Does the Simon Effect Interfere With the Synergy between Perception and Action?

Abstract

Research suggests that – particularly – the execution of precision-demanding far-aiming tasks necessitates an optimal coupling between perception and action. In this regard, the duration of the last fixation before initiating movement – i.e., the Quiet Eye (QE) – has been functionally related to subsequent motor performance. In the current study, we investigated potential mechanisms of QE by applying the Simon paradigm – i.e., cognitive interferences evoked by stimulus-effect incompatibilities over response selection. To this end, we had participants throw balls as precisely as possible, either with their left or right hand (hands condition, HC) or at left or right targets (targets condition, TC), respectively. Via monaural auditory stimuli, participants received information about the hand side and the target side, respectively, either with compatible (i.e., congruent stimulus-effect side) or incompatible (i.e., incongruent stimulus-effect side) stimulus-effect mappings. Results showed that participants reacted slower and showed later first fixation onsets at the target in incompatible vs. compatible trials, thus, replicating and extending the classical Simon effect. Crucially, in the HC, there were earlier QE onsets and longer QE durations in incompatible (vs. compatible) trials, suggesting an inhibition of cognitive interferences over response selection to preserve motor performance. These findings are in line with attentional explanations of QE, suggesting optimized attentional control with efficient management of limited cognitive resources (optimal-attentional-control explanation) or with the inhibition of alternative response parametrization (inhibition explanation).

Key words: Quiet eye, attention, cognitive interferences, inhibition function, motor performance

Introduction

Ample research has shown that motor skills that demand high precision require an optimal coupling between perception and action (e.g., Klostermann, Vater et al., 2020). The reader can observe this by solving a far-aiming task with the dominant hand. First, grasp a piece of paper, wad it up and – with this paper ball – try to hit the wall next to you. Then, pick up the paper ball go back to your desk and now try to hit the bin that should be positioned at about the same distance as in the previous throwing attempt. On average, more people will be successful with the first than with the second task, and, on reflection, the reader will have noticed that the first attempt required no substantial preparation. In contrast, for the second task, most readers will have prepared their throwing attempt by "aiming" with the eyes at the target to be hit. Thus, the higher the task demands, the greater the requirement to couple visual perception and motor action.

In sports, athletes are constantly facing similar challenges in a variety of situations. For example, imagine a golfer attempting to hole a golf ball from a distance of 10 meters, a soccer player trying to make a free kick goal by aiming at the right-upper corner , a dart thrower trying to hit the treble 20, or a basketball player shooting a free-throw. Gaze analyses have revealed that in these and similar situations, experienced (as compared to less experienced) athletes show distinct gaze patterns characterized by prolonged phases of visual information processing (i.e., a comparable small number of fixations of relatively long durations [for a recent review Brams et al., 2019]). Moreover, when studying gaze behavior synchronized to ongoing motor actions, research has suggested that a stable fixation just before movement initiation is particularly crucial for high level subsequent motor performance. For example, just before shooting the free throw, the experienced athlete focuses the gaze at the front rim of the basket and maintains this fixation until the ball has left the hand (e.g., Harle & Vickers, 2001; Klostermann, et al., 2017; Vickers, 2007; Wilson, et al., 2009). Likewise, the skilled golfer focuses on the back part of the ball just before initiating the backward movement of the golf club and maintains this fixation until the ball is struck (e.g., Klostermann, et al., 2014; Vickers, 2012). In sports science, this particular gaze behavior is known as Quiet Eye (QE; Vickers, 1996). It should be noted that – being aware of the functionality of microsaccades over fixations (e.g., Martinez-Conde, et al., 2006) – *quiet* does not imply a completely static point of gaze, but, rather, denotes the relatively precise, stable and constant gaze behavior of, for example, experienced as opposed to less experienced athletes who show a higher number of saccades, and thus a rather noisy eye. Vickers (2007) defined the QE as the "final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace ... The onset of the quiet eye occurs prior to the final movement of the task, and the offset occurs naturally when the gaze deviates off the location or object …" (p. 11).

