COGNITIVE SCIENCE
A Multidisciplinary Journal

The Simon Effect in Action: Planning and/or On-Line Control Effects?

Claudia Scorolli,[a] Antonello Pellicano,[b] Roberto Nicoletti,[c]
Sandro Rubichi,[d] Umberto Castiello[e,f]

[a]Department of Psychology, University of Bologna
[b]Section for Clinical-Cognitive Sciences, Department of Neurology Medical Faculty,
RWTH Aachen University
[c]Department of Communications Disciplines, University of Bologna
[d]Department of Communication and Economics, University of Modena and Reggio-Emilia
[e]Department of General Psychology, University of Padova
[f]Center for Cognitive Neuroscience, University of Padova

Abstract

Choice reaction tasks are performed faster when stimulus location corresponds to response location (Simon effect). This spatial stimulus–response compatibility effect affects performance at the level of action planning and execution. However, when response selection is completed before movement initiation, the Simon effect arises only at the planning level. The aim of this study was to ascertain whether when a precocious response selection is requested, the Simon effect can be detected on the kinematics characterizing the online control phase of a non-ballistic movement. Participants were presented with red or green colored squares, which could appear on the right, left, above, or below a central cross. Depending on the square's color, participants had to release one of two buttons (right/left), then reach toward and press a corresponding lateral pad. We found evidence of the Simon effect on both action planning and on-line control. Moreover, the investigation of response conflict at the level of previous trials (i.e., $n-1$), a factor that might determine interference at the level of the current response, revealed a conflict adaptation process across trials. Results are discussed in terms of current theories concerned with the Simon effect and the distinction between action planning and control.

Keywords: Simon effect; Spatial compatibility; Action planning; Motor control; Kinematic parameterization; Conflict adaptation

Correspondence should be sent to Claudia Scorolli, Department of Psychology, University of Bologna, Viale Berti Pichat, 5, 40100 Bologna, Italy. E-mail: claudia.scorolli@unibo.it

1. Introduction

Human performance is more efficient with spatially corresponding stimulus–response (S-R) associations than with spatially non-corresponding S-R associations. This occurs even when stimulus location is not relevant to perform the task and the response has to be selected on the bases of a non-spatial stimulus feature (e.g., color or shape). For instance, if participants are requested to press a left key in response to a red square and a right key in response to a green square, responses are faster if stimulus and response positions correspond compared to when they do not correspond. The influence of the irrelevant spatial stimulus feature on performance determines an interference effect termed the Simon effect (for reviews see Hommel, 2011; Proctor, 2011; Proctor & Vu, 2006; Rubichi, Vu, Nicoletti, & Proctor, 2006; Simon & Rudell, 1967).

There is a wide agreement on considering the Simon effect a response selection phenomenon due to the interaction between two parallel and independent processing routes connecting perception to action (e.g., De Jong, Liang, & Lauber, 1994; Kornblum, 1994): an indirect route, called "conditional," and a direct route, called "unconditional." When a stimulus appears, the conditional route activates the required response on the basis of task-defined associations which connect a stimulus to a specific response. These associations are established by instructions and are supposed to be short-lasting. The unconditional route activates the response that spatially corresponds to the stimulus location through pre-existing stimulus–response associations, which are independent from instructions. These associations are supposed to be either genetically determined or overlearned as a result of extensive practice (e.g., Iani, Milanese, & Rubichi, 2014; Iani, Rubichi, Ferraro, Nicoletti, & Gallese, 2013; Pellicano, Iani, Borghi, Rubichi, & Nicoletti, 2010). When the two activated responses correspond, there is no response selection conflict. Rather, the redundancy of the same response code could generate a facilitation effect (Umiltà, Rubichi, & Nicoletti, 1999). In contrast, when the two activated responses do not correspond, the incorrect response needs to be halted, thus causing a slowing of response time and an increased number of errors.

Previous studies have tested the prediction that the Simon effect is a response selection phenomenon (Rubichi, Nicoletti, Umiltà, & Zorzi, 2000; Rubichi & Pellicano, 2004). More specifically, when the lateralized stimulus was presented, participants were requested to respond with one hand by releasing a central button and pressing a close lateralized button (ballistic movement, Gan & Hoffmann, 1988) depending on stimulus color. The authors recorded both reaction times (RTs; i.e., the release of the central button) and the time from the release of the starting switch and the time at which the lateralized response button was reached (i.e., movement times, MTs). Rubichi et al. (2000) reasoned that this response could be achieved by adopting two alternative strategies. One strategy might be implemented at the time the movement is initiated, when the whole response is selected. Another strategy would imply to release the central button and then select the appropriate lateralized button. In other words, response selection processes might be completed before, in the former case, or after, in the latter case, the release of

the central button. According to the notion that the Simon effect is a response selection phenomenon, the authors found evidence of it in RTs, but not in MTs, when the response was selected before the release of the central button; and in MTs, but not in RTs, when the response was selected following the release of the central button. In a follow-up study (Rubichi & Pellicano, 2004), participants were requested to respond by using one of the two hands (right movement with the right hand and left movement with the left hand) to press a close button. This manipulation guaranteed that response selection processes clearly operated before movement initiation. In these circumstances, the Simon effect was found only at RTs level.

There is some evidence, however, that the effects of response conflict generated at the response selection stage spread at the level of movement execution. In this respect, Buetti and Kerzel (2009) studied RTs, MTs, and movement spatial trajectories during a pointing response. Specifically, they focused on the initial movement angle (IMA, the angle after one-fifth of the movement trajectory had been traversed) to investigate the possible trajectory shift toward the stimulus. The task required participants to perform left- or rightward pointing movements of the right hand to one of two boxes displayed on a flat panel screen. They found that the trajectories veered toward the target. Interestingly, these deviations decreased along with an increase of the RTs as measured at movement initiation. These authors suggested that the time course of trajectory deviations reflected the resolution of the response conflict over time. Assuming that the selection of an abstract response (e.g., right vs. left) and the programming of an overt response (e.g., force, direction, amplitude) are functionally different—though they can overlap in time—Buetti and Kerzel (2009) advanced the possibility that two independent dissociable Simon effects might exist: one associated with response selection and the other associated with response programming.

In a similar vein, Scherbaum, Dshemuchadse, Fischer, and Goschke (2010) investigated the resolution of response conflict over time. In their study, participants performed a continuous version of a spatial conflict task: After clicking the mouse button, two response boxes appeared at the upper edge of the screen and they had to move the cursor upward, to start the trial. Once they reached a movement threshold, a white arrow (imperative stimulus) appeared on the left or on the right side of the screen, pointing left- or rightward. Participants had to move the mouse cursor to the left or the right response box according to the arrow direction, while ignoring its location. Analyzing both RTs and the trajectories of mouse movements, the authors found that in a given trial the direction of the response in the previous trial influenced the early part of the mouse trajectory, whereas the degree of previous and current conflict between direction and location of arrows influenced the later parts of the mouse trajectory.

