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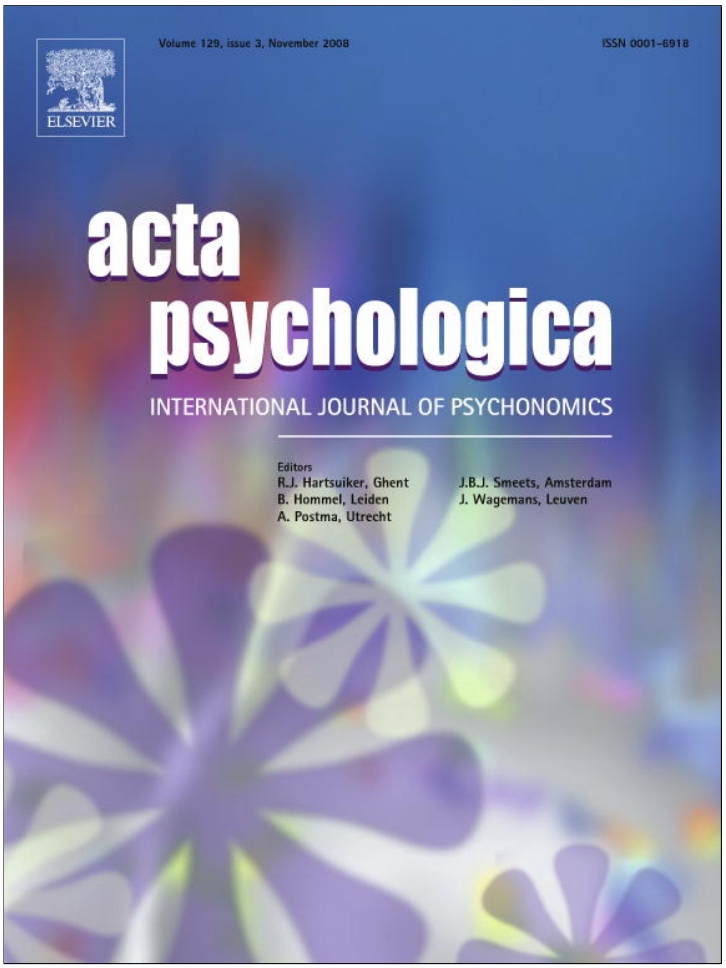

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Time course of the Simon effect in pointing movements for horizontal, vertical, and acoustic stimuli: Evidence for a common mechanism

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ABSTRACT

In the Simon effect, responses to a non-spatial attribute are faster when the irrelevant spatial position of the stimulus corresponds to the position of the response. It was suggested that there are two distinct mechanisms involved in the Simon effect. In the visuomotor Simon effect, the stimulus transiently activates the corresponding response which results in a decaying Simon effect function (i.e., the Simon effect decreases in slower reaction time [RT]-bins). In contrast, the cognitive Simon effect arises from a conflict between stimulus and response codes and is associated with a stable Simon effect function (i.e., the Simon effect is the same in fast and slow RT-bins). We recorded RTs and motor parameters of pointing movements in a Simon paradigm. Consistent with the previous research, the time course of the Simon effect in RTs was stable with vertical visual and horizontal acoustic stimuli (cognitive Simon tasks), but decreased with horizontal visual stimuli (visuomotor Simon task). In contrast, the Simon effect in motor parameters decreased across RT-bins in all conditions, supporting the idea that only a single, common mechanism underlies the Simon effect.

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1. Introduction

In a Simon task, participants are generally asked to respond to a non-spatial attribute of a stimulus while ignoring concomitant changes in spatial position. For instance, subjects may be asked to press a left key when a green square appears and to press a right key when a red square appears. Despite that stimulus location is irrelevant for the correct execution of the task, responses are faster when the stimulus appears on the same side as the required response (for an overview see Simon, 1990). For instance, left responses are faster and more accurate when the green square appears on the left (corresponding trial) than when the green square appears on the right (non-corresponding trial). The Simon effect for reaction times (RTs) is the difference between non-corresponding and corresponding trials. It is agreed upon that the Simon effect arises at the stage of response selection (e.g., De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990; Rubichi & Pellicano, 2004) and that it involves two independent and parallel response processes (Kornblum et al., 1990). On the one hand, the irrelevant spatial code directly activates the corresponding response. On the other hand, the relevant characteristic of the stimulus (i.e., color) is translated into the correct response according to pre-specified rules (e.g., press the left key on green). When the irrelevant and the relevant response codes differ, a conflict arises and the response code activated by the irrelevant stimulus position has to be aborted before the correct response wins the competition. Therefore, RTs are slower in the non-corresponding trials than in the corresponding trials.

The time course of the Simon effect is often characterized by rank ordering RTs and dividing them into bins (in general five or ten), the first bin containing the fastest RTs and the last bin the slowest. Then, a Simon effect is obtained for each bin by subtracting the mean response time in the corresponding from the non-corresponding trials (Vincentisation procedure, Ratcliff, 1979). According to Hommel (1994), the temporal overlap between response activations will determine how the Simon effect evolves across the response time distribution. The activation of the irrelevant spatial code is supposed to decay over time and to occur earlier than the activation of the instructed response. This temporal relation entails a decreasing Simon effect function: the Simon effect is largest for fast RT-bins and decreases as the automatic activation dissipates in slow RT-bins.

1.1. Visuomotor and cognitive simon effects

Wascher, Schatz, Kuder, and Verleger (2001; see also Wiegand & Wascher, 2005a, 2005b, 2007) agree with dual route models on the existence of automatic activation of the corresponding response and translation of the relevant feature of the stimulus into

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a response code. However, the authors consider these response processes as independent (so they never overlap, but alternate) and their activation depends on the task, in particular on the S–R mapping.

According to the authors, automatic activation occurs only with spatial-anatomical S–R mappings and visual stimuli. A spatial-anatomical S–R mapping refers to the overlap between stimulus and natural hand positions. That is, visual stimuli appear on the left or right, participants respond with the left or right hand, and keep their arms parallel. The resulting Simon effect was referred to as "visuomotor". Electrophysiological studies confirmed the presence of direct and automatic activation in this setting (e.g., see experiment 1 in Wascher et al., 2001): sensory (visual) and motor areas were co-activated about 260 ms after the presentation of the visual stimulus. The early negativity over the contralateral motor cortex (i.e., an early lateralized readiness potential, LRP) subsequent to stimulus presentation indicated that a response toward the irrelevant spatial position was prepared. While this early motor activation continued to grow until movement execution in the corresponding trials, it diminished with time in non-corresponding trials while the correct response was activated. Thus, automatic activation with horizontal visual stimuli facilitates the corresponding response because of spreading activation from visual to motor areas. Visuomotor activation is thought to occur early after stimulus onset but to be short-lived and hence lead to a decaying Simon effect. In sum, there are two signatures of a visuomotor Simon effect: early deflections of the LRP and decreasing Simon effect functions (i.e., the Simon effect decreases in slower RT-bins).

