



The impact of anatomical and spatial distance between responses on response conflict

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Published online: 17 May 2018
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Abstract

Different features of objects can be associated with different responses, so that their concurrent presence results in conflict. The Simon effect is a prominent example of this type of response conflict. In two experiments, we ask whether it is modulated by the anatomical or spatial relation between responses. Predictions were derived from an extended variant of the leaky, competing accumulator (LCA) model proposed by Usher and McClelland (*Psychological Review*, 108, 550–592, 2001). The relation between responses was represented by the lateral-inhibition parameter of the model. For the anatomical distance between responses the expectations were largely confirmed, but not for spatial distance. First, the Simon effect was stronger when responses were performed with two fingers of the same hand than with different hands. Second, the Simon effect was larger only for responses with different hands at short reaction times and disappeared at long ones, whereas for responses with fingers of the same hand, the Simon effect was essentially the same for shorter and longer reaction times. This difference resulted in smaller variability of reaction times in noncorresponding than in corresponding conditions. The dependence of decision processes, as modelled by the LCA model, on the anatomical relation between responses supports the broad hypothesis that the accumulation of evidence on the state of the world is intricately linked with the activation of response codes, that is, the selection of the appropriate actions.

Keywords Response distance · Response conflict · Simon effect · Lateral inhibition · Competing accumulator model

People associate particular objects in their environment with particular actions and, as a result, perceiving those objects activates the associated responses (e.g., Norman & Shallice, 1986). Hence, perceiving two different objects can activate different responses that compete for being selected and executed. A well-known source of response conflict is the presence of a spatial stimulus feature that is irrelevant for the selection of a response, but congruent or incongruent with a spatial response feature. The purpose of the present experiments is to determine whether the impact of conflicting spatial stimulus features is modulated by the relation between responses, in particular, by their anatomical and spatial distance. This specific question is motivated by the more general hypothesis that perceptual decision-making is intricately

interwoven with the specification of the associated responses (cf. Cisek, 2006; Hagura, Haggard, & Diedrichsen, 2017; Heuer, 1987).

Conflicting stimulus features: The Simon effect

In a choice reaction-time task with a congruent mapping of spatial stimuli on spatially organized responses, reaction times are faster and accuracy is higher than in tasks with an incongruent mapping of stimulus locations on response locations. This is the well-known effect of spatial stimulus–response compatibility (e.g., Fitts & Deininger, 1954; see Proctor & Vu, 2006, for a review). Spatial S–R compatibility is also effective when stimulus location is irrelevant for response selection, as in the Simon task. In a typical Simon task, participants make left or right key-press responses to the color of stimuli that randomly appear at compatible (spatially corresponding) or incompatible (spatially noncorresponding) left or right locations. Reaction time is faster (and errors are less frequent) with spatially corresponding than with spatially

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noncorresponding responses, a quite robust phenomenon called the Simon effect (e.g., Craft & Simon, 1970; for reviews, see, Simon, 1990; Proctor & Vu, 2006).

In the typical Simon task with a horizontal arrangement of visual stimuli and responses, the Simon effect is stronger for fast than for slow responses, that is, so-called delta functions have negative slopes. Delta functions in this case represent the Simon effect, the difference between noncorresponding and corresponding conditions, for each quantile of the reaction-time distribution as a function of the mean of the quantiles in the two conditions. However, delta functions with negative slopes are not found for other variants of the Simon task, for example, with vertical arrangement of stimuli and responses or with auditory stimuli (cf. Buetti & Kerzel, 2008; Buhmann, Umiltà, & Wascher, 2007; Hommel, 1994; Wiegand & Wascher, 2005, 2007a, b). The decline of the Simon effect at long reaction times implies that the intraindividual variability of reaction times is smaller in noncorresponding than in corresponding conditions in spite of the longer mean reaction time. This co-occurrence of larger mean and smaller standard deviation is an exception to the general finding of increasing reaction-time variability with increasing mean (Wagenmakers & Brown, 2007) and represents a challenge for formal models of the Simon effect (cf. Schwarz & Miller, 2012).

The most influential accounts of the Simon effect assume two parallel routes through which stimuli can activate responses (e.g., Kornblum, Hasbroucq, & Osman, 1990; Tagliabue, Zorzi, Umiltà, & Bassignani, 2000; Zhang, Zhang, & Kornblum, 1999; Zorzi & Umiltà, 1995). Stimulus location is assumed to prime a spatially corresponding response via long-term S–R associations. Simultaneously, the relevant stimulus feature is assumed to activate the instructed response on the basis of short-term S–R associations representing task instructions. Hence, in spatially corresponding conditions, both routes activate the correct response, and converging activation (or lack of conflict) allows for its quick selection and execution. In contrast, in spatially noncorresponding conditions, the two routes activate different responses, and the additional processing for resolving the conflict results in longer reaction times (e.g., Kornblum et al., 1990).

What are the mechanisms involved in solving the conflict? Here we adopt the perspective of sequential-sampling models of binary decisions (cf. Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Ratcliff, Smith, Brown, & McKoon, 2016; Smith & Ratcliff, 2004). From this perspective there are at least three mechanisms that could play a role. They are included in an extension of the diffusion model, the diffusion model for conflict tasks (DMC), that has recently been proposed by Ulrich, Schröter, Leuthold, and Birngruber (2015, 2016) and explored, for example, by Ellinghaus, Karlbauer, Bausenhart,

and Ulrich (2017), Servant, White, Montagnini, and Burle (2016), and White, Servant, and Logan (2017). In contrast to other models (Hübner, Steinhauser, & Lehle, 2010; White, Ratcliff, & Starns, 2011) of conflict tasks, the Eriksen flanker task in particular, the DMC model can account not only for increasing but also for decreasing conflict effects at longer reaction times, that is, positive as well as negative slopes of delta functions.

The first one of the three mechanisms is inherent to the architecture of essentially all sequential-sampling models: Successive samples favor the one or the other alternative, but the one more so than the other. This is not fundamentally changed by conflicting stimulus features. As long as the activation by the relevant stimulus feature is stronger than the activation by the conflicting irrelevant stimulus feature, the correct response should be selected in the majority of trials. Because of the more similar activation of both responses during each sample, a larger number of samples and thus more time would be required for a decision in the case of stimulus-driven conflict.

The second mechanism is actually a rather widespread mechanism of conflict solution, namely, mutual inhibition. In relation to conflict solution in the Simon task it seems to be discussed only occasionally (e.g., Buckholz, O'Donnell, & McAuliffe, 1996; Zhang et al., 1999; Zorzi & Umiltà, 1995). Mutual inhibition serves to increase the difference in the activation levels of competing neural or computational units. It is inherent to random-walk models and diffusion models, and thus also to the DMC model, where evidence in favor of the one alternative is also evidence against the other alternative. However, it is not inherent to accumulator models and counter models, where the evidence in favor of each alternative is sampled independently (cf. Smith & Ratcliff, 2004). Sometimes these types of model have been contrasted (e.g., Heath, 1984), though it is apparent that mutual inhibition could be graded (cf. Heuer, 1987; Usher & McClelland, 2001).

The third mechanism of conflict solution is absent in sequential-sampling models except for those that specifically address conflict tasks. The observation of declining delta functions has given rise to the notion that the influence of the irrelevant stimulus decays with the passage of time (Hommel, 1994) or is actively inhibited (Ridderinkhof, 2002; cf. Van den Wildenberg et al., 2010). This mechanism would serve to produce a majority of correct responses even when initially, immediately after stimulus presentation, activation of the error response by the irrelevant spatial stimulus feature would be stronger than activation of the correct response by the relevant stimulus feature. A declining influence of irrelevant stimuli, as implemented in models for the Eriksen flanker task (Hübner et al., 2010; White et al., 2011), however, seems insufficient to produce negative slopes

of delta functions. Thus far the only model that can produce delta functions with negative slopes is the DMC model of Ulrich et al. (2015). Its critical feature seems to be the function that governs the decline of the impact of the irrelevant stimulus feature across successive samples: This function crosses zero; that is, it reverses the instantaneous effect of the irrelevant stimulus on the accumulation of evidence (Ulrich et al., 2015; Fig. 4, lower graph).