Similarly, the present study aimed at providing a detailed investigation on how conflicts between different action tendencies are resolved but, differently from Scherbaum et al. (2010), it was our intention to maximize the separation between the action selection and its online control, with the aim to highlight the conflict resolution processes generated at the *response selection* level, and to scrutinize the way the effects produced by these processes eventually spread into movement execution. In fact, in Scherbaum et al. (2010), the response selection process was forced to occur while participants were already

moving the mouse cursor so that the effects of both response selection and action control were to be observed within the movement execution, thus potentially allowing for confounds. As opposite to them, we adopted a Simon task in which response selection processes clearly operate before movement initiation (e.g., Rubichi & Pellicano, 2004), thus favoring optimal distinction between the effects of selection and online control, as well as the observation of a neat time course of their eventual partial overlap. Furthermore, in contrast to previous research, we asked participants to perform a non-ballistic movement, that is, a movement in which corrective feedback of exteroceptive origin is allowed (for a definition of *ballistic* movement, see Craik, 1947; Glencross, 1977; Lin & Drury, 2011; Water & Strick, 1981). The choice of a non-ballistic movement was motivated by the need to investigate both the planning and the on-line control phases of the movement. Specifically this was achieved by analyzing kinematic markers, such as peak velocity and peak trajectory, occurring at the time the initial ballistic phase is ended (see Glover, 2004). Differently from Buetti and Kerzel (2009), who focused their analysis on a single kinematic landmark (i.e., IMA), we considered a complex pattern of spatial and temporal kinematic parameters related to movement response.

It is well-known that the conflict at the basis of the Simon effect, as indexed by its magnitude, is influenced by two main factors. The first is response velocity: Time course analysis of the Simon effect, obtained with horizontal stimulus and response displacements, clearly indicates that its magnitude decreases over time and tends to invert for the slower responses (e.g., De Jong et al., 1994). The second factor, which modulates the magnitude of the Simon effect in a given trial, is the nature of the response conflict in the preceding trial. That is, following a non-corresponding trial, the Simon effect has been shown to reduce (e.g., Praamstra, Kleine, & Schnitzler, 1999), disappear (e.g., Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002), or even reverse (e.g., Wendt, Kluwe, & Peters, 2006), whereas a regular effect is evident after a corresponding trial (see also Hommel, 1996). These phenomena are referred to as sequential effects (see also Iani, Rubichi, Gherri, & Nicoletti, 2009). (As to the specific cultural-religious practices also affecting the size of the Simon effect see Hommel, Colzato, Scorolli, Borghi, & van den Wildenberg, 2011). According to these considerations, in this study, we explored whether and to what extent the magnitude of the Simon effect for the planning and the on-line control phases of the movement (see later) depends on the time course of RTs, and the S-R correspondence in trial $n-1$. This allowed us to perform a continuous movement analysis as to evaluate the role of conflict adaptation for different movement phases (Egner, 2007).

In each trial, the participant waited for stimulus presentation with the index fingers of the two hands pressing two central pads (see Fig. 1). Following stimulus presentation, she had to release one of two central pads (depending on stimulus color) and reach one lateral pad that was located further to the right for the right movement (with the right hand) and further to the left for the left movement (with the left hand). The effector selection implied by this bimanual choice reaction task allowed us to be confident that the response selection process ended before the movement began (Rubichi & Pellicano, 2004). We considered RTs and error rates together with *early* kinematic events such as the time and the amplitude of peak acceleration. Indeed, as action planning generally
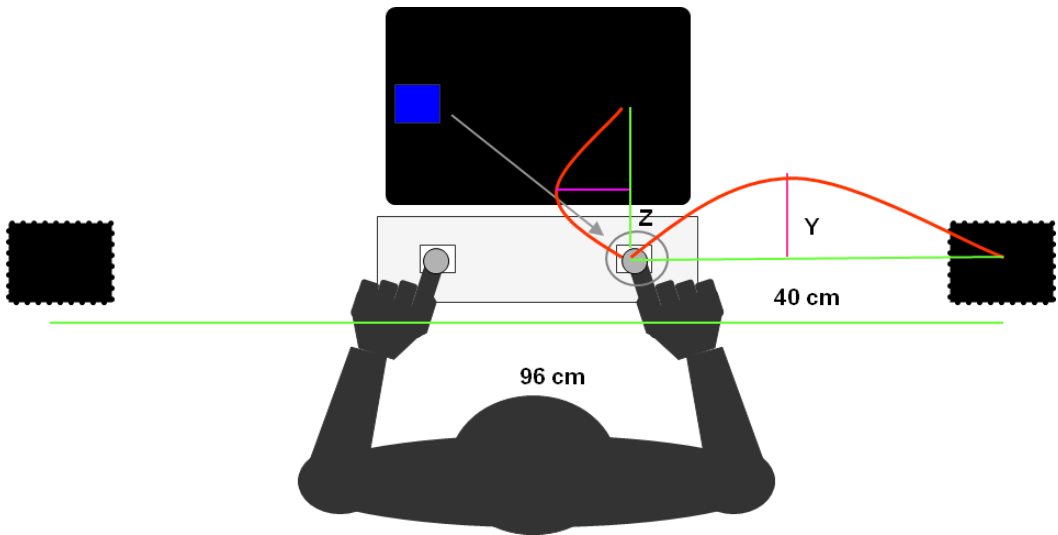
Fig. 1. The figure shows the experimental setting: A response box was aligned centrally across the body midline. Its left- and right-most buttons (16 cm from each other) served as the *start buttons*. Two custom-made external pads (left and right *end buttons*) were plugged into the response box and aligned 40 cm to the left and to the right of the corresponding start buttons.

carries over to the early phase of a movement, these early events should be influenced by it, and therefore they have the potential to reveal those interference effects that took place at the *response selection* stage. As the movement unfolds, the control component should be operative; therefore, we also collected and analyzed *late* kinematic variables, such as the time and the amplitude of peak velocity, as well as the time and the amplitude of movements trajectories. The latter parameters should be informative regarding possible adjustments occurring during the on-line control of the action. For all the considered dependent measures, the same analyses were carried out to detect possible facilitation effects for corresponding trials and interference effects for non-corresponding trials. Finally, we investigated whether the conflict emerging in the previous trial would affect the response for the current trial.

We predict an advantage for spatially corresponding stimulus–response associations and a disadvantage for spatially non-corresponding associations. On the basis of previous literature these effects should be detectable on early kinematic parameterization (i.e., at roughly 35% of movement, see Glover, 2004; Glover, 2002; Jakobson & Goodale, 1991; Jeannerod, 1984; Rubichi & Pellicano, 2004). With respect to measures occurring at the level of online control (i.e., at roughly 70% of movement), we predict that an advantage for corresponding versus non-corresponding responses will not be evident. However, in case of poor movement planning, a modulation determined by the stimulus spatial location, as well as by other sources of information (see Resulaj, Kiani, Wolpert, & Shadlen, 2009; Song & Nakayama, 2008) is foreseen, due to greater movement adjustments being required to finalize the response.