Further electrophysiological recordings showed that in some situations, notably when there is no overlap between the spatial code of a visual stimulus and the spatial–anatomical response code, the automatic activation of the corresponding response is entirely or partially inhibited (e.g., Wascher et al., 2001). This was shown for vertical S–R arrangements (e.g., Vallesi, Mapelli, Schiff, Amodio, & Umilta, 2005; Wiegand & Wascher, 2005a, 2005b), acoustic stimuli, and crossed-hand responses (Wascher et al., 2001). For instance, unlike with horizontal S–R arrangements, LRPs with vertical S–R arrangements showed no early deflection; instead, there was only a delay in response latency (e.g., Vallesi et al., 2005). Further, a stable or increasing Simon effect function was observed (i.e., the Simon effect did not decrease in slower RT-bins), indicating that the irrelevant spatial code needed more time to attain the maximum influence on behavior. Similar results were also obtained with central gaze cues (Ansorge, 2003) and central arrows (Pellicano, Lugli, Baroni, & Nicoletti, in press) that take more time to decode that lateral stimuli. Thus, it was suggested that the Simon effect without spatial–anatomical mapping was exclusively due to the interference between response codes (i.e., a translation problem), without automatic activation. It was there referred to as "cognitive" Simon effect.

1.2. Critique of the distinction between visuomotor and cognitive Simon effects

The idea of distinct mechanisms that are mirrored in the RT distribution was called into question by Roswarski and Proctor (2003). Among other things, the authors based their critique on a paper by Zhang and Kornblum (1997), which showed that analyses of RT-quintiles have to be interpreted with caution since the shape of the effect function can be directly inferred from the variability in the RT distribution. Zhang and Kornblum showed that decreasing effect functions are observed when the variance is larger in corresponding than in non-corresponding trials. One reason for increased variability may be a process that speeds up responses in corresponding trials, but is not present in incongruent trials ("advantage rule" in corresponding trials). Inversely, increasing effect functions result when the variance is larger in non-corresponding than in corresponding trials, possibly because some process that is not present in corresponding trials slows down responses in non-corresponding trials ("disadvantage" rule in non-corresponding trials). Wascher and colleagues (see e.g., Wiegand & Wascher, 2005a) identified the advantage rule with visuomotor priming in corresponding trials ("visuomotor" Simon effect) and the disadvantage rule with interference between response codes in incongruent trials ("cognitive" Simon effect). However, this hypothesis is disputed (see Roswarski & Proctor, 2003).

A further challenge for the model is the prediction that only visuomotor Simon effects result in response priming. Contrary to this prediction, LRPs showed direct and automatic response activation in the SNARC effect (Gevers, Ratinckx, De Baene, & Fias, 2006), while effect functions were stable (i.e., correspondence effects did not change across RT-bins) and thus indicate a "cognitive task" (Gevers, Caessens, & Fias, 2005; Mapelli, Rusconi, & Umiltà, 2003). This result does not support Wascher and colleague's model because it indicates that stable effect functions and significant direct route activation are not mutually exclusive. In contrast, Ridderinkhof's (2002a, 2002b) activation–suppression model interprets effect functions differently and can accommodate the above-mentioned findings. According to the author, different time courses do not imply distinct underlying mechanisms causing the Simon effect (i.e., a categorical distinction). Rather, differences in time courses have to be considered in a more quantitative manner: a decreasing function suggests that strong selective inhibition of the direct activation occurred. As the amount of inhibition decreases, automatic activation will prevail and the effect function will increase.

1.3. Simon effect in response programming

Recently, Buetti and Kerzel (in press) investigated the time course of the Simon effect in pointing movements. We measured the movement angle shortly after movement initiation. Because online corrections occurred only after this measurement, we believe that the initial movement angle (IMA) reflects response programming before movement initiation (Theios, 1975). Small IMAs indicate that participants go directly toward the instructed location. Large IMAs indicate that they initially move toward the wrong location on the opposite side. IMAs were calculated for corresponding and non-corresponding trials and also for each RT-quintile. The latter analysis informed us about the mean initial trajectory deviation as a function of response speed.

When pointing movements were performed without temporal constraint, the Simon effect in IMAs paralleled the Simon effect in RTs. IMAs were larger for non-corresponding than for corresponding trials, showing that pointing movements were attracted by the stimulus. Further, the Simon effect in IMAs was larger for fast RTs than for slow RTs, indicating that the less a response was prepared the more the motor program was biased toward the wrong side. However, the largest initial trajectory bias was not always associated with the fastest RTs (which would suggest a trade-off between RT and movement angle) but was rather associated with the largest amount of response conflict. For instance, when participants knew in advance where to move (by presenting a central imperative stimulus before a lateralized go-signal, see Hommel, 1996), the Simon effect for RTs and IMAs increased with increasing RTs which is a reversal of the typical time course.

The results also showed that IMAs capture some residual response conflict that is not noticeable in RTs. When observers were encouraged to first move and then decide where to go (see Rubichi, Nicoletti, Umiltà, & Zorzi, 2000), no Simon effect was present in RTs. However, a significant Simon effect was observed in IMAs, which was again stronger for fast responses. Because IMAs reflect

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processes preceding movement onset just as RTs do, one may conclude that IMAs are a more sensitive measure of response conflict in some situations.

1.4. Purpose of the study

Buetti and Kerzel (in press) showed that the conflict during response selection affected response programming and that the initial deviation of the trajectory is a useful measure of response conflict which faithfully mirrors the time course of automatic activation. In the present study, analysis of IMAs allows us to test for the presence of direct activation in "cognitive" Simon tasks, by bypassing the statistical concerns raised by Zhang and Kornblum (1997).

