimate sequential modulation of the Simon Effect. Therefore, for these two tasks, we can assess the role that feature repetitions play in determining the amount of sequential modulation in a two-choice task. To do this, the data from the OSXD and SLDR tasks were submitted to a five-way ANOVA, with stimulus repetition, location repetition, congruency, and previous congruency as within-subjects factors, and task as a between subject factor.

The results are summarized in Fig. 3. There was a significant main effect of stimulus repetition, $F(1,18) = 34.01$, $p < .0001$, indicating that responses were made more quickly when the stimulus repeated (608 ms) than when the stimulus alternated (662 ms). In contrast, there was no indication of a main effect of location repetition (635 ms vs. 636 ms), $F < 1$, nor was there an interaction between stimulus repetition and location repetition (repeated stimulus: 608 ms vs. 609 ms; alternated stimulus: 663 ms vs. 661 ms), $F < 1$. Thus, in the tasks where the stimulus is uncorrelated with the correct response, there is little evidence that bindings between the stimulus identity and its location play a major role in determining the amount of sequential modulation.

The most striking aspect of these data is the four-way interaction among stimulus repetition, location repetition, congruency, and previous congruency, $F(1,18) = 200.77$, $p < .0001$, which can be succinctly characterized as the following: the sequential modulation of the Simon Effect (i.e., the interaction between current and previous congruency) was found to depend on the interaction between stimulus repetition and location repetition. When both the stimulus and its location repeated, or when both the stimulus and its location alternated, a large, standard form of sequential modulation was observed: congruent trials were performed faster after congruent trials, and incongruent trials were performed faster after incongruent trials. However, when stimulus repeated and the location alternated, or when the stimulus alternated and the location repeated, a large, reversed sequential modulation was observed: congruent trials were performed faster after incongruent trials and incongruent trials were performed faster after congruent trials.

Two aspects of this surprising four-way interaction should be noted. First, the congruency \times previous congruency interaction in each of the four panels of Fig. 3 is much larger than is typically reported for a sequential modulation. In the standard (OLXR) task, which did not allow for the orthogonal manipulation of congruency sequences and feature repetitions, the congruency effect was 44 ms after congruent trials and -27 ms after incongruent trials, representing a change of 71 ms. In contrast, consider the data from the OSXD task when, for example, the stimulus repeated and the location alternated (i.e., the bottom-left panel of Fig. 3). Under these conditions, the congruency effect was -114 ms after congruent trials and 120 after incongruent