2. Method

2.1. Participants

Sixteen students of the University of Bologna (M_{age} = 20 years, SD = 3.25; eight females) were recruited and were given credit for their participation. All the participants were right handed; they had normal or corrected-to-normal vision and were free from pathologies that could affect their motor behavior. All participants gave informed consent to participate in the study and were naive as to the purpose of the experiment. The study was carried out along the principles of the Helsinki Declaration and was approved by the local ethics committee. Two participants were excluded for technical reasons and one participant was excluded for exhibiting a very low level of accuracy.

2.2. Apparatus and stimuli

Stimulus presentation was controlled by the E-Prime software (www.pstnet.com; Psychology Software Tools, Inc.). The experiment took place in a dimly lit and noiseless room. Participants were seated facing a 17 in. cathode-ray tube screen driven by a 800 MHz processor. Participants rested their head on an adjustable head-and-chin rest, so that the distance between the eyes and the screen was about 45 cm. The stimulus display was the same as in Rubichi and Pellicano (2004; Experiment 2): a central fixation cross (1° × 1° visual angle degree) and four boxes (3.8° × 2° in size), each positioned 12° right of, left of, above, and below the fixation, were presented at each trial. The presence of a neutral condition (above, below) allowed for the investigation of both facilitation and interference components of the Simon effect. Stimuli were red and green squares (2° × 2° in size). A PST (Psychology Software Tools, http://www.pstnet.com) serial response box stood in front of the participants and aligned across their body midline. Its left- and right-most buttons (16 cm from each other) served as start buttons. Two custom-made external pads (left and right *end buttons*) were plugged into the response box and aligned 40 cm to the left and to the right of the corresponding start buttons (see Fig. 1).

2.3. Procedure

At the beginning of the experiment, the participants' left and right index fingertips rested on the left and the right start buttons, respectively. Each trial started by simultaneously pressing and holding down these two buttons. A 25 ms warning tone was delivered together with the appearance of the fixation cross and the four boxes. The fixation cross and the boxes remained visible throughout the trial. After a random interval between 800 and 1,200 ms, the stimulus (a red or green square) appeared inside one of the four boxes. Participants were instructed to perform a fast leftward or rightward movement depending on stimulus color (task relevant dimension) irrespective of its location (task irrelevant dimension). A leftward movement consisted in releasing the *left start but-*

ton (whereas the right one was held down) and then reaching and pressing the *left end button* with the left hand. Conversely, a rightward movement consisted in releasing the *right start button* and then reaching and pressing the *right end button* with the right hand. The pressing of the end button determined an acoustic feedback.

The distance between the central and the lateralized pads was 40 cm. Stimulus duration lasted until the end button was pressed or up to 1,000 ms in the case of no response.

Half of the participants performed a leftward movement toward the red square and a rightward movement toward the green square, whereas the other half had the reverse assignment. Participants had to complete their movement within 500 ms from the release of the start button. Following response completion, their RTs or an error message was shown below the fixation cross in case of correct or incorrect response, respectively. Following this event, there was a 1,000 ms inter-trial interval. Each participant was tested in one experimental session, which comprised 24 practice trials followed by 320 experimental trials, divided into two blocks and separated by a brief pause.

2.4. Data recording and analysis

RTs were measured from the onset of the stimulus to the release of the start button. MTs were measured from the release of the start button to the pressing of the corresponding end button. RTs, MTs, and Error rates were collected by E-Prime software.

Movements of the participant's right and left hands were recorded using the 3D-optoelectronic SMART system (BTS Bioengineering, Milano, Italy) by means of three video cameras detecting infrared reflecting markers at a sampling rate of 60 Hz and a spatial resolution of 768×576 pixels. Two passive light-reflecting markers were applied on the tip of the left and right index fingers. The reference X, Y, and Z axes were oriented to record the leftward and rightward movements along the X axis, their height and depth along the Y and Z axes, respectively. Raw data were smoothed using a linear smoothing rectangular filter. Kinematics parameters were assessed for each individual movement. We analyzed the finger's spatial trajectory, velocity, and acceleration functions. Specifically we calculated:

1. the peak acceleration and its latency; that is, the maximum value of the acceleration vector's module (|A| max) and the time at which it occurred.
2. the trajectory peak (Y component of the trajectory vector) and its latency; that is, the maximum height reached by the finger's trajectory and the time at which this peak occurred.
3. the peak velocity and its latency; that is, the maximum value of the velocity vector's module (|V| max) and the time at which it occurred.

All kinematic parameters were calculated for each trial and then averaged for each participant. As the start of the kinematic recording was synchronized to the onset of the stimulus, we subtracted the RTs (i.e., the release of the start button) measures to the times each peak occurred. This was done to correctly refer the time of the peak values to the start of the movement.

2.5. *Early and late kinematic events*

As anticipated, we were interested in both the planning and the online components of the considered movement: They rise and fall as the movement unfolds. Consistently with previous literature, we considered a series of dependent variables that occur at roughly 35% of movement duration (*early kinematic events*) as reflecting planning rather than control (e.g., peak acceleration). And parameters occurring at roughly 70% of movement duration (*late kinematic events*) as reflecting control rather than planning (Glover, 2004; Jakobson & Goodale, 1991; Jeannerod, 1984) such as peak velocity and peak trajectory.

3. Results

Response omissions (1%), wrong key releases (3.1%), and responses with both the start keys being released (5.3%) were excluded from the analyses.

To measure the Simon effect, *corresponding* (i.e., the horizontal direction of the response movement corresponded to the horizontal location of the stimulus), *neutral* (i.e., the horizontal direction of the response movement compared to the collapsed vertical locations), and *non-corresponding trials* (i.e., the horizontal direction of the response movement that was opposite to the horizontal location of the stimulus) were compared. To test the temporal dynamics of the Simon effect, the time course of the Simon effect for all dependent variables was investigated by applying the Vincentizing procedure (De Jong et al., 1994; Proctor, Miles, & Baroni, 2011; Ratcliff, 1979; Rubichi, Nicoletti, Iani, & Umiltà, 1997). For each participant and for each corresponding, neutral and non-corresponding condition, RTs were ranked from the fastest to the slowest and then partitioned into quintiles (5 bins), with an equal percentage of observations. Mean values were calculated for each dependent variable for each of the three conditions, from the first through the fifth bin. A repeated-measures ANOVA with Bin_{RT} (bin 1st vs. 2nd vs. 3rd vs. 4th vs. 5th) and *Correspondence* (corresponding vs. neutral vs. non-corresponding S-R pairings) as within-subjects factors was performed for RTs, MTs, arcsin-transformed error rates (wrong key releases—ERs), Peak Acceleration, Time to Peak Acceleration (TPA), Peak Velocity, Time to Peak Velocity (TPV), Amplitude of Peak Trajectory (APT), Time to Peak Trajectory (TPT). Due to the rank ordering, the Bin_{RT} factor for RTs turned out to be significant and was neither reported nor discussed. Instead, for all other dependent variables Helmert and polynomial contrasts were performed to investigate the time course of the Bin_{RT} main effects across increasing RTs quintiles. Post hoc analyses were carried out using paired samples *t*-tests.

