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Is direction position? Position- and direction-based correspondence effects in tasks with moving stimuli

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Five experiments were carried out to test whether (task-irrelevant) motion information provided by a stimulus changing its position over time would affect manual left–right responses. So far, some studies reported direction-based Simon effects whereas others did not. In Experiment 1a, a reliable direction-based effect occurred, which was not modulated by the response mode—that is, by whether participants responded by pressing one of two keys or more dynamically by moving a stylus in a certain direction. Experiments 1a, 1b, and 2 lend support to the idea that observers use the starting position of target motion as a reference for spatial coding. That is, observers might process object motion as a shift of position relative to the starting position and not as directional information. The dominance of relative position coding could also be shown in Experiment 3, in which relative position was pitted against motion direction by presenting a static and dynamic stimulus at the same time. Additionally, we explored the role of eye movements in stimulus–response compatibility and showed in Experiments 1b and 3a that the execution or preparation of saccadic eye movements—as proposed by an attention-shifting account—is not necessary for a Simon effect to occur.

Insights into the question of how stimulus properties influence the selection and initiation of a response are provided by research on stimulus–response compatibility (SRC). SRC was first described by Fitts and Seeger (1953) and refers to the finding that reaction time (RT) and accuracy are a function of the mapping between stimuli and responses. A large body of empirical work has focused on the spatial relation between stimuli and responses. The major finding was that RTs are faster when the spatial arrangement of the response keys corresponds to

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the spatial arrangement of the stimuli to be responded to. For example, when participants press a left key in response to a left stimulus and a right key in response to a right stimulus, responses are faster and more accurate than with the opposite stimulus–response mapping (i.e., left key-presses in response to a right stimulus and right key-presses in response to a left stimulus). It is important to note that the spatial features of the stimulus are response relevant in research on stimulus–response compatibility proper.

The Simon effect

However, effects of stimulus–response congruity even occur when the spatial attributes of the stimulus are completely irrelevant for the task. These effects have come to be known as the (spatial) Simon effect (Simon, 1969; Simon & Rudell, 1967). In a typical Simon task, participants have to select one of two responses on the basis of a nonspatial stimulus feature (e.g., colour or shape), which is mapped onto a spatially defined response (e.g., a left or right key press). For instance, the stimuli may appear randomly on the left or right side of the display, and observers have to respond to the colour by pressing a left or right key. The typical finding is that observers are unable to ignore the location of the stimulus. They respond faster when the location of the stimulus corresponds to the response location than when it does not. The Simon effect is a stable phenomenon and has been described for different types of stimuli and in different modalities (for an overview, see Lu & Proctor, 1995; Simon, 1990).

Accounts of compatibility and correspondence effects

In the literature, effects of spatial compatibility (SRC effects) and correspondence (Simon effects) are most often attributed to processes of response selection. For instance, it was demonstrated by Eimer (1995) that the perception of a directional cue automatically activates the corresponding response. By using lateralized readiness potentials (LRP) as an index of covert response preparation, the author showed that responses corresponding to the pointing direction of a centrally presented arrow were automatically activated immediately after stimulus onset (cf. also De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995, for an overview).

Meanwhile, the most-cited account explaining the process of how the stimulus location (task relevant or irrelevant) affects response selection is the two-route model based on a seminal paper by Kornblum, Hasbroucq, and Osman (1990). The authors assume that there is a fast automatic route, which primes the corresponding response, and a slower response route, which is intentionally guided. To account for the Simon effect, it is assumed that the correct response, specified by the task instruction, is being actively selected or identified by the observer while the response corresponding to the irrelevant spatial location is automatically activated. When the automatically activated response corresponds to the intentionally selected response, fast responses result. Otherwise, the conflict between response codes leads to slow responses.

Additionally, the model postulates that automatic response priming is a function of the similarity or dimensional overlap between stimulus and response. That is, compatibility or correspondence effects arise to the extent that stimulus and response sets share features.

Similarity between stimulus and response features is defined not only by its physical properties, but also by conceptual similarity, which is assumed to be more critical for SRC or correspondence effects (e.g., Kornblum, 1991; Kornblum & Lee, 1995; Prinz, 1990, 1997; Proctor, Wang, & Vu, 2002; Wallace, 1971). Certainly, the dimensional overlap model describes how a (represented) stimulus position can affect response latency and accuracy, but nothing is said about how the spatial code is generated in a given situation.

Accounts of spatial code formation

Two accounts attempt to explain how and when the response-critical spatial code is formed. The attention-shifting account (e.g., Nicoletti & Umiltà, 1994; Stoffer, 1991; Umiltà, & Nicoletti, 1990) states that shifting attention to the target location leads to the corresponding spatial coding. For instance, a shift of attention from a central fixation mark to a target presented on the right would produce a "RIGHT" spatial code. If attention was focused to the right of the target location, however, the shift to the left would produce a "LEFT" spatial code, irrespective of the target position relative to the fixation mark. In contrast, the referential coding account denies a functional role of attention. Instead, referential coding holds that the location of the stimulus is coded in terms of the relative position with respect to a reference object or frame (Hommel, 1993; for an overview of both accounts see, e.g., Lu & Proctor, 1995; Stoffer & Umiltà, 1997). For instance, a stimulus that is presented to the right of a fixation point is related to the position of the fixation point and therefore automatically evokes a spatial code "RIGHT". There is empirical evidence for both accounts, and, presently, one cannot make a clear decision for one or the other theory. No matter whether spatial coding is a function of attention shifting or not, there is a lot of evidence that spatial coding operates in a relational manner. That is, the way a stimulus is coded as left or right depends on a second stimulus in the display (e.g., Nicoletti & Umiltà, 1989; Umiltà & Liotti, 1987), the perception of the fixation point (Lamberts, Tavernier, & d'Ydewalle, 1992), and the visual context (e.g., Hommel & Lippa, 1995).

Dynamic compatibility

SRC and Simon effects have been mostly studied in static situations, but a few studies also examined dynamic situations. In this context, Michaels (1988) was the first to extend prior work to a situation involving both dynamic stimuli and dynamic responses (see also Michaels, 1993; Proctor, Van Zandt, Lu, & Weeks, 1993). In her study, participants were confronted with two squares placed on the left or right side of a computer screen and two joysticks placed on the left or right side of the body midline. At a time 500 ms after the stimulus onset, one of the squares changed its horizontal position and expanded. The simultaneous displacement and expansion of the stimulus led to the impression that the stimulus moved either to the response location on the same side or to the response location on the opposite side. In one condition participants were instructed to respond to the *origin* of apparent motion, in another condition to its *destination* by pushing a joystick forward. Michaels found that when participants responded to the origin of the apparent motion (e.g., left), spatially corresponding responses (e.g., left) were faster. However, when participants responded to the destination, responses were faster when the stimulus appeared to move toward the side of the responding hand, even when the stimulus location did not correspond to the response location. For instance, right responses were faster when a stimulus moved from a left origin to a right destination—even when it was on the left side of the screen. Proctor et al. (1993) extended Michael's findings by demonstrating that destination compatibility effects occurred with key presses (i.e., a "stationary" response) as well.

Michaels (1988) and Proctor et al. (1993) used apparent motion in their experiments. In contrast, Ehrenstein (1994) used stimuli that moved smoothly and looked more like natural object motion. However, he did not find a Simon effect to the direction of motion in his Experiment 2. The author argued that the smooth motion of the stimulus did not capture attention because smooth stimulus motion is not an effective stimulus for the saccadic eye movement system. In contrast, abrupt displacements of a stimulus involuntarily attract attention (Posner, 1980) and also stimulate the saccadic eye movement system because shifts of attention typically precede eye movements (cf. Rizzolatti, Riggio, Dascola, & Umiltà, 1987). Thus, the absence of the Simon effect with smooth motion was interpreted as supporting the attention-shifting account of the Simon effect. However, Kerzel, Hommel, and Bekkering (2001) showed that the Simon effect does not depend on the preparation of saccadic eye movements or attention shifts: In their study a reliable Simon effect occurred to the direction of illusory motion of a stationary target induced by smoothly moving a large frame surrounding the target.

To sum up, previous studies on dynamic compatibility seem to suggest that dynamic stimuli are not qualitatively different from static stimuli. The perception of both static and dynamic stimulus features is able to activate a corresponding response. Note that this interpretation claims that a feature of the moving stimulus (i.e., its direction of motion) shares behavioural effects with a feature of a static stimulus (i.e., its relative position).

Relative position coding of moving objects

We suggest that the reason that previously reported correspondence effects for motion direction behave similarly to the much better investigated (relative) position-based correspondence effects is not the dynamic aspects of the stimulus, but rather concomitant static features (i.e., relative position). Thus, the primary purpose of the present study was to investigate how the notion of relative position coding may be applied to dynamic situations. Motion information provided by a moving object may convey position information because it involves continuous displacement of the object (i.e., a change of relative position) as well as directional information (i.e., motion information) per se. In other words, it may be that observers code motion information as relative position information or as directional information. In a situation in which an object moves away from a given starting position (i.e., to the left), the positions of the stimulus would always be displaced relative to previously occupied positions (i.e., left of), most notably the starting position. Thus, it is not motion information per se that may have been coded, but the current position of the target relative to the starting position.

The experimental protocols in previous studies on dynamic compatibility are in line with such an account. All of the published studies on dynamic compatibility used motion information that involved a displacement of the spatial position of an object over time.

Therefore, the current position of a moving stimulus could be related to previous positions of the stimulus. In particular, previous studies stressed the initial position of the target because it was presented for a rather long time. For instance, the starting position of the moving target was shown for 500ms in Michaels' (1988) and Proctor et al.'s (1993) study. It may be that the long exposure of the initial position and the resulting relative coding of subsequent target positions may be a necessary condition for direction-based Simon effects: When Ehrenstein (1994, Exp. 2, Condition A) presented a moving object that appeared on the screen and immediately moved in a certain direction, he found no Simon effect to the direction of target motion. It seems plausible that the coincidence of stimulus and motion onset prevented usage of the starting position as a reference point for relative position coding. Therefore, the "direction-based" Simon effect was absent.

Motion information without relative position information

Even though the displacement of a moving object can be reduced to shifts of relative position, motion information may also be stripped of relative position coding. For instance, motion may be contained in a pattern of random dots in which the relative position of single elements does not reveal the overall motion of the stimulus (e.g., Newsome, Britten, & Movshon, 1989). These "isolated" motion signals do not exhibit a position shift of the global stimulus over time as object motion does. Rather, these stimuli demonstrate—as already suggested by Exner (1888)—that motion detection and processing may be independent of spatial position and time intervals. In other words, motion is a self-contained dimension, which is processed in multiple stages starting with very simple mechanisms in the retina and ending with highly complex processes in the extrastriate cortex.

The question arises whether processes of response selection may be affected by "pure" motion signals. In a recent study by Bosbach, Prinz, and Kerzel (2004), Simon effects to moving stimuli that did not exhibit a shift of relative position were investigated: Observers responded to a nonspatial dimension when confronted with a drifting sine-wave grating in a stationary Gaussian window, a random dot pattern (e.g., Newsome et al., 1989), or variants of Johansson's (1973) point-light walkers that walked in place. The authors found that this kind of (irrelevant) motion information affected manual left–right responses. When the irrelevant direction of motion corresponded to the location of a left–right key press, faster responses were obtained. The effect was certainly based on motion direction per se and not on relative position because the stimuli did not change their overall position over time.