Perceptual decision-making and motor responses

The analysis of human cognition is often based on a conceptual separation of perceptual and motor processes, prominently so in chronometric research. Examples are serial-stage models based on the additive-factors rationale (cf. Sanders, 1980; Sternberg, 1998) or attempts to isolate the respective durations of different stages by means of psychophysiological analyses (cf. Leuthold, 2011). The distinction is also inherent to sequential-sampling models of perceptual decisions that are generally conceived as models of the accumulation of information on the state of the world (cf. Bogacz et al., 2006), and such “recognition of the world” should be independent of the actions to be performed. Motor responses are essentially beyond the scope of the models, except that their duration can be included in the nondecision time, which takes into account all processes not related to the perceptual decision. Although there are neural signals that have characteristics of the evidence variable of sequential-sampling models and are independent of stimulus and response modalities (e.g., Kelly & O’Connell, 2013), there is a clear temporal overlap of the decision process with motor preparation, response activation, and even overt responses. This is particularly evident from findings with conflict tasks.

Dual-route models such as the DMC model of Ulrich et al. (2015) assume an initially strong influence of the irrelevant stimulus position in the Simon task that decays (or is actively inhibited) with the passage of time. An initially stronger activation of the incorrect response in the noncorresponding condition is indeed indicated by the observation of an initial “incorrect” lateralized readiness potential that is only later replaced by a “correct” one (e.g., De Jong, Liang, & Lauber, 1994; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Valle-Inclán & Redondo, 1998). This is a quite early indication of preparing a certain response while the decision is not yet finished. Subsequent to this early indication of motor preparation, there are electromyographic indicators of response activation while the decision is not yet finished. These are incorrect small EMG bursts that are

subsequently replaced by correct strong EMG bursts (cf. Servant, White, Montagnini, & Burle, 2015; Servant et al., 2016). Finally, ongoing decision processes can also be observed in the overt responses. When the responses have an initial common component, as in lifting a finger from a start position to hit a target located at the left or right side, a Simon effect has not only been observed in reaction times but also in movement times, even when participants were instructed to start a movement only after response selection has been finished (Rubichi, Nicoletti, Umiltà, & Zorzi, 2000). These differences in movement times between noncorresponding and corresponding conditions likely result from different initial directions of lifting the finger, which are biased toward the incorrect or correct side, respectively (Buetti & Kerzel, 2008, 2009). Both the observations on the durations and the initial directions of these motor responses strongly suggest that their specification is a process inherent to the decision.

If the perceptual decision is indeed tightly interwoven with the specification of the associated responses, its duration and accuracy should not only depend on sensory input, but also on the responses, in particular, on the relation between them. Moreover, effects of input characteristics and response characteristics should interact. A specific test of this hypothesis has been reported by Heuer (1987), motivated by an extension of an accumulator model proposed by Vickers (1979). In this extension, a mutual feed-forward (or bottom-up) inhibition was introduced in that in each sample stimulus-driven activation of the one response code was accompanied by a proportional stimulus-driven (feed-forward or bottom-up) inhibition of the alternative response code. In the experiment participants responded with the left or right hand. Responses were vertical up-and-down movements of the index finger or lateral to-and-fro movements, with same or different movements assigned to the two hands. With different movements assigned to the hands, reaction time was slower, its variability was larger, and accuracy was higher than with the same movements assigned to the hands (cf. Heuer, 1990, for review). Stimuli were horizontal lines of variable discriminability. In the model, stimulus discriminability was represented by the difference between the inputs to the two response codes, and the relation between responses was represented by stronger or weaker mutual inhibition. Consistent with expectations based on model predictions, reaction time decreased and accuracy increased with increasing stimulus discriminability—reaction time more so with different movements assigned to the two hands, accuracy more so with same movements. Conversely the effects of the relation between responses (slower reaction time and higher accuracy with different than with same movements) were reduced when stimulus discriminability increased. Only the findings on the individual standard deviations did not conform to expectations.

Stimulus-driven conflict and the relation between responses

The present experiments are a first step toward identifying interactive effects of the stimulus-driven conflict in the Simon task with the relation between responses. A comparatively well-studied relation between responses is the difference between simple key presses performed with two fingers of the same hand or of different hands. Both in terms of muscles and of neural structures involved, flexions of index and middle finger of the same hand are “anatomically closer” than flexions of two fingers of different hands. For example, flexions of the two fingers of the same hand involve different tendons of the same muscle (m. extensor digitorum), and representations of the fingers in primary motor cortex are adjacent, whereas responses with different fingers involve different muscles and are represented in the primary motor cortices of different hemispheres. Thus, selective activation of the one or the other finger might require stronger mutual inhibition when fingers of the same hand are involved than when fingers of different hands are involved.

When reaction times for choice between fingers (of the same hand) and hands are compared, choice between fingers generally takes more time than choice between hands (Adam, 2000; Alain, Taktak, & Buckolz, 1993; Heuer, 1986; Kornblum, 1965; Reeve & Proctor, 1988). Similarly, when one response is prepared, switching to another response with another finger of the same hand takes more time than switching to another response with the other hand (Rosenbaum & Kornblum, 1982). These findings are consistent with the notion of stronger mutual inhibition in choosing between fingers of the same hand. However, the finding of longer reaction times for within-hand than for between-hand choices is not without exception. In particular, in precueing experiments, when different fingers of the same hand or different hands had been cued, faster reaction times of within-hand responses have been observed as well (Miller, 1982, 1985).

To specify our general hypothesis of interactive effects of stimulus-driven conflict and the relation between responses, we made use of a sequential-sampling model. This was an extension of the leaky, competing accumulator (LCA) model of Usher and McClelland (2001). The main reason for choosing this model was its lateral-inhibition parameter. Although this kind of mutual inhibition is different from the feed-forward inhibition of Heuer’s (1987) simple model, it should nevertheless be suited to represent the relation between responses, in particular, the difference between within-hand (strong lateral inhibition) and between-hand (weak lateral inhibition) choices. Note that we use the lateral-inhibition parameter of the LCA model, which has previously been found to

contribute only little or nothing to the goodness of fit of the model (Leite & Ratcliff, 2010), in a way that presupposes a tight link between the perceptual decision and the specification of the associated response. Therefore, we denote the units that accumulate the sampled evidence not as accumulators, but as response codes, the activation of which corresponds to the accumulated evidence.

Our extension of the LCA model is concerned with the conflicting input and the decay of its influence with the passage of time. Such extensions have been proposed for the diffusion model by Hübner et al. (2010), White et al. (2011), and Ulrich et al. (2015). The first two of these extensions have also been combined with the LCA model by Servant et al. (2015) and applied to the Eriksen flanker task. However, they seem not to be suited for the standard Simon task because they cannot account for the decline of the Simon effect with increasing reaction times. To account for such effects, we have chosen an extension of the LCA that differs somewhat from Ulrich et al.’s (2015) extension of the diffusion model. As in the DMC model, the weight of the irrelevant input declines with the passage of time during each decision. Different from the DMC, however, the instantaneous influence of the irrelevant input during each sample is not reversed, but only nullified. Instead of the reversal, accumulation begins after a random delay during which the influence of the irrelevant input already declines. When this delay is short, reaction time is short, and the influence of the irrelevant information is strong. But when this delay is long, reaction time is long, and the influence of the irrelevant information is weak. As a consequence, the Simon effect can decline at long reaction times, so that this extension also allows modelling delta-functions with negative slopes. From a functional perspective, our extension implies that decay (or active inhibition) of the irrelevant stimulus feature starts rather immediately upon stimulus presentation, whereas accumulation only starts after some initial processing of the relevant stimulus feature.