We investigated the time course of RTs and IMAs in "visuomotor" and "cognitive" Simon tasks. In experiment 1, we used visual stimuli and compared horizontal and vertical S–R arrangements. In experiment 2, horizontal acoustic stimuli were used. According to the previous studies, we expect a decreasing Simon effect function for RTs with horizontal stimuli in the visual modality and stable or increasing effect functions with vertical visual stimuli and horizontal acoustic stimuli (cf. Vallesi et al., 2005; Wascher et al., 2001; Wiegand & Wascher, 2005a, 2005b). If response programming is governed by the same underlying processes, we expect the same pattern for IMAs. If there was no real independence between "cognitive" and "visuomotor" mechanisms, we would expect the Simon effect for IMAs to decrease with RT-quintiles in all conditions.

2. Experiment 1: visual stimuli in horizontal and vertical S–R arrangements

In the horizontal condition, participants were asked to perform a left- or rightward pointing movement toward a right or left box displayed on a flat panel screen. In the vertical condition, they performed movements toward a box situated above and below the central fixation cross (see Fig. 1). A colored square indicated which box had to be touched. The square appeared in the box specified by its color in corresponding trials and it appeared in the opposite box in non-corresponding trials.

In the pointing condition, referred to as direction selection condition, two temporal parameters (RTs and movement times, MT) and a spatial parameter of the reach (IMA) were recorded. The IMA was coded in degrees and corresponded to the angle between a vector from the home position to the instructed target position and a vector from the home position to the finger position. IMAs were determined after 1/5 of the overall MT (see Fig. 1) which is before online corrections occurred. For instance, an IMA of 0° indicated a movement along the screen surface toward the correct box (and inversely an IMA of 180° showed that the incorrect box was touched). Thus, when the IMA was smaller than 90°, the movement was executed toward the correct direction and when it was larger than 90°, the response was initially executed toward the wrong direction. Participants were instructed to lift the finger from the screen surface, move the hand toward the correct location and touch the box. Sliding along the screen surface (0° or 180°) was considered erroneous.

In the effector selection condition, participants were required to lift either the left- or right-hand index without moving the hand. The hands were horizontally or vertically aligned. In this control condition, only RTs were recorded and the results will tell us whether we were able to replicate the previous studies (e.g., Vallesi et al., 2005; Wiegand & Wascher, 2005a). In sum, participants either selected the finger (effector selection) or the movement direction (direction selection) with vertical or horizontal stimuli.

2.1. Method

2.1.1. Participants

Eighteen psychology students at the University of Geneva participated in the experiment. They were not aware of the purpose of the experiment and had normal or corrected-to-normal vision. All participants were right-handed.

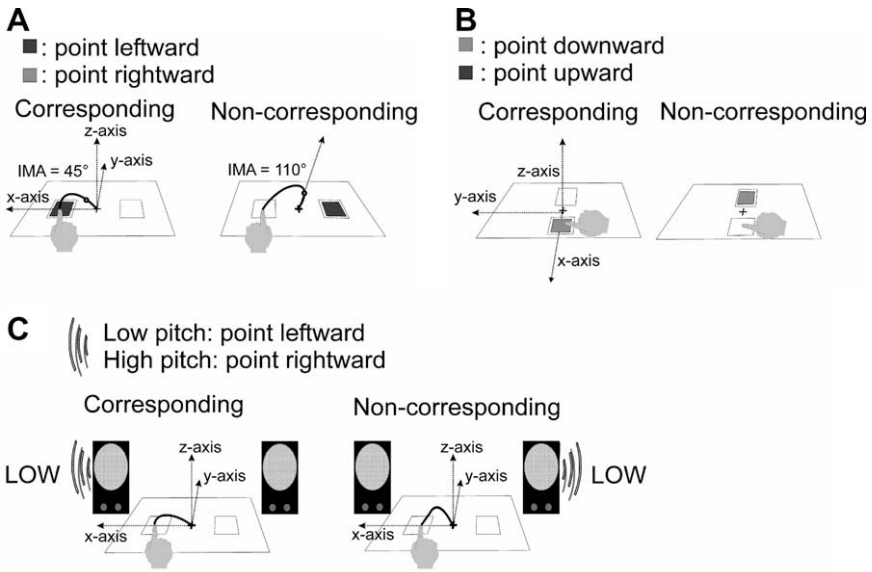

Fig. 1. Side view of the experimental situations for horizontal (panel A) and vertical (panel B) arrangements of experiment 1, and for the acoustic Simon task of experiment 2 (panel C). Only correct responses are illustrated. The initial movement angle was determined by calculating the angle between the position of the hand after 1/5 of the trajectory had been traversed (indicated by open circle, cf. panel A) and the axis running through the correct response location (marked as *x*-axis). In corresponding trials, an angle of zero denotes a straight movement to the location of the imperative stimulus. In non-corresponding trials, an angle of zero denotes a straight movement to the empty box. Subjects were requested to always lift their finger (movement along the *z*-axis), resulting in movement angles larger than zero. The IMAs in panel A would be around 45 and 110° (for the corresponding and non-corresponding condition, respectively).

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2.1.2. Apparatus and stimuli

A flat screen was placed in a frame and attached to the edge of a table. The frame allowed changing the inclination of the screen relative to the table. We chose an angle of about 20° between the screen and the table. Two empty boxes (1.8 × 1.8 cm) were displayed on a grey background and the distance from the fixation cross in the screen centre to the centre of the boxes was about 7.5 cm (either in a horizontal or in a vertical arrangement); the imperative stimulus was a green or red square of about 1.4 × 1.4 cm that was presented in one of the two boxes. An ultrasonic system (CMS20S, zebris Medical GmbH, Isny im Allgäu, Germany) recorded the *X*, Y and *Z* coordinates of manual movements at a sample frequency of 150 Hz by means of a marker positioned on the nail(s) of the finger(s) used to perform the task.

2.1.3. Procedure

The experiment took place in a dimly lit room. Participants were seated at a distance of approximately 40 cm from the flat panel screen. Participants were instructed to respond as fast and as accurately as possible to the color of the square, irrespective of its location.

In the effector selection condition, trials were initiated when both index fingers lay on the screen. For horizontal responses, the left-hand index was placed under the left box and the right-hand index under the right box. For vertical responses, the left-hand index was placed on the left of the lower box and the right-hand index on the right of the upper box. This arrangement replicates Vallesi et al. (2005). Participants responded by lifting either the left- or the right-hand index.