3.1. *Reaction times (RTs)*

A main effect of *Correspondence, F*(2, 24) = 93.21, *p* < .001, η_p^2 = .89 was observed. Paired samples *t*-tests showed that RTs for the corresponding condition were faster than those for the neutral condition (382 vs. 430 ms), *t*(12) = 13.610, *p* < .001, and that RTs

for the non-corresponding condition were slower than those for the neutral condition (442 vs. 430 ms), $t(12) = 2.809$, $p < .05$. Thus, the *facilitation* (neutral condition—corresponding condition = 48 ms) and the *interference* (non-corresponding condition—neutral condition = 12 ms) components characterizing the Simon effect were observed.

The interaction between *Correspondence* and Bin_{RT} was significant: $F(8, 96) = 3.78$, $p = .001$, $\eta_p^2 = .24$. Paired samples *t*-tests showed that RTs were faster for the corresponding compared to the neutral trials (i.e., the facilitation effect), from the 1st bin to the 5th bin, $ts(12) = 12.012, 12.868, 10.927, 7.549$, and 4.907, $ps < .001$, respectively; whereas they were slower for the non-corresponding respect to the neutral trials (i.e., the interference effect) from the 1st bin to the 4th bin $ts(12) = 4.153, 3.833, 4.527$, and 3.151, $p_s < .008$, but not at the 5th bin, $t(12) = 0.610$, $p = .553$ (see Fig. 2a).

3.2. Error rates (ERs)

A repeated-measures ANOVA with *Correspondence* (corresponding vs. neutral vs. non-corresponding S-R pairings) as within-subjects factor was performed on arcsin-transformed error rates (ERs), that is, the errors in releasing the correct start button (for the sake of clarity, actual ERs are reported in the text). The *Correspondence* factor was significant $F(2, 24) = 6.110$, $p = .007$, $\eta_p^2 = .34$. Post hoc paired-samples *t*-tests showed that the non-corresponding condition was more error-prone than the neutral condition (5.6% vs. 2.8%), $t(12) = 3.459$, $p = .005$, whereas no significant difference was observed between the corresponding and the neutral conditions (1.6% vs. 2.8%) $t(12) = 1.100$, $p = .293$.
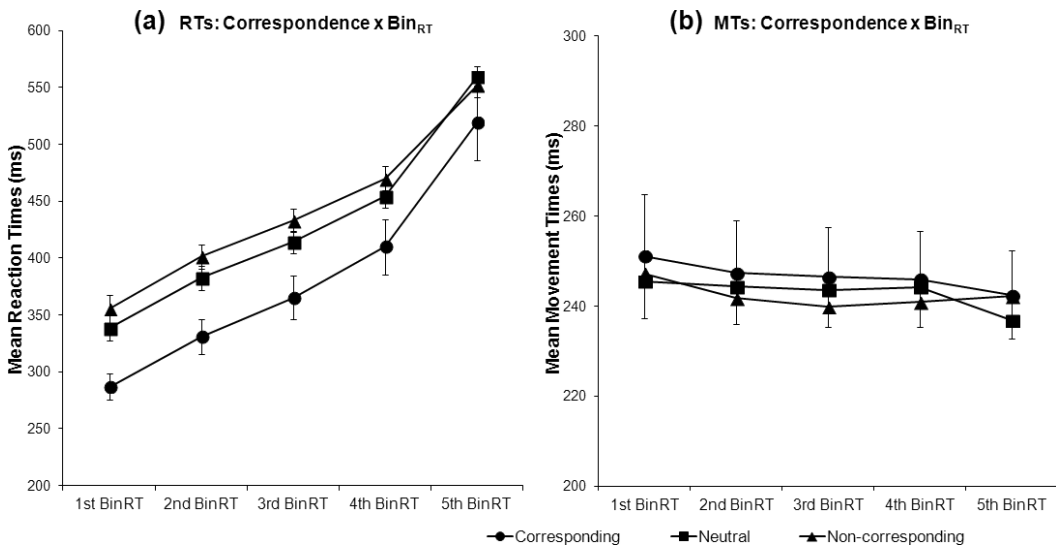

Fig. 2. (a) The significant interaction between Correspondence and Bin_{RT} for RTs. For RTs the facilitation effect was significant from the 1st to 5th bin, whereas the interference effect was significant from the 1st to 4th bin. For MTs, (b) the interaction was not significant. Error bars display standard errors.

3.3. Movement times (MTs)

The ANOVA performed on MTs showed a main effect of Bin_{RT}, $F(4, 48) = 2.64$, $p = .045$, $\eta_p^2 = .18$, and *Correspondence*, $F(2, 24) = 7.111$, $p = .004$, $\eta_p^2 = .37$. MTs decreased mostly from the 1st bin to the 2nd bin and from the 4th bin to the 5th bin, as displayed by the significant polynomial cubic contrast $F(1, 12) = 5.225$, $p = .041$. Paired-samples *t*-tests revealed that mean MTs for the corresponding condition were slower than mean MTs for the neutral condition (247 vs. 243 ms), $t(12) = 2.594$, $p = .023$. No significant difference was found between the non-corresponding and the neutral conditions (242 vs. 243 ms), $t(12) = -0.389$, $p = .704$. The *Correspondence* × Bin_{RT} interaction was not significant, $F(8, 96) = 1.09$, $p = .377$ (see Fig. 2b).

3.4. Peak acceleration (PA)

The main effects of Bin_{RT}, $F(4, 48) = 1.24$, $p = .306$, $\eta_p^2 = .09$, and *Correspondence*, $F(2, 24) = 2.90$, $p = .074$, $\eta_p^2 = .19$ (33,048 vs. 32,835 vs. 32,356 mm/s^2 for corresponding, neutral, and non-corresponding, respectively) did not reach significance. The same applies for the interaction between Bin_{RT} and *Correspondence*, $F(8, 96) < 1$, $\eta_p^2 = .04$.

3.5. Time to peak acceleration

For this dependent measure the main effect of Bin_{RT} was significant, $F(4, 48) = 4.89$, $p = .002$, $\eta_p^2 = .29$. The time at which the peak of acceleration was reached decreased from Bin_{RT} 1 to Bin_{RT} 5 (70, 68, 64, 61, and 55 ms, respectively). Helmert contrast indicates that the stronger and the more significant decrease occurs from Bin_{RT} 2 to Bin_{RT} 3, $F(1, 12) = 8.269$, $p = .014$, and from Bin_{RT} 3 to Bin_{RT} 4, $F(1, 12) = 4.824$, $p = .048$. The main effect of *Correspondence* was not significant $F(2, 24) = 2.04$, $p = .152$, $\eta_p^2 = .14$ (63 vs. 62 vs. 65 ms for corresponding, neutral, and non-corresponding, respectively). Similarly, the interaction between Bin_{RT} and *Correspondence* was not significant, $F(8, 96) < 1$, $\eta_p^2 = .02$.

3.6. Peak velocity (PV)

The main effects of Bin_{RT} and *Correspondence* were not significant, $F(4, 48) = 1.03$, $p = .402$, $\eta_p^2 = .08$, and $F(2, 24) = 1.62$, $p = .218$, $\eta_p^2 = .12$, respectively. Also the interaction between the two factors did not reach significance, $F(8, 96) = 1.33$, $p = .237$, $\eta_p^2 = .10$.