Figure 1 illustrates our specific expectations for the impact of the relation between responses, same-hand and different-hand responses in particular, on the effects of stimulus-driven conflict on mean and variability of reaction times as well as error rates. These expectations are based on simulations of the extended LCA model. Details of the model are given in Appendix 1. Figure 1 shows the simulation results for a particular set of model parameters that were chosen somewhat haphazardly, though in a plausible-appearing range (cf. Appendix 2). Thus, with different parameter sets somewhat different predictions could be produced by the model. However, qualitatively the expectations based on the simulation results are largely the same as the expectations of Heuer (1987) that were based on a model that differed considerably in detail but shared the feature of mutual inhibition of the response codes. We also varied the

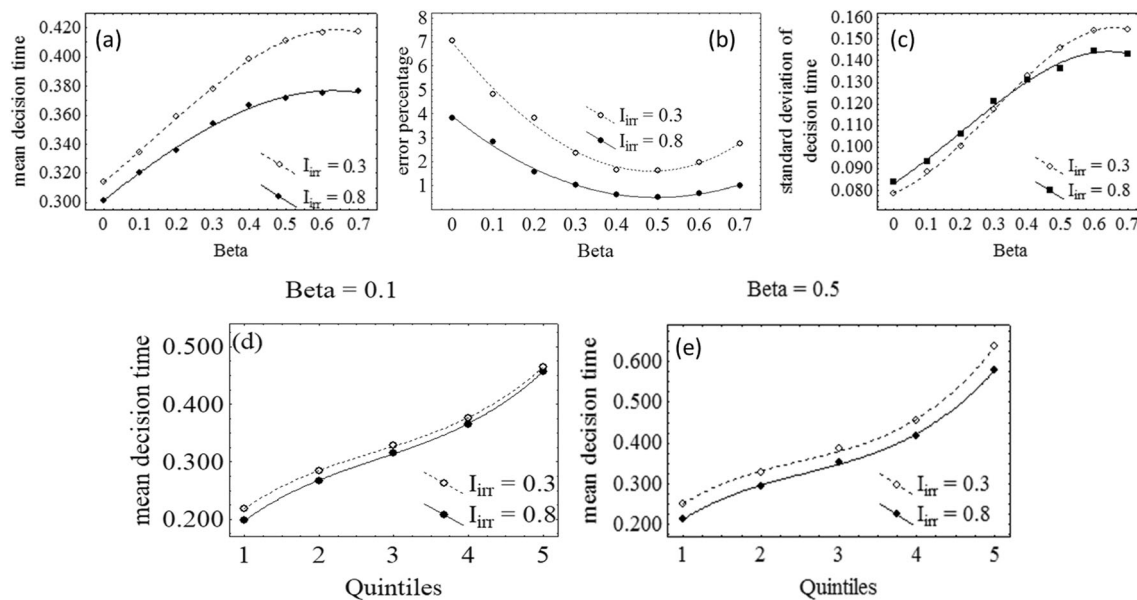


Fig. 1 Mean decision time (a), error percentage (b), and standard deviation (c) of 10,000 simulated trials per data point of the extended leaky, competing accumulator model. Details of the model are described in Appendix 1. The simulated data (parameters are listed in Appendix 3) are fitted by third-order polynomials. Continuous lines and filled circles represent corresponding conditions ($I_{irr} = 0.8$); broken lines

and open circles represent noncorresponding conditions ($I_{irr} = 0.3$). The lateral-inhibition parameter β is shown on the abscissa, with higher parameters representing smaller anatomical distance between responses. In (d) and (e), the means in the quintiles of the distributions of decision times are shown for two levels of β ; note the different scale on the abscissa to improve visibility of the convergence of curves in (d), but not in (e)

parameters of the model in a reasonable range and confirmed that the predictions illustrated in Fig. 1 hold for a large set of parameter combinations. The main results of this analysis are summarized in Appendix 2.

Figure 1a shows the mean decision time as a function of the lateral-inhibition parameter β for two levels of the irrelevant input: $I_{irr} = 0.8$ for corresponding conditions of the Simon task and $I_{irr} = 0.3$ for noncorresponding conditions. Similarly, Fig. 1b shows the error percentage, and Fig. 1c the standard deviation. With stronger lateral inhibition, decision time increases, error percentage declines, and variability increases. This triad of effects is characteristic, at least for certain relations between responses (Heuer, 1990). From Fig. 1 it is apparent that there should be boundary conditions for this pattern of results, such as a not too strong lateral inhibition.

The difference between the broken and continuous lines in Fig. 1 marks the Simon effect: the difference between noncorresponding and corresponding conditions. From Fig. 1a it is apparent that the Simon effect for mean reaction times should increase with stronger lateral inhibition, and according to Fig. 1b the Simon effect for error percentages should decline, except for very strong lateral inhibition. For the standard deviation (Fig. 1c), the expectations are slightly more complicated: With weak lateral inhibition, the standard deviation should be less in noncorresponding than in corresponding conditions. Figure 1d shows means of decision times in the quintiles of the distribution, and specifically the larger Simon effect for fast than for slow

responses that underlies the difference in variability. With increasing lateral inhibition, the decision times in successive quintiles do no longer converge (cf. Fig. 1e) and may even diverge. Correspondingly, the difference between noncorresponding and corresponding conditions in variability becomes smaller and finally is reversed—variability being larger in noncorresponding than in corresponding conditions.

The predictions of the model are based on variations of parameters, the irrelevant input that drives the correct or incorrect response (I_{irr}) and the strength of the lateral inhibition (β). Whereas the mapping of the irrelevant-input parameter on experimental conditions, noncorresponding and corresponding conditions, in particular, is quite obvious; the mapping of the lateral-inhibition parameter on different response sets is less obvious. However, as outlined above, there are good reasons to hypothesize that for a within-hand response set mutual inhibition of responses should be stronger than for a between-hands response set. In fact, the predictions for the impact of these two response sets on the Simon effect find partial support in previous studies (Buckolz et al., 1996; Cho & Proctor, 2010, Exp. 1), even though in both studies the difference in reaction time between the two response sets failed to reach statistical significance. Here, we compared the between-hands condition not only with a within-hand condition of the right hand, but implemented within-hand conditions for both hands. We also examined not only mean RT and error rate but also the intraindividual RT variability. In the

second experiment we tested whether mutual inhibition between response codes could also be varied by the spatial distance between response locations.

Experiment 1 (anatomical distance)

In Experiment 1 we investigated the impact of anatomical distance between two manual responses on the Simon effect. Participants performed a standard Simon task in two conditions. In the *between-hands* condition, they operated the left key with the index finger of their left hand and the right key with the index finger of their right hand. In the *within-hand* condition, participants operated the keys with two fingers of the same hand. One half of the participants operated the left and right key with the middle and index finger of their left hand, respectively, and the other half of the participants operated the left and right key with the index and middle finger of their right hand.

Method

Participants Forty volunteers (30 female, 10 male) with a mean age of 22 years (range 16–34 years) participated in Experiment 1. Participants gave informed consent before the experiment and received course credit for participation. All participants were naïve with respect to the purpose of the study and reported normal or corrected-to-normal visual acuity. The majority of participants ($N = 36$) were right-handers on self-report.

For Experiment 1, we determined the number of participants in accordance with Cohen (1988). He recommends a sample size of (at least) 34 participants for obtaining a medium-sized effect (e.g., $d = .50$, $\eta_p^2 = .06$), with a power of .80 in two-factorial experiments.

Apparatus and stimuli Participants sat in front of a 17-inch color monitor with an unconstrained viewing distance of approximately 50 cm. An IBM compatible computer controlled the presentation of stimuli and recorded the key-press responses. Visual stimuli appeared on a gray background (i.e., E-Prime color “silver”). The fixation point was a small plus sign (Courier font, font size 18). A red and a green square with a side length of 2 cm ($\sim 2.3^\circ$ of visual angle) served as imperative stimuli. The stimulus locations were 10 cm ($\sim 11.3^\circ$ of visual angle) to the left or right of the screen center. Participants responded by pressing the “comma” key or the “en-dash” key on a standard computer keyboard. The two keys are separated by one additional key.