In the direction selection condition, the screen was touched with the right index finger only. A trial was initiated by placing the index on the fixation cross. Participants were instructed to lift the finger from the screen surface, move the hand toward the correct location (in the horizontal and vertical axis) and touch the box with their index.

After a trial was initiated, the two outline boxes changed luminance from grey to black. After a random interval between 0.3 and 1.3 s, a colored square appeared inside one of the boxes. After 1.5 s, the colored square vanished and the outline boxes turned bright grey again to signal that a new trial could be initiated.

Latencies shorter than 100 ms and longer than 800 ms were considered anticipations and missed trials, respectively. In the effector selection condition, choice errors were trials in which the wrong index finger was lifted. In the direction selection condition, choice errors were trials in which the wrong box was touched. Hand movements with continuous contact to the screen were considered erroneous. Finally, loss of the ultrasonic signal was detected. Error feedback about anticipations, missed trials, choice errors, movement errors, and marker failures was given and the respective trial was repeated in the remainder of the experiment.

2.1.4. Design

Participants performed in two sessions separated by about one week. In the first session, half of the participants performed the horizontal task and the other half the vertical task. In the second session, the alternative spatial arrangement was presented. For each axis, the different response modes were blocked and each block was preceded by about 10 practice trials. In each block, the four possible combinations of two square locations and two square colors (or response locations) were repeated 50 times for a total of 200 trials per response mode. The order of response mode ("effector selection" vs. "direction selection") and the color-response mapping was balanced across subjects.

2.1.5. Dependent variables and offline analyses

Several dependent variables were calculated online or offline. First, we determined the time between the onset of the colored square and the onset of the movement (RT). Movement onset was defined as the first sample exceeding a velocity of 50 mm/s with the constraint that the velocity stayed above this value for at least 100 ms. Second, the angle between the screen and the finger after 1/5 of the total movement time was determined (initial movement angle, see above). Third, movement time (MT) was defined as the interval between movement onset and the final contact of the finger with the screen. A position criterion (i.e., a distance of 4 mm to the screen surface) was used to determine the time when participants touched down on the peripheral box. Across conditions, mean MTs ranged between 210 and 250 ms. Analyses of MTs and correlations between RTs, MTs, and IMAs are not presented here because they replicated the previous results (Buetti & Kerzel, in press) and are not central to the present study. Briefly, the Simon effect in MTs increased with MT-quintile because long MTs were associated with strong deviations toward the irrelevant stimulus. Further, participants traded RT for MT: in non-corresponding trials, fast RTs were followed by long MTs. However, the correlation between RT and MT was generally weak. We also calculated the ratio of RT over MT which indicates whether the movement was well prepared (long RT/short MT) or quickly initiated (short RT/long MT). The correlation of the RT/MT ratio with the IMA in non-corresponding trials was generally substantial, indicating that poorly prepared movements went toward the irrelevant stimulus.

2.2. Results

Anticipations, missed trials, and trials containing ultrasonic signal disruptions were excluded from the analyses, and choice errors were analysed separately (see Table 1). Mean RTs were calculated for corresponding and non-corresponding trials (see Table 1).

To obtain the five quintiles, RTs were rank ordered separately for each participant and condition. Then, the observations were divided into five bins, so that each quintile contained 20% of the observations. The first quintile was composed of the fastest and the fifth of the slowest responses. Further, mean IMAs were calculated for each RT bin. Like Wascher et al. (2001) and Wiegand and Wascher (2005a) we excluded the last quintile from analysis. The main effect of quintile will be mentioned in the results section but is considered trivial because it reflects the rank ordering of the trials. In cases where the assumption of sphericity was vio-

Table 1
Mean reaction time (RT, in ms), between-subject standard error (SE, in parenthesis), percentage of choice error (PE), percentage of excluded trials (PX), and difference (Δ) between corresponding (C) and non-corresponding (NC) means, for the different axis (horizontal or vertical) for experiment 1 and 2

	Mean RT (SE)			PE	PX
	C	NC	Δ		
Experiment 1	*Horizontal visual stimuli*				
Effector	381 (7)	406 (10)	25 (7)**	3	3
Direction	382 (11)	406 (11)	24 (7)*	2	4
Experiment 1	*Vertical visual stimuli*				
Effector	376 (8)	428 (8)	52 (5)***	4	4
Direction	387 (12)	426 (14)	40 (7)***	3	2
Experiment 2	*Horizontal acoustic stimuli*				
Effector	389 (9)	440 (8)	50 (4)***	5	9
Direction	356 (14)	397 (15)	41 (4)***	3	5

Participants were either instructed to select one of two fingers (effector) or the direction of a pointing movement (direction).
Note: P-values significant at the .05, .01, and .001-level are indicated by one (∗), two (∗∗) and three (∗∗∗) asterisks.

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lated, degrees of freedom were corrected using Huynh–Feldt's correction. For follow-up analysis, paired-samples *t*-tests were conducted and only the *p*-values are reported.

2.2.1. Errors

The ANOVA (response mode × axis × correspondence) on the mean error rate showed a larger error rate for effector than for direction selection (4% vs. 3%, respectively), $F(1,17) = 5.97$, $p < .05$. The error rate was also larger with vertical than with horizontal stimuli (4% vs. 3%, respectively), $F(1,17) = 13.15$, $p < .01$, as well as in non-corresponding than in corresponding trials (4% vs. 2%, respectively), $F(1,17) = 18.62$, $p < .001$. Finally, the interaction between axis and correspondence was significant, indicating that the difference between the error rate in non-corresponding and corresponding trials was larger for vertical than for horizontal stimuli (2% vs. 1%, respectively), $F(1,17) = 15.30$, $p < .01$.