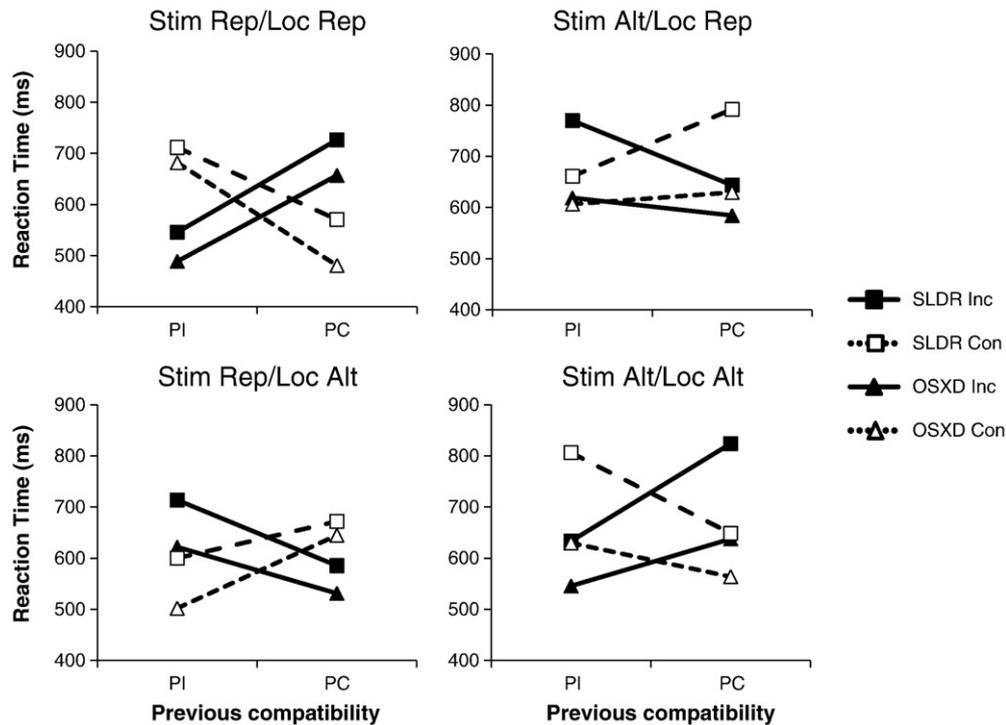


Fig. 3. Reaction times across the OSXD and SLDR tasks as a function of congruency (separate lines; Inc = incongruent; Con = congruent), previous congruency (x-axis; PI = previous incongruent; PC = previous congruent), stimulus repetition (left panels = stimulus repeated; right panels = stimulus alternated), and location repetition (top panels = location repeated; bottom panels = location alternated).

trials, representing a change of 234 ms. The same is true when the direction of the effect is the same as the standard form of sequential modulation: in the bottom-right panel of Fig. 3, the congruency effect for the OSXD task is 74 ms after congruent trials and -84 ms after incongruent trials, representing a change of 158 ms. In summary, the observed four-way interaction appears to reflect something more than the traditional sequential modulation.

Second, the four-way interaction, itself, depends on task, leading to a five-way interaction, $F(1,18) = 5.05$, $p < .05$. However, none of the four panels in Fig. 3 exhibit any reversals of the type of sequential modulation as a function of task; instead, the specific type of sequential modulation (standard or reversed) is consistently stronger for the SLDR task than it is for the OSXD task. For the OSXD task, the mean change in the congruency effect as a function of previous congruency was 205 ms; for the SLDR task, the mean change was 282 ms.

What is driving the four-way interaction between stimulus repetition, location repetition, current congruency, and previous congruency? For each combination of stimulus repetition and location repetition in Fig. 3, the short RTs are from conditions in which the stimulus identity and the response both repeated or both alternated on successive trials, and the long RTs are from conditions in which either the stimulus or response alternated and the other repeated. In other words, the four-way interaction reflects a two-way interaction between stimulus repetition and response repetition.

3.4. S–R bindings

For the present purposes, we refer to the relationship between the stimulus identity and the response as the S–R bindings (or stimulus identity–response binding), which are distinct from feature repetitions. Feature repetitions (or identity–location binding) relate to only features of the stimulus, which, in the OSXD and SLDR tasks, are uncorrelated with the response. In conventional S–R tasks, feature repetitions may vary from trial to trial, but S–R bindings remain consistent throughout the experiment.

Previous work has addressed the costs associated with new S–R bindings. For example, when many-to-one mappings are used, the stimulus can change on successive trials while the response repeats, which usually produces a cost (e.g., Schuch & Koch, 2004), but a given stimulus is never associated with a different response. To get around this limitation, Hommel and colleagues (Hommel, 1998; Hommel & Colzato, 2004) required participants to make a predetermined response to a stimulus (whose identity was irrelevant to the response but in some conditions had to be remembered) and then make a choice response based on the identity of a second stimulus, allowing for stimulus repetitions and response alternations. Under these conditions, robust costs were associated with the formation of novel S–R bindings.

OSXD and SLDR tasks allow one to examine the effects of altered bindings more directly, without having to vary task relevance of stimulus features, because the specific S–R bindings can change from trial to trial even though the task rules remain the same. Moreover, whether the S–R bindings are maintained or change between trials is independent from feature repetitions. Thus, it is possible to have a partial repetition trial (e.g., stimulus identity repeated and stimulus location alternated) in which either the S–R binding repeated (e.g., stimulus identity repeated and response repeated) or the S–R binding alternated (e.g., stimulus identity repeated and response alternated). The four-way interaction among stimulus repetition, location repetition, congruency, and previous congruency from these tasks suggests that S–R bindings have a much more powerful effect than feature repetitions.