Procedure At the beginning of the experiment, instructions were presented on the monitor describing the task, the

mapping of stimulus colors to response keys, and the sequence of events in a trial. Then participants performed three blocks of trials with the *between-hands* condition and three blocks with the *within-hand* condition; the order of conditions was counterbalanced across participants. In the *between-hands* condition, participants operated the left (comma) key with the index finger of their left hand and the right (en-dash) key with the index finger of their right hand. In the *within-hand* condition, half of the participants operated the left and right key with the middle and index fingers of their left hand and the other half with the index and middle fingers of their right hand. The first block of each condition served as practice (20 trials) and was not further analyzed. Each test block contained 60 trials in random order (2 stimulus colors \times 2 stimulus locations \times 15 repetitions). Participants could take a rest between blocks and start the next block at leisure. The experiment took about 15 minutes. The research assistant remained in the laboratory throughout the experiment and monitored the participant to ensure that he/she obeyed the correct finger-key assignment.

Each experimental trial started with a fixation point for 1,000 ms. Then the stimulus display was presented until a key press occurred or for a maximum duration of 2,000 ms. A correct response with an RT below 2,000 ms was followed by a blank screen for 1,000 ms. If a wrong key or if no key was pressed within the response period, a corresponding error message was shown for 1,000 ms in black color (Courier font, font size 24).

Design and data analysis The experiment had a 2×2 design. The first factor was Response Condition (*between-hands* vs. *within-hand*). The second factor was Spatial Stimulus–Response (S–R) Correspondence (*corresponding* vs. *noncorresponding*). Both factors were varied within participants.

Trials with RT below 100 ms or above 1,500 ms (less than 1% of trials) were discarded. Individual means and standard deviations of RTs of correct trials as well as individual error percentages (i.e., percentages of wrong key presses) were subjected to two-way ANOVAs with Response Condition and Spatial S–R Correspondence as within-participant factors. In addition we analyzed the means of the quintiles of the RT distributions by means of a three-way ANOVA with Quintile as an additional factor. Partial η^2 are given as effect-size estimates. For all effects involving the factor Quintiles we report the Greenhouse–Geisser-corrected p and the Greenhouse–Geisser ϵ .

Results and discussion

Table 1 shows the group means of the individual means and standard deviations of the reaction times of correct

Table 1 Group means (\pm standard errors) of the individual means and standard deviations of reaction times in correct trials and of the error percentages in corresponding and noncorresponding trials in the between-hands and within-hand conditions

	Between-hands		Within-hand	
	Corresponding	Noncorresponding	Corresponding	Noncorresponding
RT	407 \pm 7.2	433 \pm 7.5	414 \pm 9.2	459 \pm 10.2
Mean (ms)	<i>408</i>	<i>436</i>	<i>418</i>	<i>453</i>
RT	106 \pm 5.7	94 \pm 4.6	104 \pm 6.3	106 \pm 7.0
SD (ms)	<i>100</i>	<i>95</i>	<i>109</i>	<i>105</i>
Error Percentage	2.8 \pm 0.80	4.7 \pm 0.61	1.7 \pm 0.37	4.6 \pm 0.54
	<i>2.0</i>	<i>5.4</i>	<i>1.6</i>	<i>4.2</i>

The results of the model simulations are presented in italics below the observed data (details are given in the Appendix 3)

responses as well as the mean error percentages. It also shows the simulation results obtained with the extended LCA model, with parameters defined by its fit to the observed group means. Details of the fitting procedure as well as the parameter estimates are given in Appendix 3. The parameter estimates are somewhat fuzzy in that different estimates would be obtained with different fitting procedures. Even with one and the same fitting procedure the minimum of the deviation between simulated and observed data cannot be determined precisely (cf. Ulrich et al., 2015; White et al., 2017).

In general, the simulated means and standard deviations of reaction times as well as error percentages were rather close to the observed ones in spite of the simplified parametrization of the model (e.g., fixed response thresholds, no initial activations of both response codes). Although there were 11 free parameters in fitting the model, the differences between the four experimental conditions are captured by only two of them, the irrelevant input to the correct response code that was stronger in corresponding than in noncorresponding conditions (0.917 vs 0.346) and the lateral-inhibition parameter that was stronger in the within-hand than in the between-hands condition (0.239 vs. 0.159). These two pairs of parameter values not only account for the main effects of spatial S–R correspondence and response set, but also for their interactions.

Mean RT was longer in the within-hand than in the between-hands condition. It was also longer in noncorresponding trials than in corresponding trials, and this difference—the Simon effect—was larger in the within-hand condition (45 ms) than in the between-hands condition (26 ms). Both the main effects of Response Condition, $F(1, 39) = 11.49$, $MSE = 903.33$, $p = .002$, $\eta_p^2 = .228$, and Spatial S–R Correspondence, $F(1, 39) = 61.1$, $MSE = 815.27$, $p < .001$, $\eta_p^2 = .610$, were significant, and so was the interaction of the two factors, $F(1, 39) = 11.89$, $MSE = 293.20$, $p = .001$, $\eta_p^2 = .234$. This pattern of results corresponds to the expected pattern as illustrated in Fig. 1.

For the standard deviations of RT the mean results did also conform rather well to predictions. Overall RT variability was somewhat larger in the within-hand than in the between-hands condition. The difference between noncorresponding and corresponding trials was slightly positive (1.8 ms) in the within-hand condition, but negative (–11.8 ms) in the between-hands condition. The interaction of Response Condition and Spatial S–R Correspondence just failed to reach statistical significance, $F(1, 39) = 3.44$, $MSE = 538.05$, $p = .071$, $\eta_p^2 = .081$. However, a one-tailed t test of the specific prediction that the difference between noncorresponding and corresponding conditions is less (more negative) with between-hands responses than within-hand responses was significant, $t(39) = 1.85$, $p = .036$. Both the main effects of Response Condition, $F(1, 39) = 1.36$, $MSE = 631.18$, $p = .251$, $\eta_p^2 = .034$, and S–R Correspondence, $F(1, 39) = 1.53$, $MSE = 538.05$, $p = .223$, $\eta_p^2 = .081$, were not significant.

According to model predictions, the smaller variability in noncorresponding than in corresponding conditions with weak lateral inhibition (between-hands) should result from the convergence of mean RTs in successive quintiles of the RT distribution (cf. Fig. 1d), and the disappearance or reversal of this difference with stronger lateral inhibition (within-hand) should result from the decline, disappearance or even reversal of this convergence (cf. Fig. 1e). Figure 2 shows the corresponding plots of the observed quintile means, together with the simulated quintile means. For these simulations the parameters of the fitted model, as listed in Appendix 3, were used. There was a conspicuous similarity of the pattern of observed quintile means with the predictions (Fig. 1d–e), though for the simulations based on the model fit the difference between the two response sets was smaller (Fig. 2c–d); similarly the modulation of the difference between corresponding and noncorresponding trials in the standard deviations of reaction times was less than the observed modulation (cf. Table 1).