The QE has been found to be a valid predictor of high motor performance, in particular when it comes to motor expertise (for a recent meta-analysis, e.g., Lebeau et al., 2016). Generally, it has been found that the QE of experienced athletes is evident earlier in the movement (i.e., an earlier fixation onset) and is sustained longer throughout the movement (i.e., longer fixation durations). With regards to predicting subsequent motor performance, the effects to be expected are smaller and the empirical evidence is less homogenous (average d = 0.58, 95 % CI [0.34, 0.82]; Lebeau et al., 2016). As an example, Klostermann, et al. (2018) showed that sport science students were more accurate in a far-aiming task when throwing under experimentally manipulated long vs. short QE durations. But, in the seminal study by Vickers (1996), positive QE effects on free-throw performance were only found for the skilled, but not for the less-skilled, basketball players. Meanwhile a number of studies found positive relations to subsequent motor performance in field studies (e.g., Causer, et al., 2017) and experimental lab studies (e.g., Klostermann et al., 2018; Sun, et al., 2016). But opposite findings were also reported both in field (e.g., Walters-Symons, et al., 2018) and lab studies (e.g., Harris et al., 2021; Klostermann, 2020).

In line with discussions on the scope of the QE's functionality, its underlying mechanisms have been increasingly researched. Derived from early theories on the QE's functionality in movement preparation and control – some have addressed QE within a cognitive framework (e.g., Vickers, 1996; Williams, et al., 2002) or a psycho-ecological framework (e.g., de Oliveira, et al., 2008; Oudejans, et al., 2002), while more recent theoretical assumptions have related the QE to attentional mechanisms (e.g., Klostermann et al., 2014; Vine, et al., 2014), and to postural-control mechanisms (e.g., Gallicchio, & Ring, 2019), respectively. Those recent efforts particularly resulted from the understanding that long QE durations in experienced athletes hardly can be explained with improved information processing over movement preparation and control (e.g., Findall, et al., 2019; Harris et al., 2021; Klostermann, 2020). Rather, among elite athletes, it is efficiency that is paramount, not longer information processing (cf. Mann, et al., 2016).

Attentional explanations assume that, over the QE period, motor control is being facilitated by optimized attentional control and by the shielding of ongoing motor-control processes, respectively. The *former* predicts that over the QE period, top-down attention is facilitated allowing performers to maintain their focus on the current task goals. This avoids attention being drawn (bottom-up) to internal threatening stimuli like anxiety (for an overview, see Vine et al., 2014). Empirical evidence was derived from learning studies in which different motor skills (e.g., basketball free throw, Vine & Wilson, 2011; golf putting, Vine, et al., 2011) were trained with intervention regimens that specifically addressed optimizing the QE. Different from the learners in the classical technical intervention groups, the learners in the QE intervention groups developed a resistance against performance failure under pressure that was tested in experimentally controlled high-anxiety situations. The *latter* predicts that the QE subserves the parametrization of the currently selected from potentially viable task variants and parametrizations (i.e., inhibition hypothesis, Klostermann et al., 2014; for a neurophysiological perspective, see, e.g., Cisek & Kalaska, 2010). Empirically, the inhibition function was shown, among others, in studies that related the QE duration to demands over response selection. In experiments that manipulated the number of potential targets in a far-aiming task, longer QE durations were found if one had to select one out of four targets as opposed to selecting one pre-defined target. This suggests that potential alternative response selections required increased inhibition of the selected response, and thus, longer QE durations (e.g., Klostermann, 2019).

Thus, both attentional approaches predict that cognitive processes that interfere with motor control should be manifested in changes to the QE. A well-studied phenomenon in experimental psychology, known to evoke such cognitive interferences, is the Simon paradigm (Hommel, 2011). As emphasized by Hommel (2011), Simon and Small (1969) were the first to show that the location of the stimulus presentation – being irrelevant to the task – affects ongoing motor actions (i.e., the Simon effect; for an overview, see Lu & Proctor, 1995). Recalling the paper wad throwing task described earlier, if the paper thrower has two (vs. one) target bins and those bins are positioned to the left and to the right side of the thrower, the thrower will initiate the movement faster and more often to the correct bin if this information is presented on the same (vs. the opposite) side as the selected bin (i.e., better performance with a compatible side-stimulus presentation). Research to date, has not tested this hypothesis with complex movements like the throwing task, but only with “classical” reaction-time tasks, as in Simon and Small (1969) who required participants to press one of two potential buttons as fast as possible and presented participants with information about which of two buttons to press via auditory stimuli (high vs. low pitched tones) to the left or the right ear. If participants were required to press the left button which was signaled by the respective tone, participants were faster and more accurate if this information was signaled to the left ear as opposed to the right ear. The Simon effect has been ascribed to incompatibilities between the stimulus and the anticipated effect of the task (Hommel, 1993), with the interferences theorized to be over response selection (Kornblum, et al., 1990; Hommel, 2019).