2.2.2. RTs

Mean RTs are shown in Table 1 and the mean Simon effect in RTs is shown in the top row of Fig. 2. A four-factorial ANOVA (response mode × axis × correspondence × quintiles) performed on RTs showed no difference in latencies between effector and direction selection (398 vs. 400 ms), $F(1,17) = 0.1$, $p = .76$. Horizontal responses were faster than vertical responses (393 vs. 404 ms), $F(1,17) = 15.72$, $p < .005$. Corresponding trials were faster than non-corresponding trials (381 vs. 416 ms), $F(1,17) = 51.17$, $p < .001$. As expected, there was a main effect of quintile $F(3,51) = 690.74$, $p < .001$. The significant interaction between axis and correspondence, $F(1,17) = 34.34$, $p < .001$, showed that the Simon effect was larger for the vertical than for the horizontal axis (46 vs. 25 ms, respectively). The significant interaction between response mode, correspondence and quintiles, $F(3,51) = 6.13$, $p < .01$, indicated that when data of both axes were averaged, the time course of the Simon effect differed as a function of response mode. In the effector selection condition, the Simon effect decreased with increasing quintile (46, 41, 36, and 30 ms from the 1st to the 4th quintile), while it remained rather constant in the direction selection condition (31, 34, 33, and 29 ms from the 1st to the 4th quintile). The interaction of correspondence and quintiles approached significance, $F(3,51) = 3.47$, $p = .07$, showing that overall, the Simon effect tended to decrease with increasing RT. Importantly, the interaction between axis, correspondence and quintiles, $F(3,51) = 15.85$, $p < .001$, was significant, showing that the Simon effect decreased with quintiles for the horizontal axis and was unchanged for the vertical axis. This interaction was not further qualified by response mode, as evident in the non-significant interaction between response mode, axis, correspondence, and quintiles, $F(3,51) = 0.55$, $p = .52$.

To further confirm the modulation of the time course by the spatial axis, we ran separate ANOVAs for each response mode and focused on the interaction between axis, correspondence, and quintiles. A three-way ANOVA (axis × correspondence × quintiles) on RTs in the effector selection condition confirmed a significant interaction between axis, correspondence and quintiles, $F(3,51) = 10.67$, $p < .001$, showing that the Simon effect was stable across quintiles for vertical stimuli, while it decreased for horizontal stimuli [two-way ANOVA (correspondence × quintiles) on the net Simon effect; vertical: $F(3,51) = 0.29$, $p = .67$; horizontal: $F(3,51) = 14.28$, $p < .001$]. For the direction selection condition, the interaction between axis, correspondence, and quintiles was also significant, $F(3,51) = 3.92$, $p < .05$, showing that the Simon effect decreased across quintiles with horizontal stimuli, but it was stable with vertical stimuli [two-way ANOVA (correspondence × quintiles); horizontal: $F(3,51) = 4.09$, $p < .05$; vertical: $F(3,51) = 0.1$, $p = .35$].

2.2.3. IMAs grouped by RT-quintiles

Mean IMAs of the direction selection condition are shown in Table 2 and the mean Simon effect in IMAs for each RT-quintile is shown in the bottom row of Fig. 2. For the horizontal and vertical axis, histograms for corresponding and non-corresponding conditions as a function of RT-quintile are shown in Fig. 3. Inspection of Fig. 3 shows a bimodal distribution of the IMAs that prevailed particularly in the first non-corresponding RT-quintile. While it is clear that a single mean does not capture the central tendencies

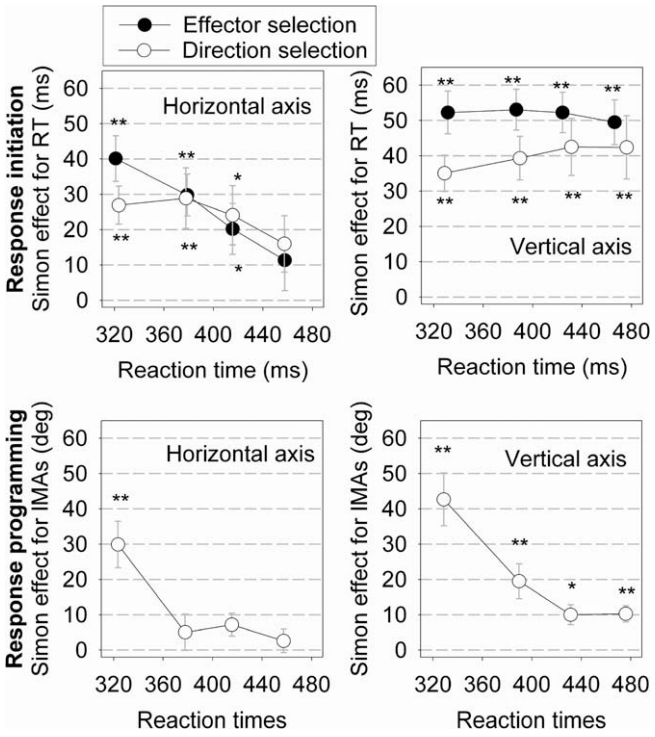

Fig. 2. Results of experiment 1. In the first row, the Simon effect for RTs (ms) is shown for the horizontal and vertical stimuli as a function of response mode and RT-quintile. In the second row, the Simon effect for response programming parameters of the direction selection condition is shown. The left and right panels show the Simon effect in IMAs (°) as a function of RT-quintile and axis for horizontal and vertical arrangements, respectively. *p*-values of .01 and .001-level are indicated by one (∗) and two (∗∗) asterisks, respectively. Non-significant *p*-values are not indicated (Bonferroni correction: significant *p*-value < .0125).

Table 2
Mean initial movement angle (IMA, in degrees) and between-subject standard error (SE, in parenthesis) in corresponding (C) and non-corresponding (NC) trials for horizontal and vertical arrangements of experiment 1 and 2

	Mean IMA (SE)			Mean IMA < 100 (SE)		
	C	NC	Δ	C	NC	Δ
Experiment 1	*Horizontal visual stimuli*					
Direction	47 (4)	58 (4)	11 (3)**	36 (3)	39 (3)	3 (1)*
Experiment 1	*Vertical visual stimuli*					
Direction	40 (3)	61 (4)	21 (3)***	35 (3)	39 (3)	4 (1)***
Experiment 2	*Horizontal acoustic stimuli*					
Direction	36 (2)	52 (4)	15 (3)***	34 (2)	38 (2)	4 (1)***

Results of the direction selection condition are shown. The difference between corresponding and non-corresponding trials is indicated by the symbol Δ. The angles were calculated for all correct trials (in which the correct box was touched). In case of a bimodal distribution of IMAs, mean IMAs were additionally calculated for only those trials in which the initial movement was toward the correct box (IMAs < 100 degrees).
Note. P-values significant at the .05, .01, and .001-level are indicated by one (∗), two (∗∗) and three (∗∗∗) asterisks.