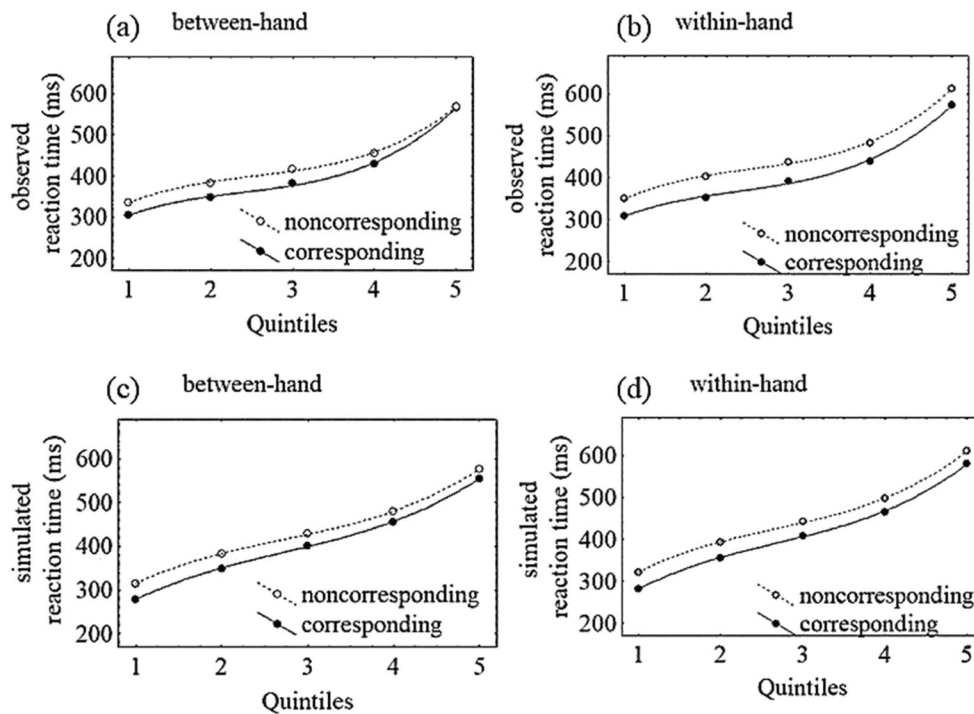


Fig. 2 Means of the quintiles of the observed reaction time distributions (a and b) and the simulated reaction time distributions (c and d) with fitted third-order polynomials

In spite of the difference between response sets, the three-way interaction of Response Condition, Spatial S–R Correspondence, and Quintile fell short of statistical significance, $F(4, 156) = 2.23, MSE = 1191.98, p = .132, \eta_p^2 = .054, \epsilon = 0.35$, while the interaction of Spatial S–R Correspondence and Quintile was significant, $F(4, 156) = 4.75, MSE = 2927.26, p = .025, \eta_p^2 = .108, \epsilon = 0.32$. Unfortunately these interaction tests suffer from strong violations of sphericity, as indicated by the quite low Greenhouse–Geisser ϵ . Therefore, we adopted an additional quite simple nonparametric test procedure. For each participant and each quintile we computed the Simon effect as the difference between noncorresponding and corresponding trials, and, as a “change score” or “quintile trend,” the difference of the mean Simon effects between the last two and the first two quintiles. A negative change score indicates a decline of the Simon effect at the longer reaction times, a positive change score an increase. The means were -16 ms in the *between-hands* condition and $+4$ ms in the *within-hand* condition, and the difference between these change scores was significant according to a two-tailed sign test ($z = 2.06, p = .040$).

Errors were more frequent in the between-hands condition than in the within-hand condition, and they were more frequent in noncorresponding trials than in corresponding trials. The effect of S–R Correspondence was slightly larger in the within-hand than in the between-hands condition. This difference is not consistent with model predictions and is not seen in the simulated error percentages. However, these variations appear random. In the ANOVA only the main effect of

Spatial S–R Correspondence reached statistical significance, $F(1, 39) = 15.99, MSE = 14.83, p < .001, \eta_p^2 = .291$, but neither did the main effect of Response Condition, $F(1, 39) = 2.45, MSE = 5.37, p = .125, \eta_p^2 = .059$, nor the interaction of these two factors, $F(1, 39) = 1.65, MSE = 6.65, p = .206, \eta_p^2 = .041$.

For the mean reaction times, the expected main and interaction effects of spatial S–R correspondence and anatomical distance of responses were fully confirmed in this experiment. For the individual standard deviations, the confirmation of expectations was slightly less convincing. Finally, for the error percentages, there were no reliable variations except for the Simon effect. Error percentages are generally rather noisy measures, so confirmation of the expected modulation of the Simon effect by the different response sets might be hard to obtain. Overall, the observed interactive effects of the stimulus-driven conflict in the Simon task and the relation between the alternative responses provide new evidence for the notion that perceptual discrimination and response specification are tightly interrelated. More specifically, the interrelation is likely of the kind captured by the extended LCA model in that sensory input rather directly activates response codes which are coupled by lateral inhibition.

Experiment 2 (spatial distance)

In Experiment 2 we investigated the impact of spatial distance between two manual responses on the Simon

effect. Participants responded with the left or right index finger to stimulus color in a standard Simon task with two response conditions. In the *small-distance* condition, the distance between the two response keys (or fingers) was 2 cm, and in the *large-distance* condition it was 35 cm. The question was whether the spatial distance between two responses would have a similar or different effect on performance as the anatomical distance.

Method

Participants Forty volunteers (30 female, 10 male) with a mean age of 22 years (range 18–34 years) participated in Experiment 2. Participants gave informed consent before the experiment and received course credit for participation. All participants were naive with respect to the purpose of the study and reported normal or corrected-to-normal visual acuity. The majority of participants ($N = 36$) were right-handers on self-report.

Apparatus, stimuli, procedure, and data analysis The apparatus, stimuli, procedure, and data analysis were the same as in Experiment 1 except for the two response conditions. In the small-distance condition, participants pressed the “comma” key for the left response and the “en-dash” key for the right response, and in the large-distance condition, they pressed the “control” key (on the left edge of the keyboard) for the left response and the “enter” key (on the right edge of the keyboard) for the right response.

Results and discussion

The group means of the individual means and standard deviations of the reaction times of correct responses as well as the mean error percentages in the four experimental conditions are shown in Table 2. Also shown are the simulation results obtained with the fitted extended LCA model. The simulated means and standard deviations of reaction times as well as error percentages were rather

close to the observed ones. The two parameters, which distinguished the four experimental conditions, were irrelevant inputs for the correct response code of 1.004 and 0.392 in the corresponding and noncorresponding conditions, respectively, and lateral-inhibition parameters of 0.197 and 0.167 in the small-distance and large-distance conditions, respectively. The difference between the lateral-inhibition parameters estimated for the two response conditions was considerably smaller than in the first experiment.

Mean reaction times were slightly faster in the large-distance condition than in the small-distance condition, and they were faster in corresponding than in noncorresponding trials. The difference between noncorresponding and corresponding trials, the Simon effect, was 21 ms in the small-distance condition and 24 ms in the large-distance condition. Only the main effect of Spatial S-R Correspondence, $F(1, 39) = 50.21$, $MSE = 399.02$, $p < .001$, $\eta_p^2 = .563$, was significant; the main effect of Response Condition, $F(1, 39) = 2.05$, $MSE = 1028.08$, $p = .161$, $\eta_p^2 = .050$, and the two-way interaction, $F(1, 39) = 0.38$, $MSE = 154.10$, $p = .544$, $\eta_p^2 = .010$, were not significant.

The standard deviations of reaction times were essentially the same in the small-distance condition and the large-distance condition. They were larger in corresponding than in noncorresponding trials, slightly more so with the small distance between response keys than with the large distance. In the ANOVA, only the main effect of Spatial S-R Correspondence was significant, $F(1, 39) = 11.59$, $MSE = 658.94$, $p = .002$, $\eta_p^2 = .229$; the main effect of Response Condition, $F(1, 39) = 0.13$, $MSE = 551.80$, $p = .725$, $\eta_p^2 = .003$, and the two-way interaction, $F(1, 39) = 2.51$, $MSE = 445.60$, $p = .121$, $\eta_p^2 = .060$, were not significant.