We claim that compatibility effects obtained with moving objects are due to relative position coding; however, this does not preclude the existence of motion-based effects with stimuli that do not allow for relative position coding. In other words, our hypothesis is that the representational mechanisms underlying motion-based correspondence effects could be twofold: One operates on the inherent dynamics of a moving object, and the other operates on the basis of the inherent static attribute of a moving object, namely its relative position (- shifting). The premise is that moving stimuli that allow for relative position coding will be coded in this relational manner. Only if relative position coding is not possible does motion-based information come into play.

Goals of the present study

The first goal of the present study was to replicate direction-based Simon effects to objects that change their position over time. As outlined above, some authors reported direction-based Simon effects whereas others did not. Additionally, we explored the role of dimensional overlap as proposed by Kornblum et al. (1990). One prediction of the dimensional overlap model is that direction-based Simon effects should be more pronounced when participants' responses are more similar to the dynamic stimuli. However, this hypothesis depends on how moving stimuli are being coded: If the relevant cognitive code was "relative position", then similarity would be defined with respect to the relative response position. If the relevant code was "motion direction", then similarity would be defined with respect to lateral shifts of the response. Second, we were interested in whether position- and direction-based Simon effects are independent of each other. In other words, we explored the relative contributions of position and direction information to spatial correspondence effects when both types of information were present. Third, because Ehrenstein (1994) showed that smooth stimulus motion was ineffective at producing a Simon effect to motion direction, we investigated the role of eye movements in position- and motion-based Simon effects. More precisely, we explored whether saccadic eye movements are necessary for a Simon effect to show up.

Seven experiments are reported here. The first experiment aimed to explore whether direction-based Simon effects can occur in a task in which a smoothly moving target is presented. Additionally, possible effects of dimensional overlap were investigated. In Experiments 1b and 3a, eye movements were monitored. In Experiment 2 a target stimulus oscillated on the screen creating a situation in which observers coded either motion direction or relative position. In Experiments 3a, 3b, and 3c relative position was "explicitly" pitted against motion direction by presenting simultaneously a static and a dynamic stimulus. In all experiments, the central questions were (a) how position- and direction-based correspondence effects interact or are modulated by each other, and (b) whether position- and direction-based codes are differently weighted or have additive effects.

EXPERIMENT 1A
Variation of response modality

Our first experiment examined whether a motion-based Simon effect can be demonstrated with stimuli moving smoothly and naturally in a certain direction. Remember that Ehrenstein (1994) failed to obtain a direction-based Simon effect in this situation. To this end we used a simple paradigm, in which we presented a small circle appearing at a left, centre, or right position of the computer screen. From one of these positions the circle started to move either to the left or to the right side at a constant velocity. After a variable delay the circle changed its colour to red or blue, which was the response-relevant feature. The colour "blue" was mapped onto a left response and "red" to a right response or vice versa. We varied the time of the (imperative) stimulus colour onset asynchrony (SCOA) relative to the motion onset to ensure unpredictability of the onset of the imperative stimulus.

The design allowed for the analysis of two types of spatial correspondence: Direction-based correspondence refers to the relation between the direction of stimulus motion and the response location. Position-based correspondence refers to the relation between stimulus position on the screen and the response location. Note that both motion direction and relative position were task-irrelevant. To investigate whether position- and direction-based correspondence were independent from each other, the possible interaction of position- and direction-based correspondence was of special interest.

Further, we varied the response modality. In the static response condition, we used left and right key presses. In the dynamic response condition, we used stylus movements to the left and right. At first glance, the physical similarity between a moving stimulus and a dynamic response is larger than between a moving stimulus and a static response. According to Kornblum et al. (1990), the similarity or dimensional overlap between stimulus and response features determines the size of correspondence effects. Thus, one may assume that a direction-based Simon effect would be more pronounced in the dynamic response condition. However, Kornblum (1991) postulated more precisely that dimensional overlap does not only follow the physically similarity, but is determined as the "characteristic of the way sets are represented, not of the physical properties of the sets themselves" (p. 5). Thus, one can assume further that a direction-based Simon effect is larger with dynamic responses if, and only if, the underlying representation regarding the moving target is motion direction and not its relative position. If the response-determining representation is based on relative position, there should be no difference between the dynamic and static response conditions or exactly the opposite—the effect should be more pronounced in the static response condition.

Method

Participants

A total of 24 students (7 male, 17 female) of the Ludwig Maximilians University of Munich, aged between 17 and 46 years, were paid for participation in single sessions of about 50 minutes. All participants reported having normal or corrected-to-normal vision, normal colour vision, and no motor impairments. None of our participants was informed in advance about the purpose of the present experiment.

Apparatus and stimuli

Stimulus presentation and data acquisition were controlled by a Matrox Millenium graphics adaptor on a Pentium 166 PC permitting a pixel resolution of 1,280 H × 1,024 V. Stimuli were presented on a 21" screen. Displays were updated at a rate of 87 Hz. The background was a light grey. The target stimulus was a circle with a radius of 0.5°. It always appeared first in black at three possible positions: either 8° to the left (−8°) or to the right (+8°) or at the horizontal screen centre. The vertical position of the stimulus was fixed at the vertical centre of the screen. When the target appeared on the left or right side of the screen, it stayed within this part of the screen. For instance, a target appearing on the left side of the screen that moved right would not cross the centre of the screen. With a viewing distance of about 50 cm the circle moved at a constant velocity of approximately 7°/s. After a variable time interval the circle turned into dark red or dark blue, the response-relevant stimulus colour. Note that stimulus onset, motion onset, and colour change occurred within one half of the screen.

In the static response condition, responses were made by pressing a left ("z" on an American keyboard) or right ("? - /") key of the computer keyboard with the corresponding index finger. The distance between the response keys was 17.2 cm. In the dynamic response condition responses were made by moving a stylus either to the left or to the right with the participant's dominant hand. Responses were recorded by a CalComp Drawing Board III with a spatial resolution of 394 lines/cm and a sampling rate of approximately 125 Hz. Recording from the graphics board started with motion onset and stopped with display termination. A velocity criterion (1.8 cm/s) was used to determine the onset of the stylus movement on the graphics tablet.

Design

Experimental conditions (static and dynamic response conditions) were blocked, and the condition order was balanced across participants. Participants worked through seven experimental blocks of 36 trials per condition, preceded by 20 practice trials. Each block was composed of the possible combinations of two target colours (or response locations or directions), three target positions, two target motion directions, and three SCOAs, randomly intermixed. Half of the participants responded to blue targets by pressing the left response key or guiding the stylus to the left and to red targets with the right response key or by guiding the stylus to the right, while the other half received the opposite colour–key or colour–stylus movement direction mapping.

Procedure

The experiment took place in a dimly lit room. Participants sat at a distance of about 50 cm from the computer screen with the head positioned on an adjustable chin rest. They were instructed to respond as quickly and accurately as possible to the colour of the target stimulus irrespective of stimulus motion or position. Following an intertrial interval of 500 ms, the next trial started with the presentation of the blank screen for 200 ms before the target stimulus appeared at one of the three possible starting positions. At a time 880 ms after stimulus onset, the circle moved to the left or right, followed by a colour change to red or blue of the target stimulus after approximately 150, 300, or 450 ms. After the colour change took place, the circle continued to move for 300 ms. Responses with RTs longer than 1,000 ms were regarded as missed trials, and responses with RTs shorter than 100 ms were regarded as anticipations. Pressing the wrong key or guiding the stylus in the wrong direction was counted as a choice error. If the response was wrong, too early or too late, auditory and visual feedback was given, while the trial was recorded and repeated at a random position in the remainder of the block. After the first experimental block (dynamic or static response condition), participants were given the opportunity to rest.

Results

Anticipations and missed trials (0.5%) were excluded from the analysis. Choice errors (4.8%) were analysed separately. Two kinds of correspondence were defined: position-based and direction-based correspondence. Trials were coded as position corresponding when the position of the target spatially corresponded to the response location. Trials were coded as direction corresponding when the motion direction of the target corresponded to the response location. To determine position- and direction-based correspondence only trials with left or right starting position were considered. Trials in which the centre of the screen was the starting position were not analysed.[1] Mean RTs were computed as a function of static versus dynamic response condition, position-based correspondence, and direction-based correspondence (cf. Appendix Tables A1 and A2).

A three-way repeated-measures analysis of variance (ANOVA) was carried out. There was a significant main effect of static versus dynamic response condition, $F(1, 23) = 4.30$, $MSE = 2{,}205$, $p = .049$, indicating faster responses in the dynamic response condition than in the static response condition (367 vs. 381 ms). The ANOVA did not reveal a main effect for position-based correspondence, $F(1, 23) = 2.07$, $MSE = 149$, $p = .16$, while a significant main effect for direction-based correspondence emerged, $F(1, 23) = 19.40$, $MSE = 349$, $p < .001$. Responses were faster when the direction of motion corresponded to the response position than when it did not (368 vs. 380 ms). The interaction between position-based correspondence and static versus dynamic response condition, as well as between direction-based correspondence and static versus dynamic response condition, were not significant, $F(1, 23) = 0.40$, $MSE = 90$, $p = .530$, and $F(1, 23) = 0.73$, $MSE = 237$, $p = .400$, indicating that both kinds of correspondence effects were not modulated by response modality. The interaction between position- and direction-based correspondence reached significance, $F(1, 23) = 18.88$, $MSE = 237$, $p < .001$, indicating that the direction-based correspondence effect was larger in trials in which position was corresponding than when it was not: 21 ms (383 vs. 362 ms) versus 2 ms (376 vs. 374 ms). No other interaction effect approached significance (ps > .41 and Fs < 1).

A second ANOVA on error rates revealed that error rates were higher in the dynamic response condition than in the static response condition (5.6 vs. 4.1%), $F(1, 23) = 7.30$, $MSE = 1.54\text{E-}03$, $p = .013$. Additionally, there was a significant interaction between position-based and direction-based correspondence, $F(1, 23) = 24.84$, $MSE = 9.91\text{E-}04$, $p < .001$. When position was noncorresponding, error rates between direction-noncorresponding and direction-corresponding trials were 6.3 to 3.4% and (reversed) 3.9 to 5.7% when position was corresponding. This shows that the interaction between position-based correspondence and direction-based correspondence in the reaction time data is compromised by speed–accuracy trade-off: Fewer errors were made in conditions with slower responses times. We found no other main effects or interaction on proportion of choice errors (ps > .25 and Fs < 1.4).

Discussion

The main finding of this experiment was that a direction-based Simon effect was confirmed with a smoothly moving stimulus. Responses were faster when the stimulus moved in

[1]The purpose of including a centre starting position was to ensure unpredictability of stimulus onset location. We refrained from analysing reaction times in trials in which the stimulus started its movement from the centre position for the following reason: Certainly, the centre starting position was initially "neutral" regarding the left/right dimension, but the response-critical colour change took place on either the left or the right half of the screen. Thus, the centre position is not a "neutral" position regarding position- and direction-based correspondence.

a direction that corresponded to the location or direction of the correct response. The effect of this correspondence relation was not modulated by response modality (cf. Kornblum et al., 1990), although stylus responses were overall faster than key-press responses. Probably, the latter result reflects methodological differences in determing the manual movement onset. However, more importantly, the former result indicates that no matter whether participants responded via fixed key-presses or more dynamically by moving a stylus to the dynamic target, a reliable direction-based effect obtained. This finding supports the notion that the relevant representation that causes the effect is not motion direction but relative position. If the dynamic features inherent in the stimulus were affecting the stimulus–response translation, the increased similarity between the dynamic stimulus and the dynamic response should have increased the size of the Simon effect. However, this was not the case, which suggests that that object motion was represented in terms of relative position. However, one cannot exclude the possibility that we did not find a larger motion-based Simon effect for movement responses than for key-presses because the movement response was a one-effector condition and the key-press response a two-effector condition. This argument is in line with the study of Proctor and Wang (1997), who found larger set–level compatibility effects with spatial stimuli (static target, which could appear either on the left or on the right side of a computer screen) and bimanual key-press responses than with unimanual aiming movements.