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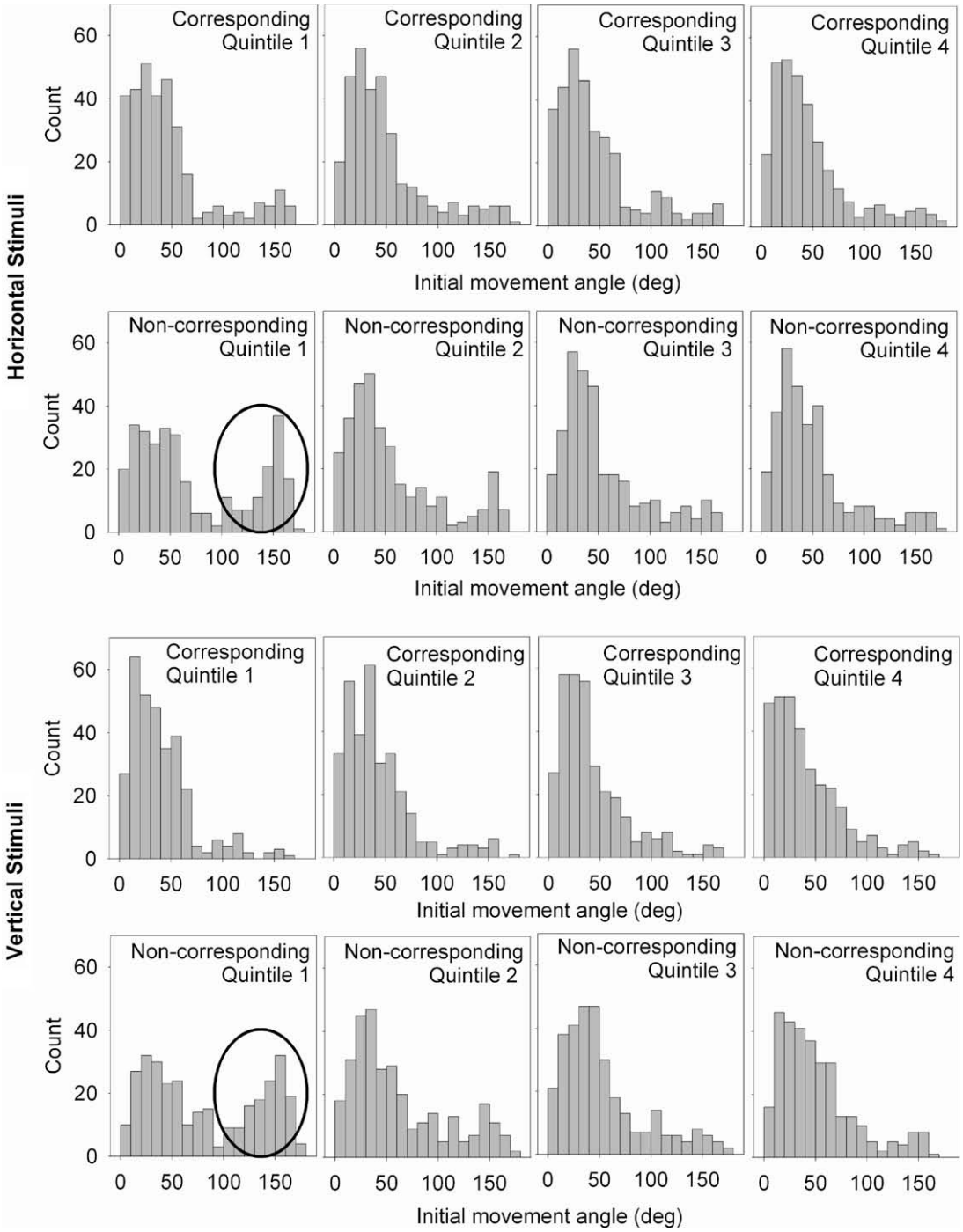

Fig. 3. Results of the direction selection condition of experiment 1. Histograms illustrate the initial movement angle as a function of correspondence and RT-quintile for horizontal (top panel) and vertical stimuli (bottom panel) from the first to the fourth quintile. Bimodal distributions, where the second peak indicates responses toward the imperative stimulus, are indicated by an ellipse.

of two sub-distributions, we nonetheless chose to run our ANOVAs on the mean of the complete distribution. We expect these means to be strongly biased toward the smaller distribution. The ANOVA allowed us to test the reliability of this pattern.

A three-factorial ANOVA (axis × correspondence × RT-quintiles) showed that IMAs did not differ between horizontal and vertical axes (52° vs. 51°), $F(1,17) = 0.31$, $p = .59$. IMAs were larger for non-corresponding than for corresponding trials (59° vs. 44°), $F(1,17) = 28.66$, $p < .001$. There also was a main effect of RT-quintile, $F(3,51) = 11.04$, $p < .001$, and an interaction between correspondence and RT-quintile, $F(3,51) = 18.91$, $p < 001$, showing that the Simon effect for IMAs decreased with increasing RTs (36°, 12°, 9°, 6°). The interaction between correspondence and RT-quintiles was not further qualified by axis, $F(3,51) = 0.98$, $p = .40$. The Simon effect in IMAs was larger for vertical than for horizontal responses (21° vs. 11°), $F(1,17) = 17.19$, $p < .001$. To rule out that the Simon effect in IMAs was due only to misdirected responses toward the wrong location in the fastest RT-quintile (see Fig. 3), we ran the same ANOVA after exclusion of IMAs larger than 100° (see Table 2). Results showed that IMAs were still larger for non-corresponding than corresponding trials (39° vs. 35°), $F(1,17) = 25.46$, $p < .001$, but the Simon effect for IMAs lower than 100°

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neither differed between axes, $F(1,17) = 3.14$, $p = .09$, nor changed with RT-quintiles, $F(3,51) = 0.50$, $p = .68$.

2.3. Discussion

Experiment 1 showed that for movement initiation (i.e., RT), the time course of the Simon effect with horizontal and vertical stimuli was the same for key-press responses and pointing movements. In both cases, the Simon effect decreased with increasing RT for horizontal S–R arrangements and remained stable for vertical S–R arrangements. Results also showed that the response conflict was stronger for vertical S–R arrangements. The Simon effect was almost twice as large in the vertical compared to the horizontal condition (46 vs. 25 ms and 2% vs. 1% errors, respectively). Also, RTs were longer and errors were more frequent with vertical than horizontal stimuli (404 vs. 393 ms and 4% vs. 3%, respectively). In contrast to the present experiment, the size of vertical and horizontal Simon effects was found to be equivalent in the previous studies (Vallesi et al., 2005; Wiegand & Wascher, 2005a). We do not have a good explanation for this discrepancy.