3.7. Time to peak velocity

The main effect of Bin_{RT} was significant, $F(4, 48) = 9.30$, $p < .001$, $\eta_p^2 = .44$. Helmert contrasts revealed that the time at which peak velocity was reached decreased significantly and progressively from Bin_{RT} 1 to Bin_{RT} 5 (147, 142, 141, 138, and 132 ms,

respectively), $Fs(1, 12) > 5$, $ps < .05$. The main effect of *Correspondence* was also significant $F(2, 24) = 5.49$, $p = .011$, $\eta_p^2 = .31$. Peak velocity occurred significantly later for the corresponding (142 ms) compared to the neutral (139 ms) $t(12) = 2.726$, $p = .018$ and to the non-corresponding trials (138 ms), $t(12) = 3.245$, $p = .007$. The comparison between the non-corresponding and the neutral trials was not significant $t(12) = .84$, $p = .418$. The interaction between the two factors was not significant: $F(8, 96) < 1$, $\eta_p^2 = .04$.

3.8. Amplitude of peak trajectory

A main effect of Correspondence was observed $F(2, 24) = 20.83$, $p < .001$, $\eta_p^2 = .63$. The maximum peak of the y component (height) was smaller for the corresponding (109 mm) than for the neutral (111 mm) trials, $t(12) = 4.292$, $p = .001$ (see Fig. 3a). And it was higher for the non-corresponding than for the neutral trials (113 vs. 111 mm), $t(12) = 2.657$, $p = .021$. Both the main effect of Bin_{RT} and the interaction between *Correspondence* and Bin_{RT} were not significant, $F(4, 48) = .44$, $p = .778$, $\eta_p^2 = .03$ and $F(8, 96) = .99$, $p = .446$, $\eta_p^2 = .08$, respectively.

3.9. Time to peak trajectory

The main effect of Bin_{RT} was significant, $F(4, 48) = 5.06$, $p = .002$, $\eta_p^2 = .30$. A close inspection revealed that the time at which the maximum trajectory peak was reached for the y component decreased at increasing RTs bins (Bin_{RT} 1 to 5 = 151, 149, 148, 147,
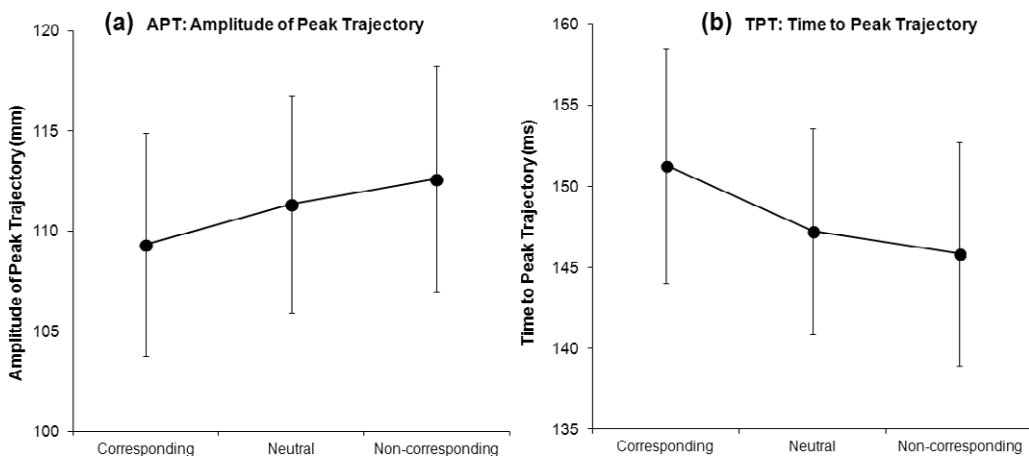

Fig. 3. (a) The significant main effect of Correspondence for Amplitude of Peak Trajectory (APT): The maximum peak of the y component was smaller for the corresponding than for the neutral trials and it was higher for the non-corresponding than for the neutral ones. (b) The significant main effect of Correspondence for the Time to Peak Trajectory (TPT): The maximum peak of the y component was reached later for the corresponding compared to the neutral trials. Error bars display standard errors.

and 145 ms). Helmert contrasts revealed that the significant decrease was between Bin_{RT} 1 and Bin_{RT} 2, $F(1, 12) = 10.551$, $p = .007$ and between Bin_{RT} 3 and Bin_{RT} 4, $F(1, 12) = 5.760$, $p = .034$. The main effect of *Correspondence* was also significant, $F(2, 24) = 9.33$, $p = .001$, $\eta_p^2 = .44$. The maximum peak of the y component was reached later for the corresponding trials (151 ms) compared to the neutral trials (147 ms) $t(12) = 2.850$, $p = .015$. The contrast between the neutral and the non-corresponding trials was not significant $t(12) = 1.269$, $p = .228$. The interaction between the two factors was not significant: $F(8, 96) < 1$, $\eta_p^2 = .10$ (see Fig. 3b).

3.10. Assessing the role of previous experience by means of sequential analyses

As said, we sought to explore whether and to what extent S-R correspondence in trial $n-1$ influences the planning and the on-line control phases of the movement in trial n. This issue was addressed in a series of ANOVAS with *Correspondence* (corresponding vs. neutral vs. non-corresponding S-R pairings in the *current* trial) and *Correspondence*-1 (corresponding vs. neutral vs. non-corresponding S-R pairings in the *previous* trial) as within-subjects factors on RTs, MTs, Peak Acceleration, TPA, Peak Velocity, TPV, APT, TPT. As the main effect of Correspondence was already assessed in the previous analyses, here we focused on the Correspondence by Correspondence-1 interaction. Post hoc analyses were conducted using paired-samples t-tests.

3.11. Reaction times (RTs)

The *Correspondence* × *Correspondence*-1 interaction reached significance $F(4, 48) = 6.375$, $p < .001$, $\eta_p^2 = .35$. Post hoc analyses showed that RTs for the corresponding trials were faster than those for the neutral trials when preceded by neutral $t(12) = 7.429$ $p < .001$, corresponding $t(12) = 7.518$ $p < .001$, and non-corresponding $t(12) = 4.005$ $p = .002$ trials. RTs to non-corresponding trials were slower than neutral trials when both were preceded by neutral or corresponding trials $ts(12) = 2.510$ and 3.182 $ps < .028$, but not when they were preceded by non-corresponding trials $t(12) < 1$ (see Fig. 4). Moreover, RTs for the corresponding trials were slower when preceded by non-corresponding trials compared to when they were preceded by neutral and corresponding trials, $ts(12) = 3.239$ and 3.053, $ps = .007$ and $.010$, respectively. These results clearly demonstrate that the facilitation effect for the corresponding trials significantly decreased if the preceding trial was non-corresponding with respect to when it was neutral or corresponding. The interference effect was present when the non-corresponding trials were preceded by a neutral or by a corresponding trial. However, it was absent when the previous trial was non-corresponding.