Surprisingly, no reliable position-based Simon effect was obtained, but position-based correspondence led to stronger direction-based correspondence as indicated by the significant interaction between position- and direction-based correspondence. However, the analysis of the proportion of error rates shows that this effect in the RT data is compromised by speed–accuracy trade-off and should not be interpreted any further. Experiment 1c shows that the interaction of position- and motion-based correspondence may be fully explained by a preference for certain combinations of motion direction and starting position of the stimulus and is unrelated to stimulus–response correspondence.

Finally, the finding of a direction-based Simon effect with smoothly moving stimuli is contrary to Ehrenstein's (1994) study, which showed that smooth motion of a stimulus is ineffective in producing a Simon effect. The absence of a Simon effect in his study—so it was argued—was due to the absence of a shift of attention that is typically associated with saccadic eye movements (Rizzolatti et al., 1987). That is, the smooth motion of the stimulus elicited smooth pursuit eye movements, which are not preceded by a shift of attention. Although Ehrenstein referred to eye movements to explain his data, observers in his study did not move their eyes at all. In fact, they were asked to maintain fixation on a central dot, and Ehrenstein discussed which eye movement system would most likely receive the motion signal. In contrast, observers in Experiment 1a were free to move their eyes, and it is almost certain that they followed the target with smooth pursuit eye movements. Smooth stimulus motion is a highly effective stimulus for smooth pursuit eye movements (Yasui & Young, 1975), and observers find it difficult not to pursue a target that is of interest to them (cf. Kerzel, 2000). Thus, it may be that the execution of smooth pursuit eye movements contributed to the occurrence of a dynamic Simon effect. In other words, the representation of a motor movement and not the representation of the stimulus motion may at least affect manual responses. The role of eye movements was explored in the following experiment.

EXPERIMENT 1B
Eye movement monitoring

The second experiment explored whether a direction-based correspondence effect could be obtained when participants were instructed to maintain central fixation, as in the study of Ehrenstein (1994). To this end, we replicated the first experiment with the exception that two conditions were compared: In a fixation condition, participants were instructed to maintain central fixation, while in a pursuit condition, participants were instructed to follow the target with their eyes. Eye movements were monitored. In this experiment we refrained from varying response modality. Responses were made only "statically" by pressing one of two keys as quickly and accurately as possible in response to a certain colour of the target.

Method

Participants

A total of 16 students (1 male, 15 female, aged between 19 and 32 years) of the Ludwig Maximilians University fulfilling the same criteria as in Experiment 1a were paid for participation. None of them had participated in Experiment 1a.

Apparatus and stimuli

Apparatus and stimuli were as in Experiment 1a, with the following exceptions. Responses were made only by pressing one of two keys (cf. Experiment 1a). Additionally, the horizontal position of the left eye was monitored with a head-mounted, infrared, light-reflecting eye tracker (Skalar Medical B.V., IRIS Model 6500). The analogue signal was digitized at a rate of 250 Hz by a DataTranslation A/D–D/A converter (DT 2821). In the fixation condition, participants had to maintain central fixation within 1° of a fixation point that was presented 4° below the target's trajectory at the horizontal centre of the screen. In the pursuit condition, participants had to pursue the target with their eye. Eye movements were recorded from 50 ms before until 250 ms after the target disappeared. When the eye did not move in the direction of motion during this interval, it was assumed that the participant did not follow the target. When participants did not maintain central fixation or did not pursue the target, the trial was aborted immediately, an error message appeared, and the trial was repeated at a random position in the remainder of the block. The fixation mark was shown in both eye movement conditions, but had to be ignored in the pursuit condition.

Design

The design was the same as that used in Experiment 1a.

Procedure

The same procedure was used as that in Experiment 1a except that eye movements were monitored. Before each experimental block, output from the eye tracker was calibrated by having observers look at five points on the screen.

Results

Anticipations and missed trials (0.5%) as well as fixation errors (2.2%) were excluded from the analysis. Choice errors (3.3%) were analysed separately. Position- and direction-based correspondence was defined as in Experiment 1a (cf. Appendix Tables A1 and A2).

A three-way repeated-measures ANOVA (fixation vs. pursuit condition by position-based correspondence by direction-based correspondence) did not reveal a significant main effect of fixation versus pursuit condition, $F(1, 15) = 0.67$, $MSE = 2{,}761$, $p = .430$. The ANOVA revealed a significant main effect for position-based correspondence, $F(1,15) = 16.79$, $MSE = 173$, $p = .001$, and a significant main effect for direction-based correspondence, $F(1, 15) = 10.57$, $MSE = 335$, $p = 005$. Responses were faster when the position of the target spatially corresponded to the position of the response than when it did not (426 vs. 436 ms), and the same was true when the direction of motion corresponded to the response location (426 vs. 436 ms). There was a significant interaction between position-based correspondence and fixation vs. pursuit condition, $F(1, 15) = 12.89$, $MSE = 186$, $p = .003$, indicating that the position-based correspondence effect (difference in mean RTs between position-noncorresponding and position-corresponding trials) was larger in the fixation than in the pursuit condition (18 vs. 1 ms). That is, responses that corresponded to the response location were initiated faster when participants maintained fixation than when they followed the target with their eyes (426 vs. 444 ms). The effect was almost absent when participants pursued the target with their eyes (428 vs. 427 ms). Also the direction-based correspondence effect was modulated by the fixation versus pursuit condition, $F(1, 15) = 5.42$, $MSE = 145$, $p = .034$, indicating that the effect was larger when participants pursued the target than when they maintained central fixation (15 vs. 6 ms). As in Experiment 1a, a significant interaction between position- and direction-based correspondence was obtained, $F(1, 15) = 26.69$, $MSE = 199$, $p < .001$, indicating that the direction-based correspondence effect was pronounced when position was corresponding and slightly inverted when position was noncorresponding (23 vs. −2 ms). No other significant interaction term reached significance (ps > .86 and Fs < 1).

A second ANOVA on error rates revealed that error rates were lower in position-corresponding trials than in position-noncorresponding trials (2.5 vs. 4.5%), $F(1, 15) = 6.58$, $MSE = 1.76\text{E-}03$, $p = .022$. No other main effects or interactions on proportion of choice errors were found (ps > .16 and Fs < 2.3).

Discussion

Again, a direction-based Simon effect was obtained. Responses were faster when the target's motion direction corresponded to the response location. Similarly, responses were faster when the position of the target relative to the screen centre corresponded to the response location. However, the effects of direction and position correspondence were modulated by eye movement instruction. When observers were asked to pursue the target with their eyes, the effect of direction-based correspondence was more pronounced than when they maintained fixation. Conversely, when observers were instructed to maintain fixation at the horizontal screen centre, the effect of position-based correspondence was more pronounced than when they pursued the target. This interaction demonstrates the importance of retinotopic coordinates in spatial coding. In egocentric coordinates (i.e., with respect to the observer), the spatial position of the target was identical in the two eye movement conditions. However, in retinotopic coordinates (i.e., with respect to the fovea), the situation was vastly different: When observers were instructed to pursue the target with their eyes, the moving target was stabilized in the fovea, regardless of where the target appeared on the screen. This may have reduced the effect of egocentric (screen-based) position codes such that the position-based correspondence effect was reduced. In contrast, the egocentric position of the target dramatically affected the retinal position of the target when observers maintained central fixation. This may have emphasized the influence of position over motion, because the retinal change of position within a trial was relatively small compared to the change of position across trials. Therefore, direction-based correspondence effects were smaller than position-based effects.

EXPERIMENT 1C
Is there a preference for outwards movements?

There are two possible interpretations of the interaction between position- and direction-based correspondence effects observed in the first two experiments. First, it may be that there are nonadditive effects of the two spatial correspondence relations. When both direction of motion and position correspond to the response location, responses may be extremely fast—faster than expected by the additive effects of the two factors. However, there is a second, more trivial explanation that is inspired by the suspicion that a speed–accuracy trade-off generated the interaction: As shown in Figure 1, trials in which position and direction corre-

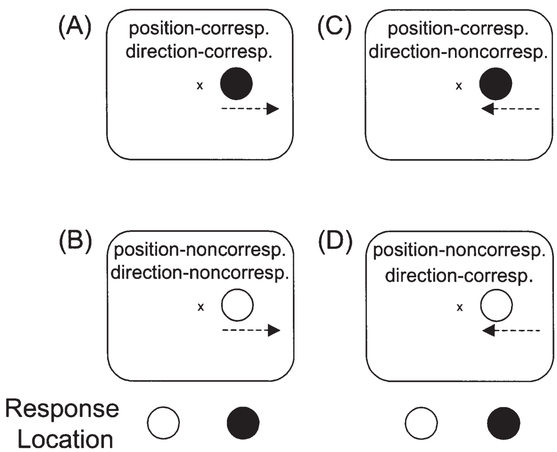


Figure 1. Interaction between position- and direction-based correspondence. The arrows indicate the circle's direction of motion. As an example, white is mapped on left-hand responses and black on right-hand responses. In the experiment, the colours red and blue were used. The results showed that the direction-based correspondence effect was stronger when absolute position was corresponding. The direction-based effect was inverted when absolute position was noncorresponding (cf. Experiments 3a and 3b). That is, reaction times in direction-noncorresponding trials were faster when absolute position was noncorresponding. That is, the responses in conditions A and B were faster than in C and B. These are the conditions in which the target was moving toward the edge of the monitor.

sponded to the response were trials in which the target was moving towards the edge of the screen.

To investigate whether the interaction of position and direction reflected a compatibility phenomenon, we measured simple response times to the onset of the imperative stimulus. Participants were confronted with the same display as in Experiments 1a and b, but they were instructed to simply press a key as quickly as possible when the circle changed its colour.

Method

Participants

A total of 12 students (4 male, 9 female, aged between 21 and 29 years) of the Ludwig Maximilians University fulfilling the same criteria as in Experiment 1a were paid for participation. None of them had participated in Experiments 1a or 1b.

Apparatus and stimuli

Apparatus and stimuli were exactly the same as in Experiments 1a and 1b. Participants used the "? - /" key on the computer keyboard for the response.

Design

Participants worked through 12 blocks per 24 trials. Block composition was as that in Experiments 1a and 1b.

Procedure

The same procedure was used as that in Experiments 1a and 1b. Eye movements were not monitored but one may assume that observers followed the target with their eyes (cf. Experiment 1b). Error feedback was given when the response was too early (< 100 ms) or too late ($> 1{,}000$ ms), while the trial was repeated at a random position in the remainder of the block.

Results

To compute the data only trials with left or right starting positions were considered. Trials in which the centre of the screen was the starting position were excluded from the analyses. Anticipations and missed trials (4.8%) were excluded from the analysis. Mean RTs were computed as a function of outwards versus inwards movements of the target stimulus. A paired-samples t test showed that mean RTs were shorter when the circle moved outwards than when it moved inwards (257 vs. 273 ms), $t(11) = 5.77$, $p < .001$.

Discussion

Indeed mean RTs were shorter when the target stimulus moved outwards than when it moved inwards. This finding supports the notion that the interaction between position- and direction-based correspondence in Experiments 1a and 1b (cf. Experiments 3a and 3b) was due to factors unrelated to stimulus–response correspondence. Faster responses to outward moving objects may result because a movement toward the edge of the screen indicates an impending "collision" of the target object with the screen. This may increase participant's attention compared to a situation in which the target moves across the screen (without any impending events).