In the present experiment, we investigated effects of this type of cognitive interference in complex movement patterns through the onset and duration of the QE. We sought to replicate and extend the classical Simon effect (i.e., longer reaction times and higher error rates for incompatible vs. compatible stimulus-effect mappings) both for the throwing movement (derived from the findings in reaction-time tasks, e.g., Lu & Procter, 1995) and for the eye movements (e.g., Lugli, et al., 2016). We manipulated both the throwing hand (right or left) and the target choice (right or left) and conditions for which stimuli might be compatible or incompatible. Critically, due to cognitive interferences in incompatible trials we predicted, earlier QE onsets and longer QE durations in incompatible vs. compatible trials, and further predicted that these QE effects, should be particularly apparent for incompatible stimuli pertaining to the throwing hand (cf. Klostermann, 2020; Klostermann, et al., 2020).

Method

Participants

A priori calculations of an optimal sample size (G*Power 3.1; cf. Faul, et al., 2009) for the predicted 2 (experimental conditions) x 2 (compatibility/incompatibility stimuli effects) ANOVA interaction revealed that – by assuming medium to large effect sizes ($f = 0.40$, e.g. Klostermann, 2020), setting the test power ($1-\beta$) to .80 and the alpha-error to .05 – a minimum number of 16 participants would be required. However, findings in pilot studies suggested that a number of participants might drop-out because of too many missing QE detections due to the Simon manipulation. Thus, to have a well-powered study, we increased the sample size to 28.

Participants were then 18 males (M_{age} = 21.8 years, SD = 1.8) and 10 females (M_{age} = 21.2 years, SD= 1.7) sport science students who had all self-reported normal or corrected-to-normal vision (by wearing lenses) and were right-handed. All participants were recruited from an ungraduated course and received course credits in return for their participation. The participants were blinded to the research question. The protocol was approved by the ethics committee of the local Faculty of Human Sciences and was carried out in accordance with the 1964 Declaration of Helsinki. All participants gave written informed consent to participate in this research.

Rationale and research design

We applied the Simon paradigm in a far-aiming task to evoke cognitive interferences over response selection and parametrization. To this end, participants were required to throw balls as accurately as possible at two potential targets. In one experimental condition, participants received auditory information cuing them to throw with the left or the right hand at one target (hands condition, HC). In the other experimental condition, balls were thrown only with the dominant hand at two potential targets, and participants received auditory information cuing them to throw at the left or the right target (targets condition, TC). In half of the trials, the stimulus-effect mapping was compatible (i.e., stimulus and effect were on the same side); in the other half of the trials, the stimulus-effect mapping was incompatible (i.e., stimulus and effect were on the opposite side). Irrespective of the experimental condition (HC vs. TC), we expected the Simon effect to elicit longer reaction times and higher rates for the incompatible versus compatible stimulus effect patterns.

Apparatus and materials

The three-dimensional (3D) kinematic data of the ball, the hands, and the head were recorded with a 10-camera VICON T20 system (VICON Motion Systems Limited, Oxford, United Kingdom; operating at 200 Hz) by use of retro-reflective markers (hands and head; marker diameter: 14 mm) and retro-reflective cover material (ball; 3M Switzerland, Rüschlikon, Switzerland), respectively. The horizontal and vertical rotations of the right eye were recorded with a system-integrated monocular eye tracker (EyeSeeCam, EyeSeeTec GmbH, Fürstenfeldbruck, Germany; operating at 220 Hz) which was connected via an active optical FireWire extension (GOF-Repeater 800, Unibrain, San Ramon, CA, USA) to a MacBook Pro (Apple, Cupertino, CA, USA) running the EyeSeeCam software. This software was only used for calibrating the eye tracker and streaming eye orientation data over the network. The data from the VICON and the EyeSeeCam systems were synchronized by self-written experimental control software (SMLC) operating in Matlab (Matlab 2014a, The MathWorks, Natick, MA, USA) ran on the main control workstation (HP Z230 Tower-Workstation, Hewlett Packard, Palo Alto, CA, USA). Additionally, SMLC calculated the 3D gaze vector in the laboratory reference frame by means of the eye orientation data and the positional and rotational head movement data (a detailed description of the system can be found in Kredel, et al., 2015). The accuracy of the integrated eye-tracking system amounts to 0.5° of visual angle with a resolution of 0.01° RMS within 25° of the participant's field of view.