To more closely examine this phenomenon, we performed a follow-up analysis that ignored congruency and directly assessed the effects of repeating the S–R binding. The data were recoded based on whether the S–R binding was old (i.e., both stimulus identity and response repeated, or both alternated) or was new (i.e., either stimulus identity repeated and response alternated, or stimulus identity alternated and response repeated). This coding of S–R binding was not only done for the current trial (i.e., whether the binding on trial N was the same as on trial $N - 1$), but for the previous trial, as well (i.e., whether the binding

on trial $N - 1$ was the same as on trial $N - 2$). We refer to whether the S–R binding on the present trial is the same as the previous (old) or violates the previous stimulus–response pairing (new) as the “current binding.” We refer to whether the binding on trial $N - 1$ was the same (old) or different (new) from the binding on trial $N - 2$ as “previous binding.” The previous binding factor was included to provide stronger evidence that S–R bindings can affect response selection processes. If S–R bindings affect response selection, there should be evidence of a sequential modulation as is seen with other forms of congruency. Finally, the data were also classified in terms of whether the stimulus repeated from the previous trial and which of the two tasks was involved. The stimulus repetition factor was included to determine whether the S–R binding effect is contingent on the stimulus being the same on consecutive trials. That is, this factor addresses whether the cost of associating a repeated stimulus to a new response is the same as associating a new stimulus to a repeated response. Note that each of the sixteen cells in this $2 \times 2 \times 2 \times 2$ analysis is composed of equal numbers of congruent and incongruent trials.

All four factors produced significant effects (OSXD vs. SLDR task: 609 ms vs. 709 ms, $F(1,18) = 6.02$, $p < .05$; stimulus repetition vs. alternation: 629 ms vs. 689 ms, $F(1,18) = 47.50$, $p < .0001$; old vs. new current binding: 589 ms vs. 729 ms, $F(1,18) = 194.36$, $p < .0001$; and old vs. new previous binding: 652 ms vs. 665 ms, $F(1,18) = 6.75$, $p < .05$). Stimulus repetition, $F(1,18) = 11.55$, $p < .005$, and current binding, $F(1,18) = 6.82$, $p < .05$, separately, both interacted with task; the effects of stimulus repetition (91 ms vs. 31 ms) and current binding (167 ms vs. 114 ms) were both greater for the SLDR than the OSXD task. Because the only interaction involving stimulus repetition was that with task, the data were collapsed across this factor to produce Fig. 4.

The main effect of current binding reflects the 140-ms cost associated with making the same response to a different stimulus or a different response to a repeated stimulus. This effect was much larger than the 61-ms cost associated with switching stimuli. Note that this binding effect is observed even though the task remains the same (e.g., press the left key if the stimulus repeats, and press the right key if the stimulus changes). In other words, making the same response to a different stimulus, or a different response to the same stimulus, appears to produce a robust cost, even when it is required on half of the trials and there is no change in the task.

The effect of the current binding also depended on the previous binding, $F(1,18) = 59.70$, $p < .0001$, as can be seen in Fig. 4. This interaction indicates that the cost associated with a new S–R binding on the current trial was much greater when the previous trial maintained the S–R bindings from trial $N - 2$ (195 ms) than when the

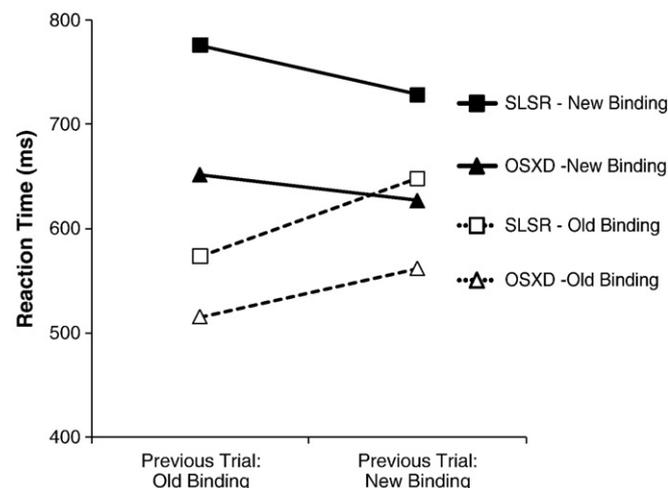


Fig. 4. Reaction times across the OSXD and SLDR tasks a function of whether new or old S–R bindings were required on the present trial, shown on separate lines and whether new or old S–R bindings were required on the previous trial, depicted on the x-axis.

previous trial also required a new S–R binding (86 ms). Thus, there was large modulation of the cost associated with forming new S–R bindings. If trials $N - 1$ and $N - 2$ used the same mapping, the cost of forming a new binding on the current trial was greatly increased. This interaction between current and previous binding was similar for both same stimulus and different stimulus trials (previous binding \times binding \times stimulus repetition: $F < 1$), indicating that the sequential modulation of the binding effect is independent from the well-known advantage for making the same response to the same stimulus. In sum, there appears to be a powerful form of compatibility between stimulus repeating/alternating and response repeating/alternating in two-choice tasks which itself is subject to a sequential modulation.