3.12. Movement parameters

The *Correspondence* × *Correspondence*-1 *interaction* reached significance only for Peak Acceleration (PA), $F(4, 48) = 3.03$, $p = .026$, $\eta_p^2 = .20$ (see Fig. 5). Paired sample
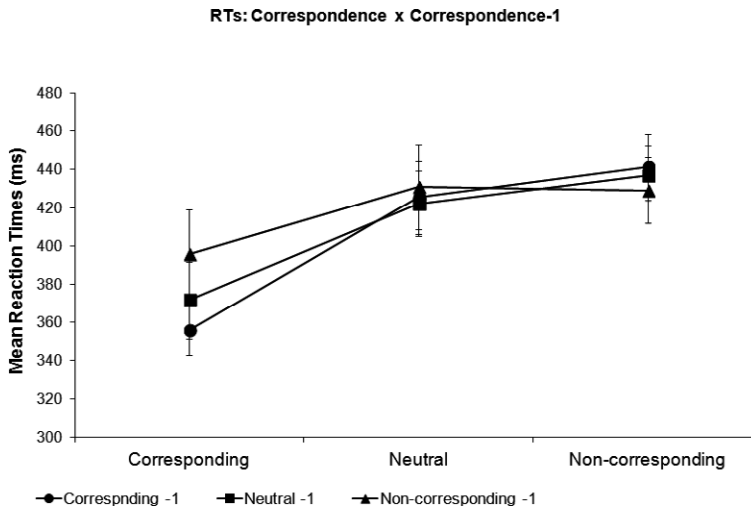
Fig. 4. The significant interaction between Correspondence × Correspondence-1 for Response Times: The only significant vertical comparisons showed RTs in corresponding trials being slower when preceded by non-corresponding compared to neutral and corresponding ones. Error bars display standard errors.
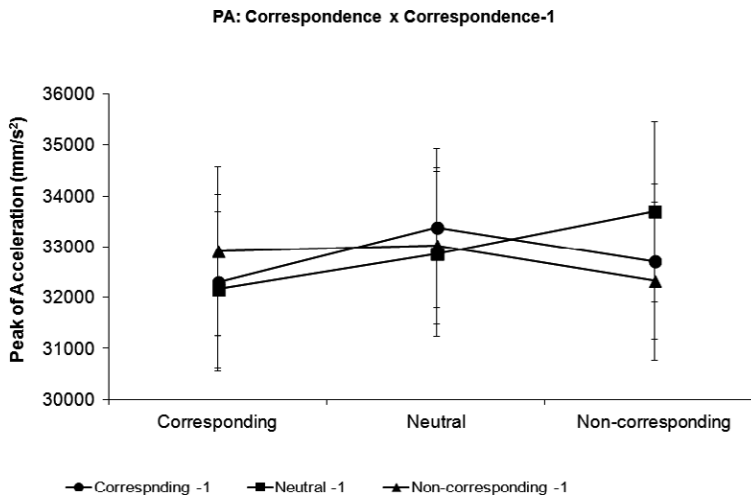

Fig. 5. The significant interaction between Correspondence × Correspondence-1 for Peak Acceleration: The peak of acceleration resulted in lower amplitude when non-corresponding trials were preceded by non-corresponding trials (conflict adaptation) than by neutral ones. Error bars display standard errors.

t-tests revealed that peak acceleration decreased for the corresponding compared to the neutral condition only when both were preceded by a corresponding trial, $t(12) = 2.457$, $p = .030$. Furthermore, peak acceleration increased significantly for the non-corresponding compared to the neutral condition only if both were preceded by a neutral trial,

$t(12) = 2.205$, $p = .048$. According to the vertical comparisons, peak acceleration was lower when non-corresponding trials were preceded by non-corresponding than neutral trials, $t(12) = 2.654$, $p = .021$. When the actual and the preceding trial corresponded, then accessing a previously used code determines a sort of facilitation that translates into a lower amplitude of peak acceleration for the actual response.

4. Discussion

In this study, we investigated the locus of response conflict during a Simon task by using a kinematic approach. Specifically, we focused on the effects of response conflict generated at the response selection stage that spread to movement execution. Participants were presented with different colored squares on the right, left, above, or below a central fixation cross. Our task forced participants to select the response before movement initiation. In addition, an extended movement response allowed us to study both the planning and the on-line control phases of the action. As measures for *planning,* we considered reaction times, error rates (two dependent measures specifically pertaining to response selection), and peak acceleration (a measure relative to movement execution, but which could reveal "planning" carryover effects, given that it occurs at roughly 35% of movement duration; see Glover, 2004). As measures for online *control,* we focused on peak velocity and peak trajectory as they occur at roughly 70% of movement duration, when the initial ballistic phase is ended, and the system is correcting errors and refining the movement online (see Glover, 2004). This refining phase would depend on the various sources of information that are present during processing, that is, at the time when the initial decision is already made, and it has to be reversed or reaffirmed (Resulaj et al., 2009; Song & Nakayama, 2008).

First, it is worth noting that this work substantially differs from previous investigations concerned with the Simon effect in action (e.g., Buetti & Kerzel, 2009; Scherbaum et al., 2010). In terms of response movements, to ensure the use of a movement that was not ballistic in nature, we located the boxes at a distance of 40 cm from the starting position; participants had to move the (right/left) hand-arm to reach the final position. This choice allowed us to investigate both the planning and the online *control* phases of the movement. In particular, the investigation of the control phase was achieved by analyzing kinematic markers, such as peak velocity and peak trajectory, which occur at the time the initial ballistic phase is ended (see Glover, 2004). In terms of kind of choice reaction task, we sought to make sure that the response selection process was ended before the movement started by employing a bimanual choice reaction task, which implied an effector selection. Indeed, according to the idea that the Simon effect originates from processes that take place at the level of response selection, an effector selection condition allows one to understand whether during movement execution the participants are still solving a possible conflict between the response code activated by the irrelevant stimulus and the response code retrieved by instruction. Alternatively, one could speculate that for the incompatible trials participants plan a different—slightly awkward—kind of response,

and therefore need to invest more heavily in on-line corrections. Nevertheless, this possibility—that does not imply a direct conflict between relevant and irrelevant information *during* the movement—seems not to be supported by the present findings (see analyses on trajectory data). With regard to the chosen kinematic variables, to investigate whether signs of the Simon effect are evident during movement execution, we considered two specific dependent measures, namely peak velocity and peak trajectory. Analysis of these measures allowed us to investigate the issues at stake here without imposing any movement constraint (which might have affected movement organization heavily). Differently from us, Buetti and Kerzel (2009) had a condition implying a time limit. Apart from the fact that imposing a time limit does not allow the movement to unfold naturally, this manipulation affects only the direction, but not the effector selection condition. This is witnessed by the fact that in their study RTs analyses showed a stronger compatibility effect for direction than for effector selection.

Finally, we highlight two further aspects that depict the novelty of this study. First, in contrast to previous studies (Buetti & Kerzel, 2009; Scherbaum et al., 2010) both our task and the complex pattern of chosen kinematic measures have the ability to fully capture whether processes occurring at the level of response selection spread into action execution. Second, rather than focusing on selection-for-action literature, we interpret our findings within the Simon effect theoretical framework. More specifically, we discuss the present data in terms of the conflict occurring during the processing of two features pertaining to the same object (i.e., spatial position and color), one of which (i.e., the stimulus spatial position) automatically captures the subjects' attentional focus.