The visual stimuli were programmed in Matlab 2016b and the resulting AVI video files were rendered with Magix Video Pro X3 (Magix Software GmbH, Berlin, Germany) into a MP4 container format with an H.264 compression (video resolution: 1280 x 960 px; audio resolution: bitrate = 128 kbit/s; sampling rate = 44.1 kHz). An LCD projector (Epson H271B LCD Projector, Nagano, Japan) streamed the visual stimuli at a life-sized white screen (width: 320 cm; height; 220 cm). The auditory stimuli were programmed with Audacity 2.4 (http://audacityteam.org/) and presented via earphones (MDR-ZX110B, Sony Corporation, Konan, Japan) that were connected to the main control workstation. Data analyses were conducted with Matlab 2017b, Microsoft Excel 2016 (Microsoft, Redmond, WA, USA), and IBM SPSS Statistics 27 (IBM, Armonk, NY, USA).

Visual stimuli

At the beginning of each trial, a fixation cross was presented in the center of the video. In the following, in the TC two targets and in the HC one target was presented with a horizontal offset of 330 px (i.e., 82.5 cm in real-world coordinates) to the left and to the right of the center, respectively. On average 4.8 seconds (min = 4.6 s; max = 5.1 s) after the start of the trial, either a high-pitched tone (500 Hz) or a low-pitched tone (200 Hz) was embedded either on the left channel or on the right channel in the audio track of the video files. For the warm-up trials the tones were embedded on both audio channels. The targets disappeared after 10 seconds which finished each trial. Crucially, between the two conditions the different timelines and the target to be thrown at were matched such that, except for number of targets presented, exactly the same videos were shown in both conditions. To state more precisely, if in a HC video the left target was presented, in the corresponding TC video the respective tone was embedded which also required the participant to select the left target.

Procedure

The experiment was conducted in the Institute's sensorimotor laboratory. Participants attended individual sessions on two separate test days within exactly seven days. Half of the participants started with the TC condition, and the other half started with the HC condition. On the first test day, participants received brief experimental instructions and provided informed consent. Next, participants were positioned at the throwing line at a distance of 2.80 m to a wall at which the visual stimuli were projected ($M_{\text{throwing distance}}$ = 2.85 meters, $SD = 0.23$). The balls were placed in a separate box positioned at hip height to the right side of the participants. After participants were equipped with the VICON markers, the EyeSeeCam, and the earphones, we showed a longer introductory video that included two warm-up blocks of 16 trials each. In each warm-up trial as well as in each test trial, participants were instructed to throw the ball as centrally as possible at the center of the target (30 cm in diameter) as soon as they perceived the auditory tone. Throwing hand and actual target depended on the pitch height. In the beginning of the trials in the HC, participants always kept two balls in their hands.

In the first warm-up block, participants became familiar with the task and warmed-up by throwing at one of the two targets presented. In these trials, no auditory tones were played. In the second warm-up block, participants received auditory information which, however, was played in stereo. Thus, the throwing hand and the target, respectively already had to be selected but – due to the stereo playback – without stimulus-effect manipulations. Instead, these trials were used to check whether participants correctly understood their individual matching between pitch level and throwing hand and target, respectively. Therefore, after each throw attempt, participants received feedback as to which hand and at which target, respectively, they should have been throwing with and should have thrown at, respectively. Additionally, the experimenter provided augmented feedback in case participants threw with the incorrect hand and at the incorrect target. It should be noted that in the test trials we provided no feedback.