4. Discussion

The present study revealed a rich set of effects and interactions underlying the performance of forced-choice tasks involving just two stimuli, two locations, and two responses. These effects appear to be similar regardless of the specific task; whether participants responded based on the identity of the stimulus, its relation to the previous stimulus, or the relationship between the present stimulus and the previous response, the same basic patterns were observed. It should be noted that in all of the tasks, none of these factors was confounded with trial frequency. That is, the frequencies of congruent and incongruent trials were balanced, the frequencies of stimulus and response identities were balanced, and, in the OSXD and SLDR tasks, the frequencies of trials requiring new bindings and trials requiring old bindings were balanced. Under these conditions, three principal findings emerged: the Simon Effect and its change across the RT distribution were largely unaffected by the particular S–R mapping; sequential modulations were robust even when dissociated from feature repetitions, and rebinding a stimulus to a response produced a robust cost which itself is subject to sequential modulations. We discuss each of these below.

4.1. The Simon Effect

Overall, the Simon Effect was not observed in any of the three tasks, but the sequential modulation of the Simon Effect was significant in every case, indicating that the spatial correspondence between the stimuli and responses did affect performance. For all tasks, participants were faster when the congruency of the previous trial matched the congruency of the present trial. Critically, this sequential modulation was observed in the two tasks that do not confound congruency sequences and feature repetitions. In the OSXD and SLDR tasks, each of the four possible combinations of current and previous trial congruency was equally likely to be complete repetitions/alternations or partial repetitions. Moreover, there were no differences in the probabilities of being complete alterations or complete repetitions. The magnitude of the sequential modulation was smaller for the OSXD and SLDR tasks, compared to OLXR task, suggesting that feature repetitions might play a small role in the sequential modulation observed in OLXR task. However, the tasks differed in terms of mean RT as well as whether feature repetitions were confounded with sequential modulations. For this reason, distributional analyses were applied to the data.

The distributional analyses indicated that the Simon Effect was present for all tasks for the fastest responses, but as RT increased, the Simon Effect diminished and became negative, which is why there was no Simon Effect in the overall analysis (see Fig. 2). When the data were separated according the congruency of the previous trial, as well as quintile, it became clear that the changes in the Simon Effect with increasing RT were qualitatively similar following congruent and incongruent trials. That is, there were no significant changes in the reduction of the Simon Effect with increasing RT as a function of the congruency of the previous trial. The data suggested that the small differences in the amount of sequential modulation across the tasks could be partly attributed to differences in mean RT across tasks,

although the SLDR task appeared to show smaller sequential modulations and less change across the distribution than the other tasks. Further work will be necessary to resolve the issue definitively given the limited power of the present experiment.

These findings are consistent with the proposal that the processes related to the fading of the Simon Effect and the processes relating to the sequential modulation may be independent, as suggested by Hommel (1994). In other words, the data suggest two distinct processes underlying the Simon Effect and its sequential modulation. One process confers an advantage to spatially congruent S–R pairs regardless of the previous trial; however, this process is transient, fading rapidly as RT increases. The other process confers an advantage to trials whose spatial congruency matches the spatial congruency of the previous trial. This second process does not appear to depend on RT.

The sequential modulation was highly dependent on whether the stimulus repeated and whether the location repeated, leading to a four-way interaction between congruency, previous congruency, stimulus repetition, and location repetition. However, this interaction was more succinctly characterized as a binding cost between the stimulus identity and the response. When the data were recoded according to whether the stimulus and response repeated, instead of whether the stimulus and location repeated, the standard form of sequential modulation was observed for every combination of stimulus repetition/alternation and response repetition/alternation. In other words, the sequential modulation is robust and consistent across stimulus and response repetitions.