Figure 3 shows the observed quintile means as well as the simulated ones. Consistent with the smaller variability in the noncorresponding than in the corresponding condition, the observed as well as the simulated means converged across quintiles in both response conditions. The

Table 2 Group means (\pm standard errors) of the individual means and standard deviations of reaction times in correct trials and of the error percentages in corresponding and noncorresponding trials in the large-distance and small-distance conditions

	Large distance		Small distance	
	Corresponding	Noncorresponding	Corresponding	Noncorresponding
RT	424 \pm 11.4	448 \pm 11.5	433 \pm 11.9	454 \pm 10.1
Mean (ms)	<i>426</i>	<i>449</i>	<i>430</i>	<i>454</i>
RT	105 \pm 7.4	97 \pm 6.9	112 \pm 7.3	93 \pm 5.3
SD (ms)	<i>104</i>	<i>97</i>	<i>106</i>	<i>101</i>
Error Percentage	1.8 \pm 0.34	3.4 \pm 0.53	1.5 \pm 0.30	3.5 \pm 0.63
	<i>1.7</i>	<i>3.6</i>	<i>1.5</i>	<i>3.3</i>

The results of the model simulations are presented in italics below the observed data (details are given in the Appendix 3)

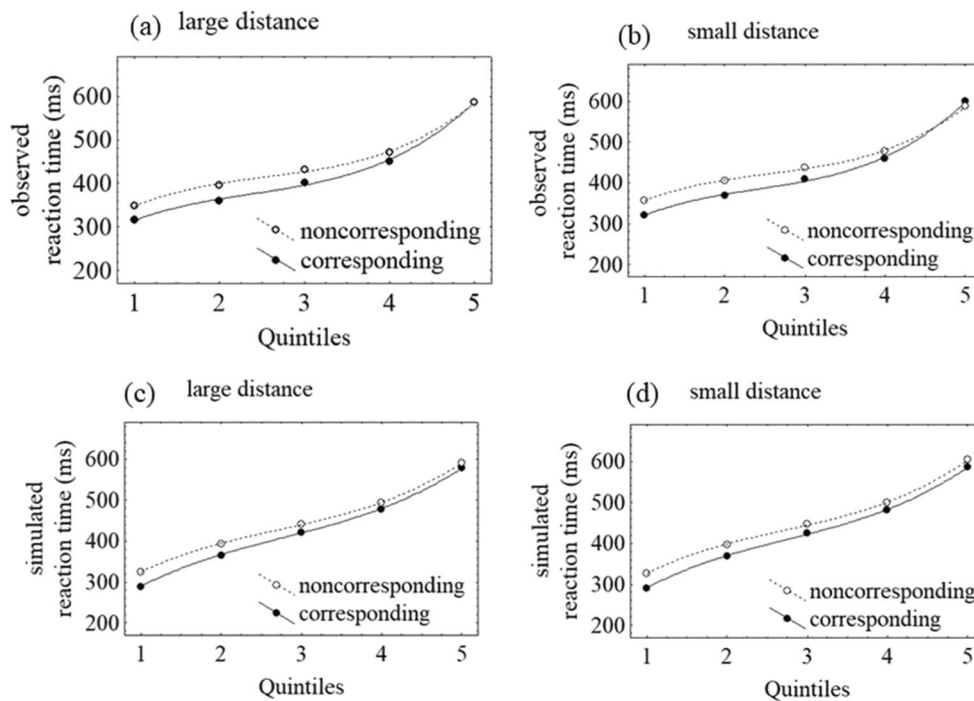


Fig. 3 Means of the quintiles of the observed reaction time distributions (a and b) and the simulated reaction time distributions (c and d) with fitted third-order polynomials

interaction of Spatial S–R Correspondence and Quintile was significant, $F(4, 156) = 16.24$, $MSE = 763.77$, $p < .001$, $\eta_p^2 = .294$, $\epsilon = 0.39$. In addition, there was only the trivial main effect of quintile and the main effect of S–R Correspondence, that is, the Simon effect.

Error percentages were almost identical in the two response conditions, with more errors in noncorresponding than in corresponding trials. Only the main effect of Spatial S–R Correspondence was significant, $F(1, 39) = 14.79$, $MSE = 8.68$, $p < .001$, $\eta_p^2 = .275$; the main effect of Response Condition, $F(1, 39) = 0.18$, $MSE = 3.40$, $p = .672$, $\eta_p^2 = .005$, and the two-way interaction, $F(1, 39) = 0.367$, $MSE = 6.84$, $p = .548$, $\eta_p^2 = .009$, were not significant.

Experiment 2 revealed no reliable difference between conditions with small and large distances between response keys. In both response conditions there was a Simon effect of essentially the same size, with the typical decline at the longer reaction times and thus smaller reaction-time variability in the noncorresponding than in the corresponding condition. These findings obviously provide no support for the general hypothesis that perceptual decisions and response specifications are tightly interwoven, but they are also not at variance with it. They only indicate that the relation between response codes, in particular their mutual lateral inhibition, is not different between the two response sets. This is so even though the model fitting revealed a small difference of the respective parameter. Probably the small difference in this parameter, which was the only parameter that could differ between the

two response conditions, served to reproduce the slightly (and statistically not significantly) longer reaction times with the small distance between response keys.

General discussion

Faced with a multitude of options, humans have to decide which action to take at each particular moment. Even when only specific properties of the environment are relevant for the decision, other properties may interfere with the selection of the correct response. The Simon task is one of the major paradigms for the study of such stimulus-driven response conflicts (cf. Hommel, 2011). Here, we ask how this type of conflict is modulated by the set of alternative responses, specifically, by the relation between them. This question is motivated by the general hypothesis that accumulation of evidence on the state of the world is intimately linked with the specification of the appropriate actions.

For the theoretical analysis of the expected modulation of the Simon effect by the relation between responses, we extended the leaky, competing accumulator (LCA) model of Usher and McClelland (2001) to account for the effects of conflicting stimuli. We chose this model because of its lateral-inhibition parameter that allows for a variable inhibition between accumulators. Based on the findings of Heuer (1987), we took this parameter to represent different relations between responses. Mapping the mutual-

inhibition parameter of the model onto the relation between the physical responses in a choice task has an implication for the interpretation of the “accumulators” of the model: They take the role of representations of the respective motor responses, that is, of response codes that can be activated.

Simulations of the model with a priori chosen parameter values (in some reasonable range) served to specify the expected interactive effects of the stimulus-driven conflict in a Simon task and the relation between responses in detail. With stronger lateral inhibition between response codes, the disadvantage of the noncorresponding condition as compared with the corresponding one in terms of mean RT, the Simon effect, is expected to increase. In contrast, the disadvantage in terms of error percentages is expected to decline (except for very strong lateral inhibition). Finally, the smaller RT variability in the noncorresponding condition as compared with the corresponding one is expected to gradually turn into a larger variability.

The model-based predictions for the different interactive effects in different dependent variables result from the variation of a single lateral-inhibition parameter of the extended LCA model. However, the step from the variation of this parameter to a variation of the response set is nontrivial in that different response sets may differ with respect to mutual inhibition between response codes, but they may also be equivalent in this respect. Here, we studied two pairs of different response sets, one with plausible a-priori reasons for different mutual inhibition of response codes—these were within-hand and between-hands response alternatives—the other one without such plausible a-priori reasons—these were different distances between response keys. Only for the within-hand versus between-hands response sets we observed a reasonable agreement of the observed interactions with the predicted ones, whereas the distance between response keys had no reliable effects. The interactive effects of stimulus-driven conflict and the relation between responses support the claim that perceptual decisions comprise the specification of the appropriate responses as an integral component. This claim is not only supported by the finding that perceptual decisions are affected by the relation between responses, but recently it has also been shown that they are affected by an asymmetry of motor costs (Hagura et al., 2017; Marcos, Cos, Girard, & Verschure, 2015).

In the extended LCA model, the specification of the appropriate response and the mutual inhibitory influence between concurrent processes of response specification is represented in a fairly simple manner, namely, as activation of responses codes and their mutual inhibition. According to experimental analyses, at least two types of response specifications, a discrete and a continuous type, should be distinguished (cf. Ghez et al., 1997). A decision

between effectors, as in the present experiment, is of the discrete type: There are two distinct alternatives without intermediate ones. In this case the probability of correct choices increases with the passage of time, corresponding to one of the core predictions of probably all sequential-sampling models. In contrast, a decision between movement directions of a single effector can be a continuous process, provided the difference between directions is not too large. There are not only two distinct alternative initial movement directions, but intermediate directions as well, so that the initial directions of the movements drift gradually from a default direction toward the correct one (Ghez et al., 1997; Heuer & Klein, 2006). With conflicting stimuli as in the Simon task, the initial movement direction has been shown to be biased toward the incorrect direction in noncorresponding trials as compared with corresponding ones (Buetti & Kerzel, 2008, 2009).