EXPERIMENT 2
Oscillating trajectory

The aim of this experiment was to further compare the parallel processing of motion direction and relative position and their respective influence on response selection. The central assumption was that correspondence effects due to coding of relative position are more pronounced than effects due to coding of motion direction when object motion is presented. The central manipulation in this experiment was that the stimulus did not move only in one direction, but oscillated across the screen with a maximum of four reversals and a minimum of zero reversals (see Figure 2).

The response-critical colour change could either occur at the reversal point or at a random point along the trajectory. The reversal point in this situation is the point defining the right- or leftmost position of the stimulus along the trajectory. At this point, the relative position of the target is emphasized, whereas the direction of motion is deemphasized as the instantaneous direction of motion does not correspond to the future direction of motion. In other words, the relative position coding should be unambiguous, whereas the coding of motion direction is highly ambiguous. In contrast, random points along and around the centre of the trajectory are less clearly classified as "TO THE LEFT OF THE TRAJECTORY CENTRE" or "TO THE RIGHT OF THE TRAJECTORY CENTRE". However, the direction of motion in these cases is unambiguous such that motion direction is emphasized over relative position at random points along the trajectory.

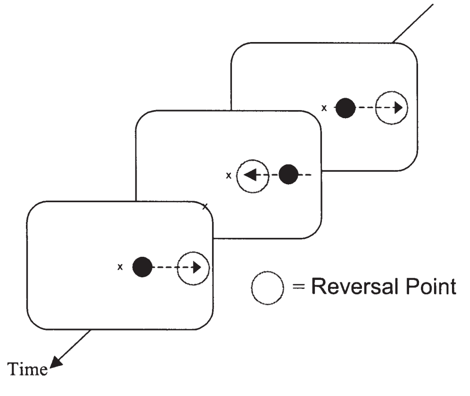


Figure 2. The target stimulus in Experiment 2 oscillated on the screen. For instance, it started in the right half of the screen and moved to the right. After a while, it turned to the left, then it turned to the right again, and so on. Within one half of the screen, the target would reverse its direction of motion between zero and four times until the response-critical colour change occurred. The colour change could take place either at the reversal point or at a random position along the trajectory.

With oscillating target motion, correspondence effects of motion direction reflect different underlying spatial codes depending on where the colour change occurs: If it occurs at a random position along the trajectory, direction-based correspondence effects reflect coding of motion direction because the position of the stimulus is ambiguous. In contrast, if the colour change occurs at a reversal point, direction-based correspondence effects reflect coding of relative position, because motion direction is ambiguous, whereas relative position with respect to the trajectory (perfectly confounded with motion direction before the reversal) is clearly discernible. It should be noted that the absolute position on the screen does not change as a function of imperative stimulus position: The complete trajectory was confined to one half of the screen. That is, the target oscillated in one half of the screen and never traversed the screen centre.

Method

Participants

A total of 12 students (3 male, 9 female, aged between 18 and 30 years) of the Ludwig Maximilians University fulfilling the same criteria as those in Experiment 1a were paid for participation. None of them had participated in Experiments 1a, 1b, or 1c.

Apparatus and stimuli

Stimulus presentation and data acquisition were controlled by the same apparatus as that in the previous experiments. Eye movements were not monitored, and responses were made by pressing one of two keys (cf. Experiment 1a). The target first appeared in black at one of two possible positions, either 8° to the left or 8° to the right of the horizontal centre of the screen. From its left or right starting position the circle started an oscillating movement −2 to −14° within the left half of the screen or 2 to 14° within the right half of the screen. Within one half of the screen, the target would reverse its movement direction between zero and four times. The critical manipulation was the part of the trajectory in which the imperative colour change took place. Either the colour change occurred at the reversal point of the trajectory (i.e., −14 and −2 °, or +2 and +14°), or at a random position around (i.e., +/− 3°) the centre of the trajectory (i.e., −8 or +8°). In other words, the target disappeared at the extreme ends of the trajectory (+/−14 and +/−2°) or somewhere in the centre of the trajectory (between +/−11 and +/−5°). The imperative colour was presented for one refresh cycle (11.5 ms) only, and the target disappeared immediately afterwards. With a viewing distance of about 50 cm the circle moved at a constant velocity of approximately 10°/s.

Design

Participants worked through five experimental blocks at 80 trials per condition, preceded by 20 practice trials. Each block was composed of the possible combinations of two target colours (or response locations), two target positions (relative to the screen centre), two coloured-target positions along the trajectory, two target motion directions, and four reversals, randomly intermixed.

Procedure

The procedure was the same as that in Experiment 1a.

Results

Anticipations and missed trials (2.1%) were excluded from the analysis. Choice errors (5.9%) were analysed separately. Mean RTs were computed as a function of coloured-target position along the trajectory, position-based correspondence, and direction-based correspondence (cf. Appendix Tables A1 and A2). Trials were coded as position corresponding when the position of the target relative to the screen centre spatially corresponded to the response location. Trials were coded as direction corresponding when the motion direction of the target corresponded to the response location. Note that direction-based correspondence at a reversal point was defined with respect to the target's last motion direction and not to its future motion direction. For instance, when a leftward moving stimulus reached its reversal point, its direction was coded as "LEFT", and, similarly, its relative position was "LEFT". As outlined above, the relative position dominates over direction at reversal points. However, for ease of presentation, the relative position at reversal points is referred to as direction of motion before the reversal.

A three-way ANOVA did not reveal a significant main effect of coloured-target position, $F(1, 11) = 0.61$, $MSE = 594$, $p = .450$. While there was no significant position-based correspondence effect, $F(1, 11) = 1.94$, $MSE = 267$, $p = .190$, a significant direction-based correspondence effect occurred, $F(1, 11) = 25.73$, $MSE = 202$, $p < .001$, indicating that responses were faster when motion direction and response location corresponded than when they did not (506 vs. 520 ms). However, the direction-based effect was modulated by the coloured-target position, $F(1, 11) = 16.61$, $MSE = 163$, $p = .002$. The direction-based correspondence effect was more pronounced when the coloured-target was at the reversal point (26 ms), than at a random position along the trajectory (4 ms). Contrary to the previous experiments, direction-based correspondence was not modulated by position-based correspondence, $F(1, 11) = 1.00$, $MSE = 175$, $p = .340$. However, a significant three-way interaction between coloured-target position, position-based correspondence, and direction-based correspondence was obtained, $F(1, 11) = 5.00$, $MSE = 254$, $p = .047$, indicating that when the coloured target was positioned at the reversal points of the trajectory the direction-based correspondence effect was larger in position-noncorresponding trials than in position-corresponding trials (35 vs. 15 ms). The reverse pattern resulted when the coloured target was positioned at random position around the centre of the trajectory. The direction-based effect was larger in position-corresponding than in noncorresponding trials (0 vs. 9 ms). There was no other significant interaction term (ps > .37 and Fs < 0.9).

A second ANOVA on error rates yielded almost the same picture as the analysis of RTs. Direction-corresponding trials were less error prone than direction-noncorresponding trials (6.4 vs. 9.3 %), $F(1, 11) = 7.72$, $MSE = 1.68\text{E-}03$, $p = .018$. However, this effect was also modulated by coloured-target position, $F(1, 11) = 8.34$, $MSE = 9.76\text{E-}04$, $p = .015$. When the coloured target was at the reversal point, the difference between direction-noncorresponding and direction-corresponding trials was 10.2 vs. 5.0 %; when the coloured target was at a random point on the trajectory the difference was 8.5 vs. 7.8 %. Additionally, we found a significant position-based correspondence effect, $F(1, 11) = 7.01$, $MSE = 6.31\text{E-}03$, $p = .02$, indicating fewer errors in position-corresponding than in noncorresponding trials (7.2. vs. 8.6%). There were no other significant results (ps > .06 and Fs < 4.3).

Discussion

The main finding in Experiment 2 was a dominance of relative position over motion direction. In this experiment, we created a situation in which the imperative stimulus could appear at the reversal point of a hypothetic trajectory or at a random position along this trajectory. The reversal point in this situation marked the right- or the leftmost position along the trajectory, whereas random points along the trajectory were rather ill-defined left or right positions. Certainly, they were on the left or right side of the screen, but regarding the start and end positions of the trajectory they were in its centre. In other words, these positions were somewhat ambiguous. As we expected, a pronounced direction-based Simon effect occurred when the response-relevant stimulus feature appeared at the reversal point of the trajectory—that is, at the point where motion direction was equivalent to relative position. The direction-based effect was markedly smaller in cases in which the imperative stimulus appeared at a random point along the trajectory. Therefore, the "direction-based" Simon effect at the reversal point may be entirely due to relative position coding.

Furthermore, the results show that the oscillating trajectory creates a reference frame for relative position coding because the position of the trajectory relative to the screen did not affect response times. Thus, the position of the target relative to the trajectory and not that relative to the screen determined response latencies.

EXPERIMENT 3A
Simultaneous presentation of static and dynamic stimuli

In this experiment we pitted direction of target motion against relative target position. To this end, we used a modified version of the paradigm devised by Nattkemper and Prinz (2001). Nattkemper and Prinz presented a circle that moved horizontally on the screen (see Figure 3). At a random point along the trajectory, a rectangle was superimposed on the circle and remained stationary at this position while the target continued to move. Simultaneous to the onset of the rectangle, the imperative feature—the colour red or blue—was presented. Importantly, the imperative feature appeared either on the moving circle or on the stationary rectangle. Therefore, colour was the relevant stimulus dimension while (relative) position and motion direction were irrelevant. Participants were instructed to make either a leftward or a rightward stylus movement or a left or right key-press in response to the colour. When the moving target carried the response-relevant colour cue, a direction-based Simon effect occurred. Responses were faster when the direction of the circle's motion corresponded to the direction or location of the response. However, when the imperative colour cue appeared on the stationary rectangle, the direction-based Simon effect was reversed. Responses were faster when the direction of circle motion did not correspond to the direction or location of the response. For instance, when the circle moved to the left and turned into red or blue at the same time as when the stationary rectangle appeared, the imperative feature was placed on the left of the rectangle because the circle continued to move to the left. Therefore, left responses were facilitated. On the contrary, when the target moved to the left, and the rectangle changed colour, the imperative feature was on the right of the circle because the circle continued to move left. Therefore, right

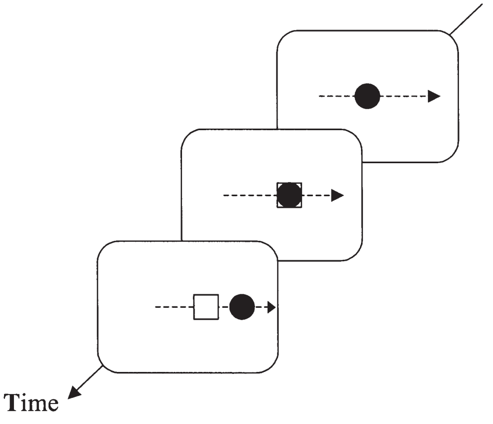


Figure 3. The figure demonstrates an example trial of Nattkemper and Prinz's (2001) study. The trial started with the presentation of a circle moving horizontally at a constant velocity to the right. At a random position along the trajectory, a rectangle was superimposed on the circle. While the rectangle remained stationary at this position, the circle continued to move. At the same time, one of these stimuli turned into a different colour (imperative feature). When the imperative feature appeared on the rectangle, responses to the left were faster than responses to the right. The opposite was true when the colour cue appeared on the circle.

responses were facilitated. This finding is consistent with the assumption that the relative position of the imperative feature determined performance.