The mean IMA did not differ between axes, indicating that despite different biomechanical constraints, the initial segment of the trajectory was comparable. A Simon effect was confirmed for both axes. This indicates a tendency to initially deviate toward the irrelevant stimulus location, in particular for fast RTs. The Simon effect for IMAs was larger for vertical than for horizontal S–R relations (21° vs. 11°), mirroring the RT data. In contrast to the time course of the Simon effect in RTs, however, the Simon effect in IMAs decreased with increasing RT-quintiles along both axes. That is, despite a stable Simon effect function for vertical responses in RTs, the Simon effect in IMAs decreased with increasing RTs. This finding suggests that the time course of the Simon effect in IMAs dissociates from the Simon effect in RTs.

Possibly, the distinction between "visuomotor" and "cognitive" mechanisms explains the different time courses in RTs for horizontal and vertical S–R arrangements. However, a challenge for this account is the highly similar time course of IMAs. For vertical and horizontal arrangements, the influence of irrelevant information on IMAs decreased with increasing RT.

3. Experiment 2: acoustic stimuli in a horizontal S–R arrangement

Wascher et al. (2001) showed that an increasing Simon effect function was observed for acoustic stimuli presented along the horizontal axis. Further, LRPs showed no bias toward the irrelevant location for incongruent trials, suggesting inhibitory top-down control of visuomotor activation. Those results indicate that the Simon effect with acoustic stimuli was due to "cognitive" mechanisms. Here, we investigated whether the time course of the Simon effect in response programming would follow the increasing/stable function as in RT data or the same decreasing function as in experiment 1.

3.1. Method

3.1.1. Participants

Sixteen psychology students from the same pool as in experiment 1 participated. Three participants were left-handed, the remaining participants were right-handed.

3.1.2. Apparatus, stimuli, and procedure

Apparatus, stimuli and procedure were as in experiment 1 with the following exceptions. The imperative stimulus was a low (100 Hz) or high (1000 Hz) pitch sine-wave tone that was presented for 200 ms by one of two loudspeakers placed 8 cm to the right and left of the screen (see Fig. 1). Participants were instructed to respond as fast and as accurately as possible to the pitch of the tone irrespective of its origin (left or right loudspeaker). In the effector selection condition, only the right hand was placed on the screen. The hand position was adjusted such that the fixation cross was visible in-between the index and middle fingers. A trial was initiated by pressing the space bar of a keyboard with the left hand. Participants responded by lifting either the index or the middle finger of the right hand. This replicates Buetti and Kerzel's (in press) procedure, in which a decreasing Simon effect was observed when visual stimuli were presented along the horizontal axis. In the direction selection condition, the screen was touched with the right index finger only. A trial was initiated by placing the index on the fixation cross. Participants were instructed to lift the hand, move to one of the two boxes and touch the box with their index.

3.1.3. Design

The same design as for experiment 1 was used with the exception that the imperative stimulus was the pitch of the tone and that only horizontal movements were required.

3.2. Results

Anticipations, missed trials, and trials containing ultrasonic signal disruptions were excluded from the analyses, and choice errors were analysed separately (see Table 1). Trials were coded as corresponding when the sound location corresponded to the response direction or location, and as non-corresponding when this was not the case. Mean RTs were calculated for corresponding and non-corresponding trials (see Table 1).

3.2.1. Errors

The ANOVA (response mode × correspondence) on the mean error showed more errors for effector than for direction selection (6% vs. 3%, respectively), $F(1,15) = 5.39$, $p < .05$, and for non-corresponding than for corresponding trials (5% vs. 3%, respectively), $F(1,15) = 35.44$, $p < .001$. The significant interaction between response mode and correspondence, $F(1,15) = 4.57$, $p < .05$, showed that the Simon effect was larger in the effector than in the direction selection condition (3% vs. 1%, respectively).

3.2.2. RTs

A three-factorial ANOVA (response mode × correspondence × quintiles) performed on RTs showed that responses were slower in the effector selection than in the direction selection condition (415 vs. 377 ms), $F(1,15) = 7.44$, $p < .05$. RTs were faster in corresponding than in non-corresponding trials (372 vs. 418 ms), $F(1,15) = 324.58$, $p < .001$. As expected, the main effect of quintile was significant, $F(3,45) = 711.16$, $p < .001$. Neither the two-way interactions ($ps > .2$), nor the triple interaction between response mode, correspondence, and quintiles reached significance, $F(3,45) = 0.95$, $p = .42$, indicating that the Simon effect remained unchanged across quintiles for both effector selection and direction selection (see Fig. 4).

3.2.3. IMAs grouped by RT-quintiles

Histograms for corresponding and non-corresponding trials as a function of each RT-quintile confirmed a bimodal distribution in the fast non-corresponding RT-quintiles similar to experiment 1 (data not shown).

A two-way ANOVA (correspondence × RT-quintiles) on IMAs of the direction selection condition showed that IMAs were larger in non-corresponding than in corresponding trials (51 vs. 37°), $F(1,15) = 35.03$, $p < .001$. There also was a main effect of RT-quintile, $F(3,45) = 4.32$, $p < .05$. Finally, the interaction between correspon-

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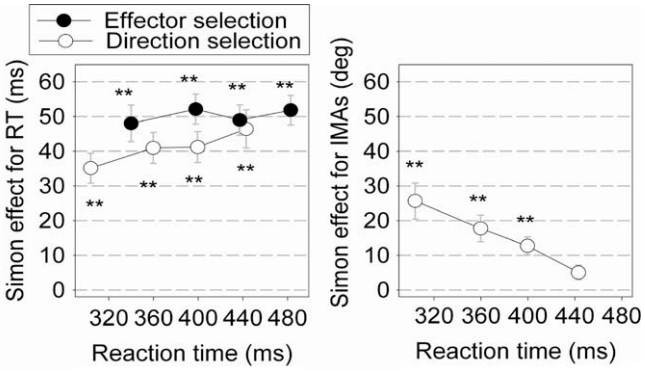

Fig. 4. Simon effect as a function of RT-quintiles and IMAs grouped by RT-quintiles for each response mode of experiment 2. *p*-values of .01 and .001-level are indicated by one (∗) and two (∗∗), respectively. Non-significant *p*-values are not indicated (Bonferroni correction: significant *p*-value < .0125).

dence and RT-quintiles was significant, $F(3,45) = 8.71$, $p < .001$, showing a decreasing Simon effect with increasing RT-quintile (see Fig. 4). The same ANOVA performed on IMAs smaller than 100° showed that IMAs still differed between corresponding and non-corresponding trials (34 vs. 38°), $F(1,15) = 24.43$, $p < .001$, but the Simon effect for IMAs smaller than 100° did not vary with RT-quintiles, $F(3,45) = 0.59$, $p = .62$ (see Table 2).