The present experiments are a first step toward understanding the modulating influences of the response set on the behavioral impact of stimulus-driven conflict. In a Simon task, we found a modulating influence of the anatomical distance between responses, but not of the spatial distance. Based on our theoretical considerations, these findings suggest a stronger mutual inhibition only for within-hand response codes than for between-hands response codes. However, it is quite unlikely that differences in mutual inhibition between response codes are specific to the difference between within-hand and between-hands response sets. For example, a stronger lateral inhibition between response codes might also be beneficial when the alternative responses are antagonistic such as movements to the left and right with the same hand as compared with movements with different hands (cf. Berlyne, 1957) or when the alternative responses are movements of the left or right hand that are subject to strong intermanual interactions so that they cannot be performed concurrently (cf. Heuer, 1990).

It is also unlikely that the modulation of stimulus-driven conflict by the response set is restricted to the Simon effect, but it might also exist with the Stroop effect or the flanker effect. In sequential-sampling models stimulus-driven conflict is modelled as additional input to response codes that affects the difference between the evidence in favor of the correct or incorrect response. We tentatively suggest that performance variations that result from such differences, and this also includes performance variations due to different levels of stimulus discriminability (cf. Heuer, 1987), will be amplified by response sets with stronger lateral inhibition. The generalization of the present findings to other types of stimulus-driven conflict and other sets of alternative responses would bolster the general hypothesis that decisions about the state of the world are inseparable from decisions about what to do in the world.

Acknowledgments The authors thank Marina Annaker for collecting the data reported in this manuscript.

Appendix 1

We used the leaky, competing accumulator model of Usher and McClelland (2001) for predictions and for fitting the present data. Some additions were made to capture important qualitative characteristics of the Simon effect. The core of the model was the difference equation that governs the increase of the activation of the two decision units (or accumulators), which in our perspective are the response codes. For the activations of the correct and error response codes the difference equations were:

$$\Delta a_c(i) = \begin{cases} 0 & \text{for } t \leq S \\ [I_c(i) - \lambda a_c(i) - \beta a_e(i)](\Delta t/\tau) + \xi(i)\sqrt{\Delta t/\tau} & \text{for } t > S \end{cases}$$

$$\Delta a_e(i) = \begin{cases} 0 & \text{for } t \leq S \\ [I_e(i) - \lambda a_e(i) - \beta a_c(i)](\Delta t/\tau) + \xi(i)\sqrt{\Delta t/\tau} & \text{for } t > S, \end{cases}$$

with inputs $I_c(i) + I_e(i) = 1$, self-inhibition gain λ , lateral-inhibition gain β , and Gaussian noise ξ with mean of zero and standard deviation σ_n . S was a uniformly distributed delay of the start of the accumulation ranging from zero to S_{\max} . In the simulations, we first added the input $I(i)$ and the noise $\xi(i)$ in each cycle i . After preliminary updating of the activation of the response codes, the leaks and the lateral inhibitions were applied. Activation of each response code was nonnegative:

$$a_c(i) = \max[0, a_c(i-1) + \Delta a_c(i)]$$

$$a_e(i) = \max[0, a_e(i-1) + \Delta a_e(i)].$$

The decision process ended whenever one of the activations reached the threshold θ . For data fitting, a constant nondecision duration T was added to the duration of the decision. The input to the correct-response code, $I_c(i)$, was defined as a weighted average of the relevant input I_{rel} and irrelevant input I_{irr} , with the weight of the irrelevant input, $g(i)$, declining with the passage of time:

$$I_c(i) = [I_{\text{rel}} + g(i)I_{\text{irr}}]/[1 + g(i)]$$

with

$$g(i) = g(i-1) - (1/\delta) \times g(i-1) \times (\Delta t/\tau),$$

δ as time constant of the exponential decay.

Appendix 2

To illustrate the joint effects of mutual inhibition and irrelevant response activation in Fig. 1, we used 10,000 simulated trials for each condition with the

following model parameters that were constant across conditions: $I_{\text{rel}} = 0.65$, $\delta = 0.07$, $\lambda = 0.3$, $\sigma_n = 0.2$, $\Delta t/\tau = 0.1$, $\theta = 1$, $S_{\max} = 0.2$, $T = 0$. The following parameters were varied across conditions: $I_{\text{irr}} = \{0.8, 0.3\}$; $\beta = \{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7\}$. The time unit was chosen as $\tau = 0.1$ s; however, the parameters with time as unit, δ and S_{\max} , are given in seconds. The initial weight $g(0)$ was set to 1, and the initial values of the accumulators $a_c(0)$ and $a_e(0)$ were set to 0.

In order to explore the generality of the results shown in Fig. 1 across a reasonable range of parameters, we simulated 10,000 trials for each of 46,656 parameter combinations. These were organized into 972 sets with 48 combinations each of $I_{\text{irr}} = \{0.9, 0.75, 0.6, 0.4, 0.25, 0.1\}$ and $\beta = \{0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7\}$. The 972 sets were generated with all combinations of the following parameters: $\theta = \{0.8, 1.0, 1.2\}$, $S_{\max} = \{0, 0.1, 0.2, 0.3\}$, $\sigma_n = \{0.13, 0.20, 0.27\}$, $\lambda = \{0.2, 0.3, 0.4\}$, $\delta = \{0.03, 0.07, 0.15\}$, $I_{\text{rel}} = \{0.55, 0.65, 0.75\}$. A set was excluded from further analysis when it contained unrealistic results, specifically, when decision times were longer than 2 seconds (the maximum number of cycles per simulated trial was 200) in more than 10% of the simulated trials, or when incorrect responses occurred in more than 35% of the simulated trials, leaving 676 data sets for further analysis.

The first type of predictions illustrated in Fig. 1 concerns the main effects of increased lateral inhibition: the increase of decision time and its variability and the decline of the error percentage. At high levels of lateral inhibition these increases or the decline can level off or reverse. For each of the six values of I_{irr} for each of the 676 data sets, we determined the peak decision time and the peak variability as well as the minimal error rate as a function of lateral inhibition β . Peak decision times and standard deviations had to be more than 0.003 s larger than the corresponding values for $\beta = 0$, and the minimal error percentages had to be smaller by 0.3% than the error percentage at $\beta = 0$ to be included in the further analyses. These criteria served to reduce the frequency of identifications of maxima or minima in essentially flat curves where the variation across increasing β was mainly due to the noise of the individual data points.

In Fig. 4a–c, the distributions of the values of β are shown at which peak decision times and peak standard deviations as well as minimal error percentages were observed. Peaks or minima occurred always at $\beta > 0.1$, that is, the predicted increase or decline was consistently present. For decision time and its variability the peak was most frequently at the strongest lateral inhibition included in the analysis ($\beta = 0.7$), whereas for the error percentages the minimum was at weaker lateral inhibitions (as was also