However, there are two alternative explanations of Nattkemper and Prinz's (2001) findings—one drawing on retinal motion and the other on relative position. The stationary stimulus in the study of Nattkemper and Prinz always appeared opposite the target's direction of motion. If one assumes that observers tracked the moving circle, the circle was in the fovea. The stationary rectangle, however, was presented in the retinal periphery (cf. Figure 4). While the target was moving physically, its retinal image remained stationary (stabilized on the fovea). In contrast, the stationary object's retinal image moved. For instance, if the observer pursued a circle moving to the right, while a stationary rectangle appeared left of the target, the image of the circle would be stationary while the image of the rectangle would appear to move to the left.

This observation would lead to the following questions: If the inverted direction-based Simon effect reported by Nattkemper and Prinz (2001) was due to the perceived retinal motion of the stationary object, it should not make any difference whether the stationary rectangle was presented to the left or right of the dynamic circle. Namely, the perceived retinal motion of the stationary object depends only on the direction of motion of the target object that is pursued. For instance, if the target moved to the right and is pursued by the eyes, objects to the left and right of the target appear to move to the left. Therefore, left responses should be faster. However, if the effect was due to relative position coding, a Simon effect to the relative position of the rectangle should be obtained. That is, if the (imperative) rectangle appeared to the right of the circle, right-hand responses should be faster. If it appeared to the left of the circle, left-hand responses should be faster.

To test accounts based on retinal motion and relative position, we replicated the paradigm of Nattkemper and Prinz (2001) with the exception that the stationary rectangle could

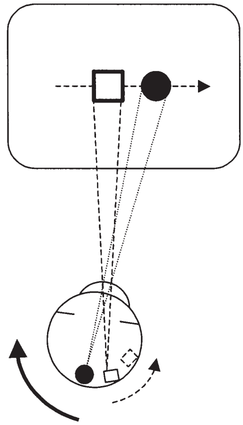


Figure 4. When following a rightward moving circle by pursuit eye movements, the eye rotates in the direction of object motion (solid arrow). However, the image of the pursuit target (circle) is stabilized on the fovea (i.e., there is no retinal motion despite physical motion). If a square appears left of the circle and remains stationary at this position, the image of the stationary square will move across the observer's retina (thin dotted arrow). The retinal motion is perceived as motion of the square from right to left (mirror-reversed to the retinal motion).

appear in or opposite to the motion direction of the circle. As in the previous experiments, participants responded to the coloured stimulus by pressing one of two keys as quickly and as accurately as possible.

The design allowed for the analysis of three types of correspondence: Direction-based correspondence refers to the relation between the direction of stimulus motion and the response location. Absolute position-based correspondence refers to the relation between stimulus position on the screen and the response location. Finally, relative position-based correspondence refers to the relation between the position of the stimulus carrying the imperative colour cue relative to the second stimulus and the response location.

Additionally, eye movements were monitored, and a fixation and a pursuit condition were compared (cf. Experiment 1b), because we aimed to investigate whether a certain retinotopic representation of the moving and stationary objects during eye movements leads to a different coding of spatial relationships. Namely, if one pursued a moving target, the image of this stimulus is stabilized on the fovea while the image of a simultaneously presented stationary stimulus appears to move in the opposite direction (of course, only in a retinotopic, not in an egocentric representation). On the other hand, if one fixates the screen centre, only the image of the moving target travels across the observer's retina, while the image of the stationary target remains static.

Method

Participants

A total of 16 students (6 male, 10 female, aged between 21 and 39 years) of the Ludwig Maximilians University fulfilling the same criteria as in Experiment 1a were paid for participation. None of them had participated in Experiments 1a, 1b, 1c, or 2.

Apparatus and stimuli

The same apparatus for stimulus presentation was used as that in the previous experiments. Eye movements were monitored by the same apparatus as that in Experiment 1b. Again, a black filled circle with a diameter of 1° was the target stimulus, which could be displayed −10°, 0°, or 10° from the horizontal centre of the screen. It moved horizontally to the left or to the right at a constant velocity of approximately 7°/s. After 600 ms two simultaneous events happened: The first event was the occurrence of an outline black 1° square either 4° to the left or 4° to the right from the circle, which remained stationary at this position, while the circle continued to move for 350 ms. The second event was that either the stationary square or the moving circle turned into red or blue. The colour cue indicated a certain response, which was executed by pressing one of two keys (cf. Experiment 1a). In 50% of the trials the imperative colour cue appeared on the square in the other 50% on the circle. As in the fixation condition of Experiment 1b, participants were asked to maintain central fixation; in the pursuit condition they were asked to follow the target with their eyes.

Design

The fixation and pursuit conditions were blocked, and the condition order was balanced across participants. Participants worked through 10 blocks at 48 trials per condition, preceded by 20 practice trials. Each block was composed of the possible combinations of two target colors (or response locations), two kinds of target (stationary square or moving circle), three target (stimulus with the imperative colour cue) positions on the screen, two target motion directions, and two target positions relative to the other stimulus, randomly intermixed.

Procedure

The same procedure was used as that in the previous experiments with the following exceptions: After an intertrial interval of 1,000 ms, the circle appeared at one of the three possible starting positions. At a time 880 ms after the stimulus onset, the circle moved to the left or right. After 600 ms a square appeared at the left or the right side of circle and remained stationary, while the circle continued to move. At the same time either the stationary square or the moving circle turned into red or blue. Error feedback was as in Experiment 1a.

Results

Anticipations and missed trials (0.5%) as well as eye movement errors (4.1%) were excluded from the analysis. Choice errors (5.6%) were analysed separately. Three kinds of correspondence were defined: absolute position-based correspondence, direction-based correspondence, and relative position-based correspondence. Trials were coded as absolute position corresponding when the position of the target relative to the screen centre spatially corresponded to the response location. Trials were coded as direction corresponding when the motion direction of the target corresponded to the response location. Finally, trials were coded as relative position corresponding when the position of the imperative (coloured) target stimulus relative to the second stimulus corresponded to the response location. Mean RTs and error rates were computed as a function of fixation versus pursuit condition and absolute position-based, direction-based, and relative position-based correspondence (cf. Appendix Tables A1, A2, A3, and A4).

A four-way ANOVA did not reveal a significant main effect of fixation versus pursuit condition, $F(1, 15) = 0.03$, $MSE = 7{,}193$, $p = .870$, but a significant main effect of absolute position-based correspondence emerged, $F(1, 15) = 48.33$, $MSE = 117$, $p < .001$, indicating that responses that spatially corresponded to stimulus location relative to the screen centre were faster than those that did not (409 vs. 418 ms). Also, a significant main effect of relative position-based correspondence was obtained, $F(1, 15) = 26.85$, $MSE = 269$, $p < .001$, indicating that responses were initiated faster when the position of the coloured stimulus relative to the other stimulus corresponded to the response location than when it did not (408 vs. 419 ms). However, there was no significant effect for direction-based correspondence, $F(1, 15) = 0.05$, $MSE = 149$, $p = .820$, although we found a significant interaction between absolute position-based correspondence and direction-based correspondence, $F(1, 15) = 26.86$, $MSE = 622$, $p < .001$, indicating—as in the Experiments 1a and 1b—an advantage of direction-corresponding trials when response and absolute position corresponded (401 vs. 417 ms), and the reverse effect when absolute position and response did not correspond (426 vs. 411 ms). However, this inversion effect was more pronounced in the pursuit condition (−22 vs. 23 ms) than in the fixation condition (−9 vs. 10 ms) as indicated by the significant interaction between fixation versus pursuit condition and absolute position-based and direction-based correspondence, $F(1, 15) = 13.51$, $MSE = 214$, $p = .002$. Finally, relative position-based correspondence was modulated by absolute position-based correspondence, $F(1, 15) = 11.16$, $MSE = 130$, $p = .004$. This interaction effect indicated that the advantage of relative position-based corresponding trials was larger in absolute position-noncorresponding trials than in position-corresponding trials (15 vs. 6 ms). However, this effect was more pronounced in the fixation condition (17 vs. 1 ms) than in the pursuit condition (15 vs. 11 ms), as indicated by the significant three-way interaction between fixation versus pursuit condition and absolute position-based and relative position-based correspondence, $F(1, 15) = 6.78$, $MSE = 90$, $p = .020$. Finally, there was a significant interaction between fixation versus pursuit condition and absolute position-based correspondence, $F(1, 15) = 8.45$, $MSE = 167$, $p = .011$, indicating—as in Experiment 1b—that the absolute position-based correspondence effect was larger in the fixation condition than in the pursuit condition (14 vs. 5 ms). There was no other significant interaction (ps > .05 and Fs < 4.4).

A second ANOVA on error rates revealed nearly the same pattern as the analysis of RT: Absolute position-noncorresponding trials were more error prone than were corresponding trials (6.6 vs. 5.2%), $F(1, 15) = 12.65$, $MSE = 9.36\text{E-}04$, $p = .003$. The same was true for relative position-noncorresponding versus position-corresponding trials (7.2 vs. 4.6%), $F(1, 15) = 11.8$, $MSE = 3.01\text{E-}03$, $p = .004$. Additionally, a significant interaction between absolute position-based correspondence and direction-based correspondence emerged, $F(1, 15) = 9.84$, $MSE = 1.27\text{E-}03$, $p = .007$. When absolute position was noncorresponding, the error rates of direction-noncorresponding and direction-corresponding trials were 7.5 to 5.7%, and when absolute position was corresponding, they were 4.6 to 5.7%. This indicates that the interaction between absolute position-based and direction-based correspondence in the reaction time data is compromised by speed–accuracy trade-off: Fewer errors were made in conditions with slower response times. Additionally, a significant interaction between fixation versus pursuit condition and direction-based correspondence was found, $F(1, 15) = 7.33$, $MSE = 8.74\text{E-}04$, $p = .016$. In the fixation condition more errors were made when direction was noncorresponding than when it was corresponding (6.1 vs. 4.6%). The reverse was true in the pursuit condition (6.2 vs. 6.8%). No other significant effect was found (ps > .05 and Fs < 4.4).

Discussion

The main findings of the present experiment were the following: Independent of whether participants maintained central fixation or tracked the target with their eyes, overall RTs were shorter and more accurate when the target position relative to the screen centre and relative to the second object corresponded to the response location. This result shows that the retinal motion of the stimulus is far less important than the relative position of the stimulus: If retinal motion had determined response times, no effect of relative position should have emerged because retinal motion of the complete stationary scene was opposite to target motion. Therefore, the present results further corroborate the hypothesis that the motion of objects is coded in terms of their position relative to (a) the starting position and (b) other stationary objects.

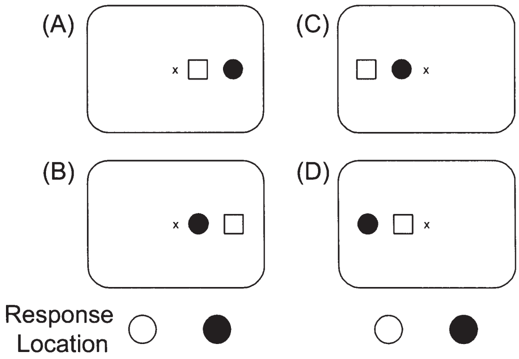
As in Experiment 1b the absolute position-based correspondence effect was larger when participants were asked to maintain central fixation than when they were asked to follow the target, supporting the notion that the position of the target relative to the egocentric axis may dominate over its retinal position.