Following the last trial of the second warm-up block, the EyeSeeCam was calibrated which required participants to consecutively fixate five equidistant points (8.5 ° of visual angle) on the life-sized screen. The EyeSeeCam was re-calibrated if the point of gaze deviated by more than 1 ° of visual angle from one of the five points of the calibration grid. Calibration quality was checked after every eighth test trial. The first of eight test blocks with 16 trials each started (TC: 2 stimulus sides x 2 stimulus-effect mappings x 2 target positions x 16 repetitions / HC: 2 stimulus sides x 2 effector sides x 2 stimulus-effect mappings x 2 target positions x 8 repetitions). The stimulus-effect mapping was counter-balanced such that half of the participants had to throw with their right hand and at the right target, respectively, if a low-pitched tone was played. For the other half, a low-pitched tone required to throw with the left hand and at the left target, respectively. In half of the trials, the stimulus-response mapping was compatible; in the other half the mapping was incompatible. The trials were presented in random order with the constraint of the same number of high-pitched/low-pitched, compatible/incompatible trials, and target positions after 4 blocks.

On the second test day, participants were tested in the other experimental condition with very similar procedure. Again, participants had two warm-up blocks with 16 trials each and 8 test blocks with 16 trials each. The stimulus-effect mapping was kept constant across test days. Thus, if participants had to throw with their right hand at a low-pitched tone on the first test day, then on the second test day a low-pitched tone again required them to throw at the right target. The testing on each test days lasted about 75 minutes. At the end of the second testing session, participants were thanked and informed about the aims of the study.

Measures

Data check. After data collection from each participant, 256 data files were available with 64 trials in each condition/stimulus-response-mapping combination. Before data aggregation, however, some trials had to be excluded because of technical errors over data collection (*M* = 1.9 trials, *SD* = 2.0 trials), and missing QE detections (*M* = 15.5 trials, *SD* = 15.8 trials). Further, all trials with reaction times faster than 150 milliseconds (ms) and slower than 2800 ms (exclusion criteria from Hommel, 1993, adapted to the current motor task) were also excluded from further data analyses (*M* = 0.6 trials, *SD* = 3.7 trials). Error trials (i.e., trials in which participants did not throw with the correct hand and/or at the correct target) were used for the manipulation check only but were excluded for the calculation of the remaining dependent measures.

As expected, mainly due to a high number of missing QE trials, there were participants with a large number of trials that could not be included in the final analyses of the dependent measures. To ensure a high validity of the aggregated scores, participants needed at least 16 valid trials before we could test for the crucial 2 (conditions) x 2 (stimulus-effect mappings) interaction (e.g., Klostermann, 2020). Since the data sets of eight participants did not match this requirement, these data sets could not be considered in the following data aggregation and had to be removed from the sample. Thus, the final sample for these analyses consisted of 20 participants. For these 20 participants, on average, we used 46.8 trials for further data aggregation (HC compatible: Range = 18-63 trials, *M* = 42.1; HC incompatible: Range = 20-64 trials, *M* = 43.0 / TC compatible: Range = 22-63 trials, *M* = 51.6; TC incompatible: Range = 25-63, *M* = 50.6). Due to data removal, our effort to perfectly balance the stimulus-effect mappings was slightly affected such that 11 participants had one and 9 participants had the other stimulus-effect mapping.

Percent of errors. An error was detected if participants threw the ball with the incorrect hand and at the incorrect target, respectively. The number of errors was separately aggregated for each condition/stimulus-effect mapping combination and divided by the individual number of valid trials per participant for each condition/stimulus-effect-mapping combination. Finally, to obtain percentage values, these values were multiplied by 100.

Movement phases. For the calculation of the participants reaction time and the movement initiation (i.e., initiation of the forward swing, e.g., Klostermann et al., 2018), in each trial, initially, the markers of the hands were filtered with a Savitzky-Golay-Filter (polynomial order = 3; frame length = 41) and averaged to obtain one central hand marker. Next, the moment of movement initiation was determined as the most backward position in the throwing movement before the moment of ball impact. Finally, reaction time was assessed by searching backwards in the timeline starting with the moment of movement initiation. The first VICON frame in which the velocity of the hand turned positive was chosen as the reaction time. The detection of the movement phases was visually verified and statistically confirmed by very high split-half reliability coefficients (all *r*s > .995).