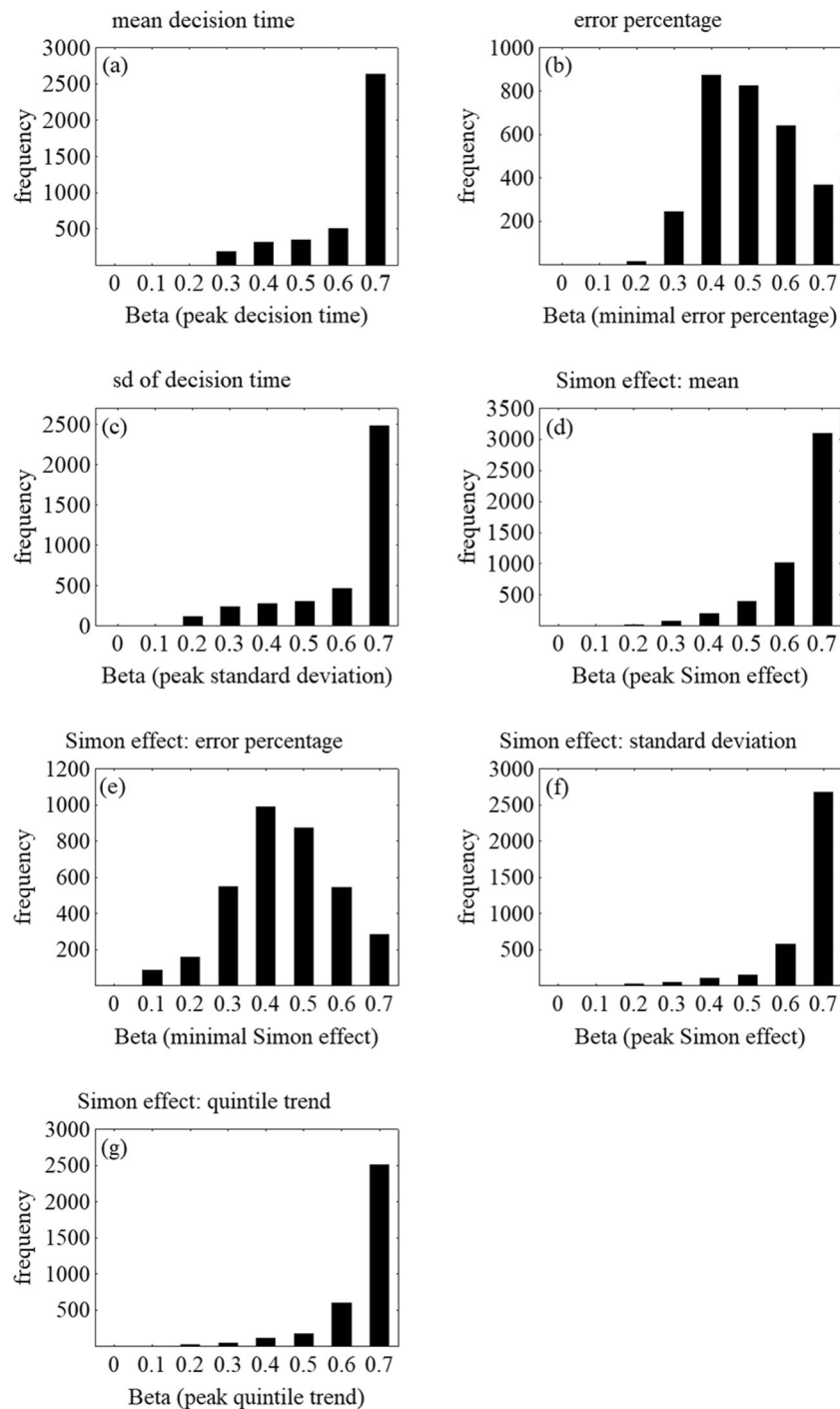


Fig. 4 Distributions of lateral-inhibition parameters β at which peaks or minima were reached for (a) mean decision time (peak), (b) error percentage (minimum), (c) standard deviation of decision time (peak), (d) Simon effect for mean decision time (peak), (e) Simon effect for error

percentage (minimum), (f) Simon effect for standard deviation of decision time (peak), (g) relative increase of Simon effect across quintiles of the decision-time distributions. Distributions were computed across large sets of parameter combinations as explained in the text

the case in the example of Fig. 1). In a few instances the subsequent increase resulted in a higher error percentage at $\beta = 0.7$ than at $\beta = 0$, as revealed by a complementary analysis in which peaks were identified for error percentages and minima for decision times and their variability. The latter were essentially always located at $\beta = 0$.

The second type of predictions illustrated in Fig. 1 concerns the variations of the Simon effects, that is, the differences between noncorresponding and corresponding conditions, for decision time, its variability, and the error percentage. For each data set there were nine combinations of three noncorresponding conditions with

$I_{irr} = \{0.40, 0.25, 0.10\}$ and three corresponding conditions with $I_{irr} = \{0.60, 0.75, 0.90\}$. For each of these combinations we computed the Simon effects as a function of lateral inhibition. In addition we computed an estimate of increasing or decreasing slopes of delta plots, which we call the “quintile trend”: The Simon effect was computed for each quintile, and the mean of the Simon effects in the first two quintiles was subtracted from the mean of the Simon effects in the last two quintiles. Positive quintile trends (or change scores) indicate a positive slope of the delta plots, and negative quintile trends a negative slope. The Simon effects as well as the quintile trends as a function of lateral inhibition were analyzed in the same way as the mean decision times, standard deviations, and error percentages, except that larger values were chosen for the required differences between peak values or minimal values and values at $\beta = 0$, respectively (0.006 s for the Simon effects in decision time and its variability, 0.6% for the Simon effect in error percentage, and 0.01 s for the quintile trend).

Peak Simon effects for decision time and its variability were mostly found at the strongest lateral inhibition analyzed, as shown in Fig. 4d and f, whereas the minimal Simon effect for error rates was found at weaker lateral inhibitions. The subsequent increase was sometimes that strong that at $\beta = 0.7$ the Simon effect for error rates was larger than at $\beta = 0$, as revealed by the complementary analysis of the location of peaks rather than minima. The peak quintile trend, that is, the strongest increase of the Simon effect across quintiles was mostly at the strongest lateral inhibition. Minima of Simon effects for decision time, its variability, and the quintile trend as a function of lateral inhibition were only rare at $\beta > 0$, and these exceptions are likely chance results with parameter combinations that produced only small effects of lateral inhibition.

According to the above analyses, the predictions illustrated in Fig 1 hold for a reasonable range of parameter values. Nevertheless, there are parameter combinations where the effects of lateral inhibition are only small and masked by the noise of our estimates based on 10,000 simulated trials each. We are not aware of a parameter combination for which an increase of the strength of lateral inhibition would produce effects opposite to the ones described here. Among the several thousand functions of lateral inhibition analyzed, there was only a small minority for mean and standard deviation of decision time and the respective Simon effects as well as for the quintile trend with the smallest value not at $\beta = 0$, and for the error percentage and the respective Simon effect there were some more cases with a peak at $\beta = 0.7$ subsequent to a minimum at some intermediate level of β .

Appendix 3

The observed mean data of both experiments were fitted to the model by an approximate minimization of the following root mean squared deviation:

$$RMSD = 1000 \cdot \sqrt{\frac{1}{12} \sum_{i=1}^4 (p_{obs} - p_{pre})^2 + (m_{obs} - m_{pre})^2 + (s_{obs} - s_{pre})^2},$$

where p is error probability, m is mean RT (in seconds), and s is the RT standard deviation (in seconds), with all observed variables averaged across participants. Squared deviations were summed across the four experimental conditions. The summation across squared deviations with different units has the consequence that a squared deviation of 1 ms for a mean or a standard deviation has the same weight as a squared deviation of 0.1% for an error percentage. Multiplication with 1,000 improves readability and implies a unit of ms/0.1% for the root mean squared deviation computed. The minimization was approximate because the costs could be estimated only with random errors for each set of parameters. After an initial search in parameter space the number of simulated trials for each experimental condition was increased up to 100,000, using the MATLAB function `fminsearch` in repeated runs with 100 iterations each. Subsequently the found parameters were used for a cross-validation run. The final RMSD (from the cross-validation run) and the final parameter values are listed in Table 3. The other parameters were fixed as for the illustrative simulations for Fig. 1. Although there were 11 free parameters in total, the differences between the four conditions were accounted for by only two parameters, one parameter that accounted for the difference between noncorresponding and corresponding conditions and one parameter that accounted for the difference between response sets. These two “main-effect” parameters accounted also for interactions.

Table 3 Results of parameter estimations for the two experiments

Parameter	Experiment 1	Experiment 2
RMSD	4.6	3.1
I_{rel}	0.657	0.667
I_{irr} (corresponding)	0.917	1.004
I_{irr} (noncorresponding)	0.346	0.392
δ	0.086	0.074
λ	0.322	0.325
β (between-hand/large)	0.159	0.167
β (within-hand/small)	0.239	0.197
σ_n	0.210	0.214
θ	0.944	0.944
S_{max}	0.205	0.222
T	0.100	0.114

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