Back to the findings, we found evidence of a Simon effect on RTs. That is, corresponding trials yielded faster responses than non-lateralized responses (i.e., the facilitation component of the Simon effect). And non-corresponding trials were slower than neutral ones (i.e., the interference component of the Simon effect). The facilitation effect remained constant across all RTs bins, whereas the interference effect was constant until 4th bin and then disappeared at the slowest 5th bin. A similar pattern of results was obtained on ERs. An interference effect for non-corresponding compared to neutral trials and a facilitation (though only close to significant) effect for corresponding compared to neutral trials were found.

With regard to action planning, the results concerned with the time of peak acceleration show no-difference for the corresponding and the non-corresponding conditions. However, regardless of the correspondence between stimulus and response locations, we found delayed acceleration peaks for faster response times, as indicated by the bin distributional analysis.

Although sequential analysis basically replicated the above mentioned findings, it highlighted an interesting pattern of data on the movement planning phase, as indexed by RTs and peak acceleration. We found faster RTs for corresponding trials preceded by neutral and corresponding trials (N-C; C-C) compared to non-corresponding trials (NC-C), as if participants were paying a switching cost. The conflict on "previous trial" strongly affected response times for corresponding trials, whereas it specifically affected peak acceleration for non-corresponding trials (please refer to Fig. 4 vs. Fig. 5). Therefore, the

switching seems to determine a cost to be paid on response times as far as corresponding trials are concerned (N-C: slower RTs) and on peak acceleration for non-corresponding trials (N-NC: higher acceleration peak). With pairings of congruent conflicting trials (NC-NC), analyses on peak acceleration showed evidence of a conflict adaptation (Egner, 2007). Therefore, differently from Scherbaum et al. (2010), we found that the conflict on the previous trial affects the early part of the movement: Specifically, contrasts n vs. $n-1$ revealed that overall the advantage of corresponding trials—due to stimulus location but also to the specific "previous trial"—is stronger during the planning phase of the motor response (see RTs, corresponding trials), whereas the disadvantage of non-corresponding trials (due to both stimulus location and previous trial) becomes evident immediately after movement initiation (see PA for non-corresponding trials). Moreover, peak acceleration seems to be sensitive to a switching cost passing from the neutral (boxes along the vertical axis) to the corresponding conditions. In this respect, the NC-NC pair (conflict adaptation) differed from the N-NC pair, but not from the C-NC pair.

Turning on the online control phase of the movement, the analysis on the latency of peak velocity showed a non-corresponding trials advantage compared to neutral and corresponding trials. This might signify that following movement onset (until its completion), the *control system* takes over. In the case of "stronger constraints" the planning system would require more time (i.e., non-corresponding conditions) and, therefore, might be more error-prone; symmetrically the control system will take advantage of a more detailed planning (less interference of the lateral target-button processing; less noise in the neuromuscular system). To date, the finding of an advantage for the non-corresponding conditions might be suggestive of a reversal of the Simon effect (Hedge & Marsh, 1975; Ivanoff & Peters, 2000; Proctor et al., 2011; Rubichi et al., 1997; Simon, Sly, & Vilapakkam, 1981). Nevertheless, we do not favor this interpretation as analyses on kinematics parameters (as well as on MT) distribution over time did not show an increasing function that indexes a reversed Simon effect (no interaction between correspondence and bin factors). Support for this contention comes from the significant main effect of the bin factor: The time at which the peak of both velocity and acceleration were reached decreased progressively across RTs.

Data on both latency of trajectory peaks and MTs basically replicate those obtained for peak velocity: The maximum peak of the y component was reached later and the overall movement was slower for the corresponding trials (compared to the neutral trials), whereas no significant differences were found between the non-corresponding and the neutral conditions. Consistent with the Simon effect, we found this kind of modulation on early kinematic parameters. First, we detected a difference during on-line control between conditions that strongly differed in the planning phase (i.e., corresponding vs. neutral conditions), but no difference between conditions for which the planning phase was performed at about the same time (neutral and non-corresponding conditions). Second, bin analyses showed that the latency of peak trajectory as well the overall movement time decreased at increasing RTs bins. A fine-planned movement requires a less accurate spatial analysis (i.e., short latencies) compared to a more approximate movement plan.

The most intriguing aspect of the present findings regards trajectory peaks. This is because they provide information on the actual position of the fingers during the reaching and pressing movements. This measure was not affected by the response time distributions (i.e., no effect of bin). Rather, these analyses showed that the maximum peak of the Y component (movement maximum height) was shorter for the corresponding than for the neutral trials, and it was higher for the non-corresponding than for the neutral trials. When stimulus and response location corresponded, the participant's finger trajectory roughly matches the minimum distance between the central pad and the lateralized button (even if the movement was executed more slowly than for the non-corresponding trials). This finding might be due to the facilitation and the interference components of the Simon effect (as found for RTs), but it is not consistent with the delayed occurrence of the Y trajectory peak. A plausible explanation rests on a *response-effect compatibility* (Pfister, Kiesel, & Melcher, 2010; Pfister & Kunde, 2013) that is on anticipation of body-related action effects. These anticipative processes cause facilitation or interference effects depending on the spatial correspondence of response key and effect location (i.e., intended environment-related effects), regardless of the effector involved (for a recent study on effect anticipations with joint actions, see also Pfister, Dolk, Prinz, & Kunde, 2014). In our paradigm, responses for the corresponding conditions could be considered as spatially compatible with their "effects" in the environments; the reverse is true for the non-corresponding conditions. To date, the lateralized stimulus *remained* on the screen, until the end button was pressed, but since "salient" task goal established by instructions (i.e., performing a fast movement to the color feature of the stimulus: releasing the start button, and *then* reaching and pressing the end button) was accomplished by releasing the pad, participants might have waited for an effect of the pressing action, and then coded the ("final") stimulus location as it was. This hypothesis might be rather speculative, and it certainly needs to be tested in future studies (i.e., lateralized button pressing producing compatible vs. non-compatible response effects). Nevertheless, it is consistent with the idea that responses can be coded also in terms of distal effects of the action (action effects); the processes responsible for the response-effect compatibility should be independent from the processes responsible for the Simon effect (Yamaguchi & Proctor, 2011).

As a final point, the present findings could be framed with the theoretical model proposed by Glover (2004). This model distinguishes between *planning* and *online control* of movement. The planning system selects an adequate motor program to reach the current actor's goal, taking into account the specific environment as well as the peculiar bio-mechanical body constraints. The control system, instead, is devoted to minimizing the spatial error of the movement, and quickly monitoring and, if necessary, adjusting motor programs in flight. As to the time course, these two movement stages partially overlap, since the very early stages of the movement (i.e., the initial kinematic parameterization of the movement) might be still under the influence of the planning system. Our findings offer the opportunity to explain action-related Simon effects under this view. For the first time, we report that there is a strict link between the stimulus–response associations formed during action planning and how the level of complexity characterizing such

associations reflects on the manner the Simon effect unfolds in time. To elaborate, our findings might signify that during an action Simon task the two stages of action are temporally overlapping. Prior to movement initiation, planning is entirely responsible for the initial determination of stimulus–response association, and it continues to be highly influential early in the movement. As movements progress, however, the influence of control on the spatial parameters of the action increases. As planning is generally operative early in a movement and control late in a movement, the influence of each will rise and fall as the movement unfolds.