Quiet Eye and first fixation onset. We analyzed the gaze data using the dispersion-based algorithm by Nyström and Holmqvist (2010). The point of gaze was classified as a fixation if it became stable within a circular area of 1.2 ° of visual angle for at least 120 ms (for more details, see Kredel et al., 2015). The QE was defined as the final fixation on the target disk before movement initiation (i.e., the initiation of the hand's forward swing). The onset and offset were identified as the first and last VICON frames of the QE fixation, respectively. QE onset and offset were then calculated as relative values in relation to movement initiation. Thus, negative values represent moments in time before movement initiation; positive values denote moments in time after movement initiation. The QE duration was calculated as time interval between QE onset and QE offset. In addition, as a manipulation check, we analyzed the onset of the first fixation on the target after the onset of the Simon stimulus (i.e., first fixation onset). Similar to the QE onset, first fixation onset was calculated as the relative value to the onset of the Simon stimulus. QE onset, QE offset, QE duration, and first fixation onset were separately aggregated for the 2 (conditions: HC vs. TC) x 2 (compatibility: compatible vs. incompatible stimulus-effect mappings) factors. Moreover, median splits of QE duration were performed to calculate short vs. long QE durations trials (cf., e.g., Causer et al., 2017; Klostermann, 2018).

Throwing performance. Throwing performance was obtained by computing radial-error scores. To this end, the position of the center of the target disk was determined by converting the relative position of the target in the video scene to the physical screen's frame of reference. The metric deviation of the ball from the target center at ball impact could then be calculated. The throwing performance was separately aggregated for the 2 (conditions: HC vs. TC) x 2 (compatibility: compatible vs. incompatible stimulus-response mapping) factors as well as for long vs. short QE-duration trials.

Statistical analyses

All dependent measures were analyzed with 2 (condition: HC vs. TC) x 2 (compatibility: compatible vs. incompatible stimulus-response mappings) ANOVAs with repeated measures on both factors. In addition, throwing performance was further analyzed with a 2 (split: long vs. short QE duration trials) x 2 (condition: HC vs. CT) x 2 (compatibility: compatible vs. incompatible stimulus-effect mapping) ANOVA to study predicted performance-enhancing effects of long QE durations. Significant interaction effects were further analyzed with one-sided dependent t-tests and with additional Wilcoxon signed rank tests in case of non-normality distributed data. The significance level α was set .05. A posteriori effect sizes were computed as Cohen's d_z-values and partial eta squared, η_p^2.

Results

Manipulation checks

There were differences in percent of errors as a function of condition (M_{hands} = 15.1 %, SD = 13.7; M_{targets} = 6.3 %, SD = 6.4), $F(1, 19) = 5.41$, $MSE = 1526.6$, $p < .05$, $\eta_p^2 = .22$, but not as a function of compatibility, $F(1, 19) = 1.64$, $MSE = 37.5$, $p > .05$, $\eta_p^2 = .08$. The interaction of condition x compatibility was not significant, $F(1, 19) = 0.71$, $MSE = 16.2$, $p > .05$, $\eta_p^2 = .04$. The analysis of the reaction time, however, revealed a significant main effect for compatibility, $F(1, 19) = 19.57$, $MSE = 24684.1$, $p < .05$, $\eta_p^2 = .51$, with longer reaction times in incompatible ($M = 1342.9$ ms, $SD = 409.4$) as compared to compatible trials ($M = 1307.7$ ms, $SD = 416.3$). The main effect for condition, $F(1, 19) = 3.67$, $MSE = 266266.1$, $p > .05$, $\eta_p^2 = .16$, and the condition x compatibility interaction, $F(1, 19) < 0.01$, $MSE = 6.1$, $p > .05$, $\eta_p^2 < .01$, were not significant. Moreover, analyses of the relative onset of the first fixation revealed that participants showed later onsets in incompatible ($M = 846.6$ ms, $SD = 236.1$) than in compatible ($M = 812.5$ ms, $SD = 233.8$) trials, $F(1, 19) = 14.41$, $MSE = 23250.2$, $p < .05$, $\eta_p^2 = .43$. The remaining tests did not reach the pre-determined level of significance (all ps > .38, all $\eta_p^2 < .04$).