In the fixation condition, the relative position-based correspondence effect was larger when the absolute position of the stimulus (i.e., relative to the screen centre) did not correspond to the response location. This effect was nearly absent with pursuit of the target and may be explained by the influence of the retinal position of the imperative stimulus in the fixation condition (see Figure 5). Generally, it is easier and faster to respond to colour and motion stimuli that appear closer to the fovea (Tynan & Sekuler, 1982). When absolute position was corresponding, the coloured target was far from the fovea in relative position-corresponding trials. Therefore, effects of retinal eccentricity and relative position correspondence may have cancelled each other. In contrast, when absolute position was noncorresponding, the target was close to the fovea in relative position-corresponding trials. Therefore, effects of eccentricity and relative position correspondence may have added up.

Importantly, a direction-based Simon effect did not emerge either in the pursuit or in the fixation condition. Thus, when the direction of target motion was pitted against relative target position, motion direction did not influence response selection processes. As in the previous experiments, the interaction between absolute position- and direction-based correspondence reached significance. We suggest that this interaction effect is not a real correspondence phenomenon, but may reflect an advantage of responses to outward (i.e., toward the edges of the screen) motion of the stimulus (cf. Experiment 1c).

In sum, a dominance of relative target position over motion information was again confirmed with object motion. First, the target position was coded relative to the screen centre, which gave rise to effects of absolute position correspondence. Simultaneously, the position of the moving target was coded relative to some reference point. In the absence of concurrently presented objects, the starting position may serve as a reference point. In this case, a direction-based Simon effect was observed (see Experiments 1a and 1b). If, however, an alternative reference is presented, it may overwrite the coding relative to the starting position for two reasons: First, the starting position is no longer visible, and, second, the sudden appearance of the reference is much more salient.

Finally, these results demonstrate that spatial correspondence effects are independent of eye movements. Thus, there is reason to doubt that the preparation or execution of saccadic



	Absolute Position Correspondence	Relative Position Correspondence
A	Yes	Yes
B	Yes	No
C	No	Yes
D	No	No

Figure 5. This figure illustrates the interaction between absolute (i.e., screen centre is the reference) and relative (i.e., position of the coloured stimulus relative to the second) position-based correspondence. To simplify matters different colours of the imperative signals are shown in black and white. As an example, white is mapped onto left-hand responses, and black is mapped onto right-hand responses. The interaction showed that the relative position-based correspondence effect is stronger when absolute position is noncorresponding (C vs. D) than when absolute position is corresponding (A vs. B). Inspection of the eccentricity of the imperative (i.e., coloured) stimulus shows that it is closer to the fovea B and C. Stimuli that are closer to the fovea are easier to detect and respond to. Thus, eccentricity counteracts effects of relative correspondence when absolute position is corresponding (A vs. B), and it works in the same direction as that of relative position correspondence when absolute position is noncorresponding (C vs. D).

eye movements plays any role in spatial stimulus–response compatibility as pointed out by Ehrenstein (1994) or Umiltà and Nicoletti (1985, 1990). Spatial stimulus features can be coded in the absence of saccadic eye movements and concurrent shifts of attention.

EXPERIMENT 3B
SOA circle–square variation

In Experiment 3a, we mentioned that the relative position code—generated with the appearance of the second stimulus—possibly overwrote the initial relative position code formed with respect to the starting position of the moving circle. The question tackled in this experiment was why the initial code related to the starting position was overwritten. Two possible answers come to mind: First, it may be that the code formed with respect to the stationary object was stronger and more salient. This is plausible because the starting position is no longer present. Second, it may be that the code formed with respect to the stationary object was temporally the last code generated, such that it overwrote other entries in the object's event file of the given situation (Hommel, 1998). To test these two assumptions, we replicated Experiment 3a with the exception that the onset between the circle and the square varied. In one variation, both stimuli—that is, the circle and the square—were presented statically for some time at the beginning of a trial. Then, the circle started to move in a certain direction, while the square remained stationary. In a second variation, the square appeared with the motion onset of the circle, and in a third variation the square appeared—as in Experiment 3a—with the onset of the imperative colour cue. If the time of code formation mattered, differences should emerge between these three conditions.

Method

Participants

A total of 16 students (4 male, 12 female, aged between 19 and 27 years) of the Ludwig Maximilians University fulfilling the same criteria as in Experiment 1a were paid for participation. Three of them had participated in Experiment 1b.

Apparatus and stimuli

Apparatus and stimuli were as those in Experiment 3a with the following exception: The stimulus onset asynchrony (SOA) between circle and square varied. With an SOA of 0 ms, the square appeared at the beginning of a trial simultaneous with the circle, and both stimuli remained stationary for 880 ms before the circle started to move. With an SOA of 880 ms, the square appeared simultaneous with motion onset of the circle, and with an SOA of 1,480 ms, it appeared simultaneous with the onset of the imperative colour cue (as in Experiment 3a). The colour cue always appeared 600 ms after motion onset either on the stationary square or on the moving circle. The coloured target stayed on for 350 ms. In every SOA variation the square was horizontally placed either 5° to the left or 5° to the right of the circle. Eye movements were not monitored in this experiment but observers were instructed to follow the moving target with their eyes.

Design

Participants worked through three blocks at 144 trials, preceded by 20 practice trials. Each block was composed of the possible combinations of two target colours (or response locations), two kinds of target, three SOAs circle–square, three target (stimulus with the imperative colour cue) positions on the screen, two target motion directions, and two target positions relative to the other stimulus, randomly intermixed.

Procedure

The same procedure was used as that in Experiment 3a.

Results

Anticipations and missed trials (0.8%) were excluded form the analysis. Choice errors (5.1%) were analysed separately. Mean RTs for absolute position-based, direction-based, and relative position-based correspondence were calculated (cf. Appendix Tables A1, A2, A3, and A4).

A four-way ANOVA (SOA circle–square by absolute position-based correspondence by direction-based correspondence by relative position-based correspondence) on RT revealed a significant main effect of absolute position-based correspondence, $F(1, 15) = 12.05$, $MSE = 570$, $p = .003$, indicating that responses were faster when the position of the target relative to the screen centre corresponded to the response location than when it did not (395 vs. 403 ms). The same was true for relative position-based correspondence (387 vs. 412 ms), $F(1, 15) = 69.30$, $MSE = 788$, $p < .001$, but, again, no direction-based correspondence effect was found, $F(1, 15) = 0.79$, $MSE = 495$, $p = .390$, although the interaction between absolute position-based correspondence and direction-based correspondence reached significance, $F(1, 15) = 18.35$, $MSE = 415$, $p = .001$. As in Experiment 3a, the direction-based effect was inverted when absolute position was noncorresponding (−7 ms, 400 vs. 407 ms), and in the usual direction when absolute position was corresponding (10 ms, 400 vs. 390 ms). However, the significant interaction between SOA circle–square and absolute position-based and direction-based correspondence, $F(2, 30) = 6.30$, $MSE = 443$, $p = .005$, indicated that this inversion effect was −7 vs. 3 ms at 0-ms SOA, −2 vs. 2 ms at 880-ms SOA, and—most pronounced–13 vs. 26 ms at 1,480-ms SOA circle–square. Another significant interaction occurred between absolute position-based and relative position-based correspondence, $F(1, 15) = 5.71$, $MSE = 687$, $p = .030$, indicating—as in Experiment 3a—that the relative position-based effect was more pronounced in absolute position-noncorresponding trials than in absolute position-corresponding trials (31 vs. 18 ms; cf. Figure 5). Finally, a significant interaction between SOA circle–square and absolute position-based, direction-based, and relative position-based correspondence emerged, $F(2, 30) = 3.39$, $MSE = 250$, $p = .047$. No other significant interaction effect was found (ps > .07 and Fs < 2.9).

A second ANOVA on error rates revealed that relative position-noncorresponding trials were more error-prone than position-corresponding trials (7.3 vs. 2.8%), $F(1, 15) = 13.85$, $MSE = 1.45E\text{-}02$, $p = .002$. A significant interaction between absolute position-based correspondence and direction-based correspondence emerged, $F(1, 15) = 7.48$, $MSE = 3.70E\text{-}03$, $p = .015$, indicating that in absolute position-noncorresponding trials the proportion of error rates between direction-noncorresponding and direction-corresponding trials was 6.7 to 4.1%, and in absolute position-corresponding trials, 4.2 to 5.1%. This shows—as in Experiment 1a—that the interaction between absolute position-based and direction-based correspondence in the reaction time data is compromised by speed–accuracy trade-off: Fewer errors were made in conditions with slower responses times. Additionally, a significant interaction between absolute position-based correspondence, direction-based correspondence, and relative position-based correspondence emerged, $F(1, 15) = 10.94$, $MSE = 1.81E\text{-}03$, $p = .005$, showing that when absolute position was noncorresponding, the relative position-based correspondence effect on error rates (difference in percentage of errors between noncorresponding and corresponding trials) was larger in direction-noncorresponding trials than in direction-corresponding trials (7.9 vs. 3.4%). Instead, when absolute position was corresponding, this effect was larger in direction-corresponding trials than in direction-noncorresponding trials (2.8 vs. 4.1%). No other significant effect was found (ps > .07 and Fs < 3.8).

Discussion

The results of Experiment 3b mirrored those of Experiment 3a. While absolute and relative position-based correspondence effects were obtained, a direction-based effect was absent.

That is, the perceived motion direction had again no influence on response latency, while the position of the target relative to the screen centre or relative to the second stimulus speeded up corresponding responses. As in Experiment 3a, this effect was more pronounced in situations in which the imperative stimulus was positioned between the second stimulus and the screen centre.

The variation of the time interval between the onset of the square and the circle did not affect correspondence effects. It seems that the position codes, especially the relative position codes formed with respect to other stationary objects in the visual scene, are stronger than any directional-based codes and that this dominance is independent of the time of code formation.

EXPERIMENT 3C
Dynamic display

Experiment 3c addresses the question of whether the dominance of relative position information compared to directional information is also present when both types of information are dynamic. To this end, we replicated Experiment 3a with the exception that the initially stationary square moved in the same direction as the circle. The velocity of the square matched the velocity of the circle. Therefore, the distance between circle and square did not change. Because observers were instructed to follow the circle with their eyes, there was no retinal motion of the square. Rather, it remained at a fixed eccentricity. As in Experiment 3a, the imperative colour cue was shown simultaneously with the onset of the square.

Method

Participants

A total of 16 students (4 male, 12 female, aged between 20 and 40 years) of the Ludwig Maximilians University fulfilling the same criteria as in Experiment la were paid for participation. One of them had participated in Experiment 3a and one in Experiment 1b.

Apparatus and stimuli

Apparatus and stimuli were as those in Experiment 3a with the following exception: The square appeared simultaneously with the onset of the imperative colour-cue horizontally either 4° to the left or 4° to the right beside the circle (as Experiment 3a), and moved in the same direction as that of the circle for 350 ms. Eye movements were not monitored in this experiment, but participants were instructed to follow the target with their eyes.

Design

Participants worked through 10 blocks at 48 trials, preceded by 20 practice trials. Each block was composed of the possible combinations of two target colours (or response locations), two kinds of target, three target (stimulus with the imperative colour cue) positions on the screen, two target motion directions, and two target positions relative to the other stimulus, randomly intermixed.

Procedure

The same procedure was used as that in Experiment 3a.

Results

Anticipations and missed trials (0.4%) were excluded from the analysis. Choice errors (6.8%) were analysed separately. Mean RTs for absolute position-based correspondence, direction-based correspondence, and relative position-based correspondence were calculated (cf. Appendix Tables A1, A2, A3, and A4).