4.2. Binding costs

Although the sequential modulation was observed even when the congruency sequence was uncorrelated with feature repetitions, this is not to say that binding did not play a major role in determining RT. The binding between stimuli and their locations played little role in the two novel tasks, but the binding between stimuli and responses had a dramatic effect on performance. When the stimulus and response both repeated or both alternated, RTs were about 150 ms faster than when one repeated and the other alternated. This result is not observable in standard tasks with two stimuli and two responses (due to unavoidable confounds), but it is consistent with previous claims that response selection entails the binding of stimulus features with response features (Hommel & Colzato, 2004; Hommel, Müssele, Aschersleben, & Prinz, 2001; Hommel et al., 2004). According to these accounts, when a response is selected, the stimulus features and response features are bound together, so that if, on the subsequent trial, a particular stimulus feature (task-relevant or task-irrelevant) is associated with a different response, a cost is observed. However, for the present purposes we make no strong claims about the underlying mechanism.

The costs associated with rebinding features is typically in the neighborhood of 10–30 ms when one of the features is irrelevant on both the previous trial and the present trial, and in the neighborhood of 40–60 ms when the feature is irrelevant on the previous trial but is relevant on the present one (see Hommel, 1998; Hommel & Colzato, 2004). Hommel and Colzato (2004) examined bindings between stimulus and response features on successive trials by manipulating whether the features of the first stimulus needed to be remembered (attended) or could be ignored (unattended). They found a much larger cost associated with rebinding the stimulus features with the response when it had to be attended (70–100 ms) than when it was unattended (20–40 ms), even though the stimulus features themselves were not relevant for the first response.

In the present experiment, the rebinding involved a feature that was relevant for the response on both the previous and current trial, allowing not only for the evaluation of the effects of S–R bindings but also for the evaluation of any sequential modulation of these effects. The overall cost under these conditions was 140 ms, consistent with the proposal that the task relevance of the features plays a critical role in determining the magnitude of the costs. It is also possible that the

nature of the OSXD and SLDR tasks plays a role in the large rebinding costs.² In these tasks, participants must remember the previous response (OSXD) or the previous stimulus (SLDR) to produce the correct response. The requirement to retrieve this information might enhance binding costs by activating a representation of the events of the previous trial. Tasks using S–R mappings in which multiple stimuli are associated with particular responses have reported costs associated with unrepeated stimuli requiring repeated responses (e.g., Schuch & Koch, 2004). However, these costs, like those associated with conventional binding effects, are typically much smaller than those observed in the present case (e.g., 20–40 ms). In the OSXD task, repeating the response to a novel stimulus produced RTs that were 130 ms slower than repeating the response to the same stimulus. Further study is necessary to elucidate this phenomenon. At present, we speculate that the larger costs may stem in part from the fact that the novel stimulus may also have to be unbound from its previous response association when the unusual tasks are used.

The cost of rebinding was more than 100 ms smaller when the previous trial also required rebinding; like congruency effects, the binding effect is modulated by the previous trial, and the magnitude of the modulation appears to be proportional to the magnitude of the effect. To the best of our knowledge, this is the first demonstration that binding costs are subject to a sequential modulation. The finding suggests that the binding that occurs during response selection is not entirely automatic, in the sense that it is modulated by the persistence of the binding on the previous trial. Moreover, the sequential modulation in this case cannot readily be attributed to changes in input attention. That is, the trials that require rebinding stimuli to responses did not differ in terms of any stimulus properties. For example, an exact repetition of the stimulus display required response repetitions on half the trials and a response alternation on the other half. In short, no change in the relative weighting of various stimulus features could mediate the reduction in the rebinding cost. Thus, the changes in task operations leading to the modulation of the rebinding cost must occur downstream from perceptual processes.

4.3. Summary

The present findings revealed the complexity of response selection processes even in conditions with small sets of stimuli and responses. Although an overall Simon Effect was not observed, distributional analyses revealed that performance was sensitive to spatial congruency—fast responses showed a robust Simon Effect whereas the slow responses showed a reverse Simon Effect. Previous congruency also contributed to the size of the Simon Effect but did not consistently alter the rate at which it faded with time, suggesting that fading and sequential modulations reflect distinct processes. Moreover, RTs were strongly influenced by the events of the previous trial. This pattern was not simply based on whether particular stimulus features repeated or not. Rather, there was a robust cost associated with rebinding stimuli and responses—a cost that was essentially the same whether the stimulus repeated and the response changed or the response repeated and the stimulus changed. Finally, the binding cost itself was subject to a large sequential modulation, indicating that it may not be associated only with automatic processes. Response selection processes appear to rapidly reconfigure after each trial, encoding complex relationships and dynamically adjusting their contributions to performance.

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² We are grateful to Mike Wendt for pointing out this possibility.

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