3.3. Discussion

For movement initiation, RTs were slower with effector than with direction selection. However, the size of the Simon effect did not differ between response modes and the shape of the Simon effect function was similar. For both response modes, the Simon effect was unchanged across RT-quintiles. Results for response programming (i.e., IMAs) were similar to experiment 1. The trajectory deviations were stronger for fast responses, indicating decaying visuomotor activation.

4. General discussion

Several studies suggested that the Simon effect is not a homogeneous phenomenon and that depending on the task requirements, different mechanisms resolve the response conflict (e.g., Wascher et al., 2001; Wiegand & Wascher, 2007): when there is an overlap between the spatial code of the stimulus and the anatomical response code, the Simon effect is caused by the automatic activation of the corresponding response (cf. visuomotor Simon effect). When there is no such direct overlap (for instance, with acoustic stimuli, with crossed-hand responses or in a vertical Simon task), the Simon effect arises from a translation problem (cf. cognitive Simon effect). According to Wascher and colleagues, the presence or absence of direct activation is indexed by the time course of the Simon effect (decreasing vs. stable/increasing, respectively).

The aim of the present study was to characterize the time course of the Simon effect in RTs ("when") by parameters of movement programming ("how"). Therefore, we calculated IMAs for each RT-quintile and wondered whether IMAs would follow the same time course as RTs. The obvious advantage of looking at IMAs is that they are not plagued by the statistical concerns raised by Zhang and Kornblum (1997): as IMAs were not vincentised, but grouped on the basis of RT-vincentisation, differences in the variability of IMAs between corresponding and non-corresponding trials should not matter.

The time course of the Simon effect in IMAs does not support the existence of distinct visuomotor and cognitive Simon effects. The Simon effect in IMAs decreased with increasing RTs for horizontal visual, vertical visual, and horizontal acoustic stimuli. In all conditions, trajectory deviations were particularly large for fast responses. This may be taken as evidence for direct motor activation: consistent with Simon's, 1969 notion of reflex-like orienting toward the source of stimulation, pointing movements are attracted by the sudden onset. In this context, direct visuomotor activation may mean that the stimulus has access to highly overlearned response patterns, such as hitting or intercepting an object (i.e., goal-directed actions). As time passes, the automatic activation is inhibited (see also, Welsh & Elliott, 2004) which can also be observed when looking at trials following a non-corresponding stimulus (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002).

There are other aspects of Wascher et al.'s (e.g., Wascher et al., 2001; Wiegand & Wascher, 2005a) model that are incompatible with the present results. In our pointing task, only the right hand was used and the movements always started at the centre of the screen. Therefore, it is unlikely that the Simon effect in RTs with pointing movements and horizontal stimuli was due to spatio-anatomical activation of the effector (because left and right stimuli were both mapped onto the right hand). Nonetheless, we observed a decreasing Simon effect function. Further, Buhlmann, Umiltà, and Wascher (2007) recently showed that increasing (supposedly cognitive) Simon effect functions occurred when the effector location was separated from the horizontally aligned goal of the response: participants pressed a remote button with a stick. Our pointing task is similar to this situation because the initial position of the hand was separate from the action goal. Nonetheless, we obtained decreasing effect functions similar to those obtained with spatio-anatomical congruency between the stimulus and the hand.

Despite the apparent difficulty of integrating our results in the categorical distinction between visuomotor and cognitive Simon effects, there is an avenue for doing so. Previous LRP studies showed that the activation of the spatial code is quickly inhibited when more cognitive processes are required (Vallesi et al., 2005; Wascher et al., 2001; Wiegand & Wascher,2005a, 2005b). The idea of rapidly inhibited activation may account for the dissociation between RTs and IMAs if one assumes that response selection and motor programming have different thresholds for stimulus-driven activation. In particular, even if the spatial code is rapidly inhibited, its partial activation may still be integrated in the initial motor plan. Buetti and Kerzel (in press) showed that response programming (IMAs) could be affected by residual response conflict without visible effects on response selection (RTs). The reason for lower thresholds in response programming may be explained as follows. For well-prepared responses, the abstract response is selected before the parameters of the response are determined (Theios, 1975). For fast RTs, however, response selection may not always be completed which results in a temporal overlap between response selection and programming (Ghez, Hening, & Favilla, 1989; van Sonderen & Denier van der Gon, 1991). Given that the motor system sometimes starts a response before the appropriate response is entirely selected, it may be that the initial rough motor plan integrates even some short-lived activation. As a consequence, responses are programmed toward the source of stimulation (see Buetti & Kerzel, in press; Simon, 1969), irrespective of whether the stimulus arrangement is mapped onto the spatio-anatomical response (as with horizontal responses) or not (as with vertical responses). Thus, fast responses with incomplete response selection are biased toward the stimulus. Later on, the initial activation is inhibited. In some cases, inhibition may be strong enough to produce trajectory deviations away from the stimulus (Welsh & Elliott, 2004).

Further, different neural substrate may also contribute to the dissociation between RTs and IMAs. Event-related potentials showed that the fronto-parietal network was involved in the directional coding of the target into motor output (Berndt, Franz,

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Bülthoff, & Wascher, 2002). In contrast, LRPs recorded over the motor cortex did not vary with movement direction, but only indicated which hand was programmed to do the pointing. Thus, it could be that the Simon effect in IMAs was more related to the fronto-parietal activation.

In sum, our study investigated the time course of RTs and movement parameters in "visuomotor" and "cognitive" Simon tasks. For horizontal stimuli, the Simon effect in RTs was larger for fast RTs than for slow RTs (decreasing Simon effect function). Consistent with the previous research, no such time course was observed with vertical and acoustic stimuli. Importantly, the Simon effect in the initial movement angle showed an invariant time course across visuomotor and cognitive tasks: movement trajectories deviated more toward the stimulus with fast RTs than with slow RTs. Taken together, these findings may be most parsimoniously explained by a single underlying mechanism. However, it is not impossible to integrate our findings into accounts claiming multiple mechanisms involved in the Simon effect.

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