Contrary to the Experiments 3a and 3b, a three-way ANOVA on RT did not reveal a significant main effect for absolute position-based correspondence, $F(1, 15) = 3.07$, $MSE = 649$, $p = .100$. However, motion direction had an influence on response latency as indicated by a numerically small but significant direction-based correspondence effect, $F(1, 15) = 30.07$, $MSE = 247$, $p < .001$. That is, responses were faster when motion direction corresponded to response location (398 vs. 394 ms). Additionally, a significant effect for relative position-based correspondence was obtained, $F(1, 15) = 4.61$, $MSE = 197$, $p = .049$, indicating that responses were faster when the position of the coloured target relative to the second stimulus corresponded to the response location than when it did not (389 vs. 405 ms). However, the relative position-based correspondence was modulated by the direction-based correspondence $F(1, 15) = 12.18$, $MSE = 211$, $p = .003$. The relative position-based effect was more pronounced in direction-noncorresponding trials than in corresponding trials (26 vs. 8 ms). Another significant interaction occurred between absolute position-based and relative position-based correspondence, $F(1, 15) = 15.83$, $MSE = 157$, $p = .001$, indicating that the relative position-based effect was larger in absolute position-noncorresponding trials than in corresponding trials (19 vs. 15 ms; cf. Figure 5). No other significant interaction effect was found ($p > .20$ and Fs < 1.8).

A second ANOVA on error rates revealed that direction-noncorresponding trials were more error-prone than direction-corresponding trials (8.2 vs. 5.3 %), $F(1, 15) = 9.14$, $MSE = 7.88E\text{-}03$, $p = .009$. The same was true for relative position-noncorresponding trials (8.9 vs. 4.6%), $F(1, 15) = 5.35$, $MSE = 5.23E\text{-}03$, $p = .035$. No other significant effect was found (ps $> .15$ and Fs < 2.3).

Discussion

Contrary to Experiment 3a and 3b no Simon effect to the absolute position was obtained, while an effect for relative position-based correspondence was confirmed. Again, processing of the target's position relative to the second stimulus affected response selection. As in the two previous experiments, relative position was modulated by absolute position-based correspondence as well as by direction-based correspondence. More importantly, a direction-based Simon effect occurred even though a second, moving object was presented. That is, responses to the (moving) target were faster when its motion direction corresponded to the response location than when it did not. In the Experiments 3a and 3b, the direction-based Simon effect was not observed when a second, stationary object was shown. The reasoning was that coding of the moving target's position relative to the starting position was suppressed by the presentation of the stationary target. Instead, the moving target's position was coded relative to the second, stationary object. In the present experiment, coding relative to the second object occurred, but at the same time, the direction-based code persisted and resulted in a direction-based Simon effect. Thus, one may assume that only stationary reference objects may overwrite codes that refer to motion direction or rather to the starting position of a dynamic object. This is consistent with the finding that the object has to be shown in its initial position for some time for relative coding to occur: When the target appeared and moved immediately, the direction-based Simon effect was absent (cf. Ehrenstein, 1994). Therefore, a stationary reference position may be necessary to generate or suppress relative coding of target motion with respect to the starting position.

GENERAL DISCUSSION

In the present series of experiments, we investigated whether (task-irrelevant) motion information provided by a stimulus changing its position over time would affect manual left–right responses. So far, some studies reported direction-based Simon effects whereas others did not. Seven experiments were carried out to test whether direction-based Simon effects are real phenomena. In the Experiments 1a, 1b, 1c, and 2, a stimulus moved smoothly on a horizontal trajectory. At some unpredictable point the colour of the stimulus turned into red or blue, which specified a certain response. Motion direction and position of the stimulus relative to the screen centre were always irrelevant to the task. In Experiment 1a, no position-based effect was observed, but a direction-based Simon effect was found, which was not modulated by the response modality: Whether participants responded by pressing one of two keys or by moving a stylus in a certain direction did not change the results. The finding indicates that the representation of stimuli and responses show "dimensional overlap" (cf. Kornblum et al., 1990; Prinz, 1990, 1997) in terms of their relative position, but not in terms of a dynamic change of (lateral) position. That is, we assumed that observers process or represent object motion as a shift of position relative to the starting position and not as directional information.

In Experiment 2, a pronounced Simon effect occurred when the imperative stimulus appeared at the reversal point of an oscillating trajectory, but not when it appeared at a random position around the centre of the trajectory. At reversal points, motion direction was ambiguous whereas relative position was unambiguous. In contrast, motion direction was unambiguous but relative position was ambiguous at random positions around the centre of the trajectory. This pattern of results is evidence for the dominance of relative position over motion-based codes. The dominance of relative position coding was also present in the Experiments 3a, 3b, and 3c, in which relative position was pitted against motion direction by presenting an additional element in the visual scene. When the second element was stationary, effects of motion-based correspondence were eliminated, but pronounced effects of relative position-based correspondence occurred, indicating that relative position codes generated with respect to a context element possibly "overwrote" relative position codes formed with respect to the starting point of motion. The second element may have overwritten the start-related position code for two reasons: First, the appearance of the second element was accompanied by a sudden onset that typically captures attention. Second, appearance of the second element followed the starting position in time, such that the start-related code may have decayed. However, when the complete scene moved, the direction-based Simon effect re-emerged, indicating that only stationary objects may overwrite the relative code formed with respect to the starting position.

Additionally, we explored the role of eye movements in SRC and showed in Experiments 1b and 3a that the execution or preparation of saccadic eye movements—as proposed by some proponents of the attention-shifting account—is not necessary for a spatial Simon effect to occur. The stimuli in our experiments moved continuously at a velocity which reliably elicited smooth pursuit eye movements. It turned out that the direction-based Simon effect was not influenced by whether participants tracked the target or fixated a point at the screen centre. Thus, the effect per se was independent of the type of eye movement. However, eye movements modulated the relative strength of direction- and position-based Simon effects. When participants fixated the screen centre, the position-based Simon effect was more pronounced than the direction-based effect, whereas when participants tracked the target, direction-based effects were stronger. This finding indicates that participants possibly generated spatial codes based on a retinotopic coordinate system (see below). When participants fixated the screen centre, the fixation cross served as a reference for left and right coding of a stimulus, while in the pursuit condition, the target that was stabilized in the observer's fovea was used. As a result, the direction-based correspondence effect was stronger with pursuit eye movements, whereas effects due to absolute position were rather weak. However, an explanation in terms of retinotopic spatial representations is not sufficient to explain all our spatial correspondence effects: In Experiments 3a–3c, spatial coding of a secondary object in the visual array also produced correspondence effects (i.e., a relative position-based correspondence effect). Furthermore, the simultaneous existence of direction-based and position-based correspondence effects in Experiment 1b and the simultaneous existence of absolute and relative position-based effects in Experiments 3a–3c gave rise to the assumption that observer process more than one spatial relationship at the same time. In other words, observers may use more than one spatial reference point for coding the target position. The idea of simultaneously active multiple stimulus–response codes has been previously established by the study of Lamberts et al. (1992).

Simultaneous coding of different spatial relationships

Although a position-based Simon effect did not occur in every experiment, the interaction between direction- and position-based correspondence was almost always reliable. At first glance, the interaction effect indicates that both kinds of correspondence depend on each other. The interaction effect showed that the direction-based effect was stronger when position was corresponding. However, the effect was inverted when position was noncorresponding. That is, reaction times were faster in direction-noncorresponding trials. The inversion is somewhat surprising and not in line with Lamberts et al.'s (1992) assumption that the more spatial codes converge, the stronger the observed correspondence effects. However, further interpretation of the interaction of motion direction and position is not warranted for two reasons. First, when simple responses were recorded in response to a colour change of a stimulus moving away from or toward the screen centre, reaction times were shorter when the stimulus moved away from the screen centre toward the edges of the monitor. Second, an analysis of the proportion of error rates showed that the interaction of direction- and position-based correspondence was compromised by a speed–accuracy trade-off. Thus, it seems plausible to assume that the interaction between position and direction-based correspondence was not due to "joint compatibility effects" in the sense of Lamberts et al. (1992) but to some other, unrelated factors. Additionally, the notion of over-additive efficacy of spatial codes in the sense that the more spatial codes correspond, the stronger correspondence effects should be, was also not supported in Experiments 3a–3c in which two stimuli were presented simultaneously. Certainly, we found that relative position-based correspondence (i.e., with reference to the other stimulus) was modulated by whether absolute position of the target (i.e., with reference to the screen centre) was corresponding or noncorresponding, but it turned out that this interaction effect did not reflect a certain correspondence phenomena but might be due to a "retinal eccentricity effect". That is, our participants responded faster in situations in which the coloured target was presented closely to the fovea and therefore was easier to detect. In sum, there is evidence that interaction effects between certain spatial correspondence relations are due to some unrelated factors and do not reflect "real" compatibility phenomena. This again indicates that different spatial correspondence effects manifest themselves rather independently of each other. That is, parallel coding of the target's current position relative to the screen centre (i.e., to an egocentric reference), relative to a secondary stimulus in the visual array, and also relative to previous target positions (i.e., target motion) may have independently an impact on response selection processes.

The role of attention shifts in SRC and the Simon effect

In our Experiments 1b and 3a, eye movements were monitored, and some new insights into the role of attention in SRC and the Simon effect were gained. As a proponent of the attention-shifting hypotheses, Ehrenstein (1994) emphasized the role of saccadic eye movements for the emergence of spatial Simon effects because shifts of attention typically precede visually guided saccadic eye movements. That is, attention and saccadic eye movements are coupled in a mandatory fashion (cf. Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995). The main argument was that the last shift of attention before the response determines the spatial code formed with respect to the stimulus. Therefore, one may come to the conclusion that saccade preparation is closely coupled to the occurrence of the Simon effect. However, contrary to Ehrenstein and in line with the study of Kerzel et al. (2001), our experiments showed that saccadic eye movements or their preparation are not necessary for a direction-based Simon effect to occur. Rather, a Simon effect was also observed with pursuit eye movements of a smoothly moving target.

Even though this finding poses a problem for "saccade-based" accounts of the Simon effect, the general attention-shifting account may certainly accommodate our results. Van Donkelaar (1999) demonstrated that attention shifts in the direction of a target's motion while participants track a moving target. Applied to our experiments, this means that attention anticipated future target positions during smooth pursuit, and these anticipatory shifts of attention may have produced a corresponding direction code. Similarly, an attention shift account may explain why the direction- and position-based correspondence effect in Experiments 1b and 3a differed as a function of the eye movement instruction. When observers fixated the screen centre, a target presented on the left or right side of the screen primarily elicited a shift of attention to the left or right. Even if the target moved, this would not alter the primary direction of the attention shift because target motion was always confined to one side of the screen. Similarly, attention moved primarily in the direction of motion when observers were asked to follow the target with their eyes. In this situation, it was not necessary to shift attention to the target position, because the eyes (and attention) were already centred on the target. However, an attention-shifting account may have difficulty in explaining why the spatial code persisted for such a long time: Throughout our experiments, the target was shown in its starting position for 880 ms, which is sufficient time for an attention shift to be complete. Thus, the onset of the imperative stimulus did not require an additional shift of attention, because attention had ample time to settle on the target. Future research will have to determine the temporal properties of attention-based spatial codes.

Action effect anticipation

The assumption of an important role of eye movements in spatial compatibility or correspondence effects is to a certain extent in line with a core notion of the theory of event coding (TEC; Hommel, Müsseler, Aschersleben, & Prinz, 2001). Essentially, TEC postulates that the activation of an action effect automatically evokes a corresponding movement. At this point it is important to note that this works especially for to-be-planned, controlled actions. To a certain extent, saccadic eye movements are goal-directed actions programmed as consequence of covert attention shifts. In the present context this means that the representation of a saccadic eye movement toward a certain position in space would lead to an automatic activation of all corresponding responses. In other words, the spatial parameters used for saccade programming may be directly used for programming the corresponding manual response (cf. Rizzolatti et al., 1987).