In sum, with an average Simon effect of 35.1 ms ($SD = 34.6$) for reaction time and an average Simon effect of 34.1 ms ($SD = 39.1$) for first fixation onset the classical Simon effect was replicated and extended to the more complex far-aiming task.

Quiet Eye

The analyses revealed for the QE duration (Figure 1a), $F(1, 19) = 6.39$, $MSE = 14203.8$, $p < .05$, $\eta_p^2 = .25$, and the QE onset (Figure 2a), $F(1, 19) = 7.67$, $MSE = 2878.9$, $p < .05$, $\eta_p^2 = .28$, significant condition x compatibility interactions. For both variables, the main effects (condition: all ps > .36, all $\eta_p^2 < .04$; compatibility: all ps > .41, all $\eta_p^2 < .04$) were not significant. Likewise, for QE offset, neither the main effects nor the interaction effect were significant (all ps > .16, all $\eta_p^2 < .11$).

To better visualize the interaction effects for QE duration and QE onset, in Figure 1b (QE duration) and Figure 2b (QE onset), average differences between incompatible and compatible trials are depicted for each of the 20 participants as a function of condition. All positive values denote longer QE durations and earlier QE onsets in incompatible as compared to compatible trials. It can be seen that for both dependent measures one participant showed extreme repeated-measures effects in the hand condition. Therefore, the results of the parametric dependent t-tests were followed-up by respective non-parametric tests. For QE duration, it was found that in HC, $t(19) = 1.95$, $p < .05$, $d = .44$; $Z = 2.01$, $p < .05$, participants showed longer QE durations in incompatible trials ($M = 599.9$ ms, $SD = 314.0$) as compared to compatible trials ($M = 561.2$ ms, $SD = 315.0$). Descriptively, the opposite was found for the TC, with longer QE duration in compatible trials ($M = 562.0$ ms, $SD = 326.1$) vs incompatible trials ($M = 547.3$ ms, $SD = 308.8$). This difference, however, was not statistically significant, $t(19) = 0.97$, $p > .05$, $d = .22$; $Z = 0.93$, $p > .05$. For QE onset, similar differences were revealed with earlier QE onsets in incompatible vs. compatible trials in HC, and the opposite result pattern in TC. However, those descriptive differences were not significant – HC: $t(19) = 1.39$, $p > .05$, $d = .31$; $Z = 1.64$, $p = .05$; TC: $t(19) = 1.43$, $p > .05$, $d = .32$; $Z = 1.53$, $p > .05$.

With regards to the QE-performance splits, on average participants were slightly more accurate in long QE-duration trials ($M = 177.5$ mm, $SD = 46.1$ mm) vs. short QE-duration trials ($M = 181.2$ mm, $SD = 50.8$ mm). But, the respective ANOVA revealed neither a significant main effect for split, $F(1, 19) = 0.36$, MSE = 578.4, $p > .05$, $\eta_p^2 = .02$, nor further significant interactions with split as factor (all ps > .25, all $\eta_p^2 < .07$).

Discussion

The current study aimed to further our understanding of underlying mechanisms of the QE. Among other suggested mechanism (for an overview, e.g., Gonzales et al., 2017), there have been two approaches which relate the QE to attentional processes over movement parametrization. Although being different in the specific mechanism – i.e., optimal attention control necessary to manage limited cognitive resources (e.g., Vine et al., 2014) vs. shielding of the ongoing movement parametrization against optional parametrization (e.g., Klostermann et al., 2014) – both approaches would allow us to predict increased QE durations in response to cognitive interferences over response selection. In the former case, this is because of the necessity to optimize the attentional focus on the actual action goal. In the latter case, this is to inhibit alternative movement parametrization evoked by the incompatible stimulus-effect mapping.

We tested this exact prediction by applying the Simon paradigm to a far-aiming task that evoked cognitive interferences over the response-selection phase of a throwing movement, as evidenced by prolonged reaction times and delayed fixations at the target. Thus, the Simon effect was successfully replicated for a rather complex motor tasks which required participants to precisely control the movement of an object in space.