Acknowledgments

References

Buetti, S., & Kerzel, D. (2009). Conflicts during response selection affect response programming: Reactions towards the source of stimulation. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(3), 816–834.

Craik, K. J. W. (1947). Theory of the human operator in control systems I: The operator as an engineering system. *British Journal of Psychology*, *38*(56–61), 142–148.

De Jong, R., Liang, C.-C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus ± response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 731–750.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience*, *7*(4), 380–390.

Gan, K., & Hoffmann, E. R. (1988). Geometrical condition for ballistic and visually controlled movements. *Ergonomics*, *31*, 5.

Glencross, D. J. (1977). Control of skilled movement. *Psychological Bulletin*, *84*(1), 14–29.

Glover, S. (2002). Visual illusions affect planning but not control. *Trends in Cognitive Sciences*, *6*, 288–292.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, *27*, 3–78.

Hedge, A., & Marsh, N. W. A. (1975). The effect of irrelevant spatial correspondence on two-choice response-time. *Acta Psychologica*, *39*, 427–439.

Hommel, B. (1996). S-R compatibility effects without response uncertainty. *Quarterly Journal of Experimental Psychology*, *49A*, 546–571.

Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*, 189–202.

Hommel, B., Colzato, L. S., Scorolli, C., Borghi, A. M., & van den Wildenberg, W. P. M. (2011). Religion and action control: Faith-specific modulation of the Simon effect but not stop-signal performance. *Cognition*, *120*, 177–185.

Iani, C., Milanese, N., & Rubichi, S. (2014).The influence of prior practice and handedness on the orthogonal Simon effect. *Frontiers in Psychology*, *5*(39), 1–7.

Iani, C., Rubichi, S., Ferraro, L., Nicoletti, R., & Gallese, V. (2013). Observational learning without a model is influenced by the observer's possibility to act: Evidence from the Simon task. *Cognition*, *128*(1), 26–34.

Iani, C., Rubichi, S., Gherri, E., & Nicoletti, R. (2009). Co-occurrence of sequential and practice effects in the Simon task: Evidence for two independent mechanisms affecting response selection. *Memory & Cognition*, *37*, 358–367.

Ivanoff, J., & Peters, B. (2000). A shift of attention may be necessary, but it is not sufficient, for the generation of the Simon effect. *Psychological Research*, *64*, 117–135.

Jakobson, L. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: A kinematic analysis of human prehension. *Experimental Brain Research*, *86*, 199–208.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior*, *16*, 235–254.

Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop- and Simon-like stimuli. *Psychological Research/Psychologische For-schung*, *56*, 130–135.

Lin, J., & Drury, C. G. (2011). Verification of two models of ballistic movements. *Human Computer Interaction*, *6762*, 275–284.

Pellicano, A., Iani, C., Borghi, A. M., Rubichi, S., & Nicoletti, R. (2010). Simon-like and functional affordance effects with tools: The effects of object perceptual discrimination and object action state. *The Quarterly Journal of Experimental Psychology*, *63*, 2190–2201.

Pfister, R., Dolk, T., Prinz, W., & Kunde, W. (2014). Joint response-effect compatibility. *Psychonomic Bulletin & Review*, *21*, 817–822. Doi: 10.3758/s13423-013-0528-7

Pfister, R., Kiesel, A., & Melcher, T. (2010). Adaptive control of ideomotor effect anticipations. *Acta Psychologica*, *135*, 316–322.

Pfister, R., & Kunde, W. (2013). Dissecting the response in response-effect compatibility. *Experimental Brain Research*, *224*, 647–655.

Praamstra, P., Kleine, B. U., & Schnitzler, A. (1999). Magnetic stimulation of the dorsal premotor cortex modulates the Simon effect. *NeuroReport*, *10*, 3671–3674.

Proctor, R. W. (2011). Playing the Simon game: Use of the Simon task for investigating human information processing. *Acta Psychologica*, *136*, 182–188.

Proctor, R. W., Miles, J. D., & Baroni, G. (2011). Reaction time distribution analysis of spatial correspondence effects. *Psychonomic Bulletin & Review*, *18*, 242–266.

Proctor, R. W., & Vu, K.-P. L. (2006). *Stimulus–response compatibility principle: Data, theory, and application*. Boca Raton, FL: Taylor & Francis.

Ratcliff, R. (1979). Group reaction time distributions and an analysis of distribution statistics. *Psychological Bulletin*, *86*, 446–461.

Resulaj, A., Kiani, R., Wolpert, D. M., & Shadlen, M. N. (2009). Changes of mind in decision-making. *Nature*, *461*(7261), 263–266.

Rubichi, S., Nicoletti, R., Iani, C., & Umiltà, C. (1997). The Simon effect occurs relative to the direction of an attention shift. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1353–1364.

Rubichi, S., Nicoletti, R., Umiltà, C., & Zorzi, M. (2000). Response strategies and the Simon effect. *Psychological Research*, *63*, 12–136.

Rubichi, S., & Pellicano, A. (2004). Does the Simon effect affect movement execution? *European Journal of Cognitive Psychology*, *16*, 825–840.

Rubichi, S., Vu, K.-P. L., Nicoletti, R., & Proctor, R. W. (2006). Spatial coding in two dimensions. *Psychonomic Bulletin & Review*, *13*, 201–216.

Scherbaum, S., Dshemuchadse, M., Fischer, R., & Goschke, T. (2010). How decisions evolve: The temporal dynamics of action selection. *Cognition*, *115*, 407–416.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*, 300–304.

Simon, J. R., Sly, P. E., & Vilapakkam, S. (1981). Effect of compatibility of S-R mapping on reaction toward the stimulus source. *Acta Psychoiogica*, *47*, 63–81.

Song, J. H., & Nakayama, K. (2008). Numeric comparison in a visually-guided manual reaching task. *Cognition*, *106*, 994–1003.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based priming in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 1345–1363.

Umiltà, C., Rubichi, S., & Nicoletti, R. (1999). Facilitation and interference components in the Simon effect. *Archives Italiennes de Biologie*, *137*, 139–149.

Water, P., & Strick, P. L. (1981). Influence of 'strategy' on muscle activity during ballistic movements. *Brain Research*, *207*, 189–194.

Wendt, M., Kluwe, H. R., & Peters, A. (2006). Sequential modulations of interference evoked by processing task-irrelevant stimulus feature. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 644–667.

Yamaguchi, M., & Proctor, R. W. (2011). The Simon task with multi-component responses: Two loci of response–effect compatibility. *Psychological Research*, *75*, 214–226.