While the notion of action effect anticipation may be easily applied to saccades, the situation is somewhat more complicated for smooth pursuit eye movements. Smooth pursuit eye movements are sometimes modelled as automatic responses in a closed-loop system with retinal motion as input into a negative feedback loop that tries to minimize retinal motion. However, this low-level engineering model of smooth pursuit eye movements cannot account for known effects of expectations on smooth pursuit. Studies by Kowler (1989) and Boman and Hotson (1992) challenged the traditional view that smooth pursuit eye movements operate in a purely closed-loop fashion without higher level, mental action planning. The authors showed that pursuit eye movements can be anticipatory and are driven by cognitive expectations about the direction of certain object movements.

The thesis that anticipated movement effects are the basis of the Simon effect is corroborated by our finding that a pronounced direction-based Simon effect occurred when observer tracked the target stimulus, while the effect was nearly absent when observer fixated the screen centre. That is, it could be the case that the representation of the to-be-executed eye movement contributed to the visual perception of the target's motion (cf. the early work of Lotze, "theory of local signs", 1852; see also Koenderink, 1990; Van der Heijden, Müsseler, & Bridgeman, 1999) and to the formation of other action-related spatial codes. For instance, planning an eye movement to the left may prime the code for a manual response to the left. In other words, the effect may not be due to attention shifts during pursuit eye movements but due to the representation of the specific oculomotor behavior and the automatic induction of a corresponding manual response.

In sum, the present study showed that direction-based Simon effects are real phenomena, which occur when observers are confronted with stimuli moving smoothly in a certain direction. That is, the perception of a moving object—although motion direction was task irrelevant—speeded up responses that spatially corresponded to the motion direction. The study provided evidence that the underlying representation was not based on motion, but on relative position. It may be that observer related the actual position of the dynamic target to its previously occupied positions—most notably the starting position. Thus, our direction-based Simon effects may be explained by the concept of similarity or dimensional overlap of stimuli and response sets: Participants may have related the relative stimulus position to the horizontal displacement or relative position of the response location. Effects of motion direction and absolute position were found to depend on the eye movement instruction. With smooth pursuit eye movement, direction-based effects were stronger than with eye fixation. Conversely, position-based effects were stronger with fixation than with pursuit. Thus, code formation may operate in a retinotopic representation or oculomotor demands may contribute to spatial code formation.

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TABLE A1

Mean reaction times, percentage of errors, and difference in mean reaction times in Experiments 1a, 1b, 2, and 3a–3c as a function of absolute position-based,[a] direction-based, or relative position-based[b] correspondence

		(Absolute) Position-based corresp.					Direction-based corresp.					(Relative) Position-based corresp.				
		Noncorresp.		Corresp.			Noncorresp.		Corresp.			Noncorresp.		Corresp.		
Experiment		*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*
1a	Main effect	375	4.9	373	4.8	2	380	5.1	368	4.5	12					
	Static	383	4.3	379	3.9	4	388	4.6	374	3.6	14					
	Dynamic	368	5.5	366	5.7	2	372	5.7	362	5.5	10					
1b	Main effect	436	4.5	426	2.5	10	436	3.8	426	3.3	10					
	Fixation	444	4.7	426	3.2	18	438	4.0	432	3.9	6					
	Pursuit	428	4.4	427	1.8	1	435	3.6	419	2.6	16					
2	Main effect	515	8.6	511	7.2	4	520	9.3	506	6.4	14					
	Reversal	512	8.9	510	6.4	2	524	10.2	498	5.0	26					
	Random around centre	518	8.4	512	7.9	6	517	8.5	513	7.8	5					
3a	Main effect	418	6.6	409	5.2	9	414	6.1	414	5.7	0	419	7.2	408	4.6	11
	Fixation	420	6.5	406	4.2	14	413	6.1	413	4.6	0	417	6.6	409	4.0	8
	Follow	417	6.8	412	6.2	5	415	6.2	414	6.8	1	421	7.2	408	5.2	13
3b	Main effect	403	5.4	395	4.6	8	400	5.5	398	4.6	2	411	7.3	387	2.8	24
	SOA = 0 ms	404	4.4	397	4.8	7	400	5.2	401	4.0	–1	413	6.5	388	2.8	25
	SOA = 880 ms	401	5.5	390	4.7	11	395	5.4	396	4.8	–1	409	7.3	383	2.9	26
	SOA = 1,480 ms	405	6.5	398	4.3	7	405	5.8	398	5.0	7	412	8.2	391	2.6	21
3c	Main effect	400	6.9	392	6.5	8	398	8.2	394	5.3	4	405	8.8	388	4.6	17

Note: Means are shown for each experimental condition and averaged across these conditions (main effect). Note that Experiments 1a, 1b, and 2 did not allow for the analysis of relative position-based correspondence. Noncorresp. = noncorresponding. Corresp. = corresponding. RT = reaction time, in ms. PE = percentage of error. ΔRT = difference in mean RTs.

[a]Screen centre is reference.

[b]Second stimulus is reference.

TABLE A2

Mean reaction times, percentage of errors, and difference in mean reaction times in Experiments 1a, 1b, 2, and 3a–3c as a function of (absolute) position-based[a] and direction-based correspondence

		(Absolute) Position-based correspondence									
		Noncorresp. Direction-based correspondence					*Corresp. Direction-based correspondence*				
		Noncorresp.		*Corresp.*			*Noncorresp.*		*Corresp.*		
Experiment		*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*
1a	Main effect	376	6.3	374	3.4	2	383	3.9	362	5.7	21
	Static	384	6.0	381	2.4	3	391	3.1	367	4.8	24
	Dynamic	368	6.6	367	4.4	1	375	4.8	357	6.5	18
1b	Main effect	435	5.1	437	4.0	–2	438	2.5	415	2.5	23
	Fixation	440	5.0	447	4.4	–7	435	3.0	417	3.4	18
	Pursuit	429	5.2	427	3.6	2	441	1.9	412	1.6	29
2	Main effect	524	10.0	506	7.3	18	517	8.7	505	5.3	12
	Reversal	530	9.8	495	4.2	35	517	6.3	502	3.1	15
	Random around Centre	518	6.3	518	6.8	0	516	6.5	507	4.6	9
3a	Main effect	411	7.5	426	5.7	–15	417	4.6	401	5.7	16
	Fixation	415	8.0	425	4.8	–10	411	4.0	401	4.3	10
	Follow	406	7.0	428	6.5	–22	424	5.3	401	7.0	23

(Continued)

Table A2 (Continued)

		(Absolute) Position-based correspondence									
		Noncorresp. *Direction-based correspondence*					*Corresp.* *Direction-based correspondence*				
		Noncorresp.		*Corresp.*			*Noncorresp.*		*Corresp.*		
Experiment		*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*
3b	Main effect	400	6.7	407	4.1	–7	400	4.2	390	5.1	10
	SOA = 0 ms	401	5.5	407	3.2	–6	398	5.0	395	4.7	3
	SOA = 880 ms	400	7.1	402	3.9	–2	391	3.7	389	5.8	2
	SOA = 1480 ms	398	7.7	411	5.3	–13	411	3.9	385	4.7	26
3c	Main effect	406	8.0	395	5.9	11	391	8.3	394	4.7	–3

Note: Means are shown for each experimental condition and averaged across these conditions (main effect). Noncorresp. = noncorresponding. Corresp. = corresponding. RT = reaction time, in ms. PE = percentage of error. ΔRT = difference in mean RTs.

[a]Screen centre is reference.

TABLE A3

Mean reaction times, percentage of errors, and difference in mean reaction times in Experiments 3a–3c as a function of (absolute) position-based[a] and (relative) position-based[b] correspondence

		(Absolute) Position-based correspondence									
		Noncorresp. (Relative) Position-based correspondence					*Corresp. (Relative) Position-based correspondence*				
		Noncorresp.		*Corresp.*			*Noncorresp.*		*Corresp.*		
Experiment		*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*
3a	Main effect	426	8.3	411	4.9	15	412	6.0	406	4.3	6
	Fixation	428	8.4	412	4.5	16	406	4.8	406	3.5	0
	Follow	424	8.2	410	5.3	14	418	7.2	407	5.1	11
3b	Main effect	419	8.3	389	2.6	30	404	6.4	386	2.9	18
	SOA = 0 ms	420	6.6	389	2.1	31	407	6.3	387	3.4	20
	SOA = 880 ms	418	7.6	385	3.4	33	399	7.1	380	2.4	19
	SOA = 1,480 ms	419	10.6	391	2.4	28	405	5.7	391	2.9	14
3c	Main effect	410	8.8	392	5.1	18	400	8.9	385	4.1	15

Note: Means are shown for each experimental condition and averaged across these conditions (main effect). Noncorresp. = noncorresponding. Corresp. = corresponding. RT = reaction time, in ms. PE = percentage of error. ΔRT = difference in mean RTs.

[a]Screen centre is reference.

[b]Second stimulus is reference.

TABLE A4

Mean reaction times, percentage of errors, and difference in mean reaction times in Experiments 3a–3c as a function of absolute position-based,[a] direction-based, and relative position-based[b] correspondence

	(Absolute) Position-based correspondence																			
	Noncorresp. Direction-based correspondence										*Corresp. Direction-based correspondence*									
	Noncorresp. (Rel.) Pos.-based corresp.					*Corresp. (Rel.) Pos.-based corresp.*					*Noncorresp. (Rel.) Pos.-based corresp.*					*Corresp. (Rel.) Pos.-based corresp.*				
	Noncorresp.		*Corresp.*			*Noncorresp.*		*Corresp.*			*Noncorresp.*		*Corresp.*			*Noncorresp.*		*Corresp.*		
Experiment	*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*	*RT*	*PE*	*RT*	*PE*	*ΔRT*
3a ME	418	9.5	403	5.5	15	434	7.0	419	4.4	15	421	5.5	414	3.8	7	403	6.6	399	4.8	4
Fixat.	425	10.5	405	5.5	20	431	6.2	418	3.5	13	413	5.2	408	2.7	5	399	4.5	403	4.2	–4
Follow	412	8.4	400	5.6	12	437	7.9	419	5.0	18	429	5.7	419	4.8	10	407	8.6	394	5.5	13
3b ME	414	10.7	387	2.8	27	424	5.8	391	2.5	33	408	5.6	393	2.8	15	400	7.1	379	3.0	21
0 ms	419	9.4	384	1.6	35	421	3.8	394	2.6	27	406	5.8	391	4.2	15	408	6.8	383	2.6	25
880 ms	415	10.9	386	3.2	29	421	4.2	384	3.7	37	397	6.8	385	0.5	12	403	7.3	375	4.2	28
1480 ms	407	11.7	390	3.7	17	431	9.5	393	1.1	38	420	4.2	402	3.7	18	390	7.3	381	2.1	9
3c ME	421	10.3	391	5.6	30	399	7.3	390	4.5	9	402	10.8	380	5.9	22	398	6.9	390	2.4	8

Note: Means are shown for each experimental condition and averaged across these conditions (main effect). Noncorresp. = noncorresponding. Corresp. = corresponding. Rel. = relative. ME = main effect. Fixat. = Fixation. RT = reaction time, in ms. PE = percentage of error. ΔRT = difference in mean RTs.

[a]Screen centre is reference.

[b]Second stimulus is reference.