Turning to our main research question, these successful manipulation checks allowed us to examine the response of the QE to these cognitive interferences. Our findings, however, did not provide the clear-cut picture we expected. First, as evidenced by inferential statistics, the effect of the manipulation was not as strong as expected. Although the interaction effects for QE duration and QE onset were significant, the results of the crucial comparisons between compatible and incompatible stimulus-effect-mapping trials were not conclusive. Second, we found exactly the opposite TC condition pattern from what was expected – i.e., by a tendency toward shorter QE durations in incompatible stimulus-response-mapping trials. Of note, recent findings have suggested that the proposed inhibition function over long QE durations, rather than the final effect, should be assumed to be aligned with internal predictions regarding movement parametrization (cf. Klostermann, et al., 2020). The inhibition hypothesis does not allow the prediction of shorter QE duration if there is interference with selection of the final effect. Thus, in an attempt to better understand these two open questions, we conducted further post-hoc analyses that will be explained in the following sections.

Post-hoc analyses – Size of the Simon effect

Research suggests that the size of the Simon effect decreases over time. This decrease is partly explained by an automatic decay of the respective response code activation (Hommel, 1994, 2019). This means that if a stimulus on the left side – wrongly – activates a left-side response, this incorrect activation decays with time and, thus, interference with the – correct – right-side response decreases as well (e.g., Simon, et al., 1976; Experiment 1). Accordingly, one might assume that also in the current experiment cognitive interference decreased while the movement was evolving (e.g., Buetti & Kerzel, 2009). Thus, one can predict that the small effects found for the QE could be explained by decay of the interference. Consequently, when one calculates the QE to an earlier movement phase and thus, earlier, to the onset of the Simon stimulus – like the reaction time – larger effects should be revealed. To test this assumption, we also calculated the QE as last fixation before reaction time (i.e., QE_{RT}).

This required us to re-calculate the QE onset and the QE duration resulting – as would be expected – in a further drop in the number of valid trials that remained for all 20 participants above the minimal threshold of 16 trials per condition-compatibility combination. The following results were based on averaged 42.3 valid trials per condition-compatibility combination. For QE_{RT} onset and QE_{RT} duration, both condition x compatibility interaction effects were still significant – QE_{RT} onset: $F(1, 19) = 7.57$, MSE = 8359.6, $p < .05$, $\eta_p^2 = .28$; QE_{RT} duration: $F(1, 19) = 7.88$, MSE = 19520.7, $p < .05$, $\eta_p^2 = .29$ – with, on average, slightly larger effect sizes as compared to the previous analyses. The subsequently performed compatibility comparisons showed that, for HC, earlier QE_{RT} onsets and longer QE_{RT} durations were found in incompatible as compared to compatible trials. Still, the opposite result pattern was apparent in TC, meaning that the general pattern of our results were maintained. But, the effect-size analyses of the compatibility comparisons in HC confirmed the predicted increased cognitive interference to be present over QE_{RT}. For QE_{RT} onset ($d = .58$, $p < .05$; $Z = 2.42$, $p < .05$) and QE_{RT} duration ($d = .46$, $p < .05$; $Z = 2.16$, $p < .05$), for which larger statistical effects were found. For the TC the effect sizes decreased (QE_{RT} onset, $d = .16$; QE_{RT} duration, $d = .21$; all *p*s > .05).

Post-hoc analyses – Reversed result pattern in the CT

One potential explanation for the unexpected pattern of results in the TC might be an increased number of errors in the eye movements. Thus, the Simon manipulation might have led to a stark increase in fixations at the opposite target – i.e., the wrong target – which could have disrupted the coordination of the eye movements and the throwing movement. To control for this confound, in each valid trial we calculated post-hoc the average number of trials with fixations at the opposite target in the TC and the HC for compatible vs. incompatible trials. It should be noted that in the HC only one target was present. Thus, as opposed to the TC, in the HC, we calculated fixations at an empty position at which, however, the potential second targets disk would have been positioned. These results showed, as expected, that participants made more erroneous eye movements in the TC (0.8 % of all trial) vs. the HC (2.2 % of all trials); and they made more erroneous eye movements in incompatible trials (1.6 % of all trials) vs. compatible trials (1.3 % of all trials). However, those numbers were way too low to allow for the interpretation of a general disruption of the coupling between perception and action. Thus, this additional post-hoc analysis did not allow us to better understand the TC pattern of results. Further, while one might suggest that, in the TC, QE durations were sufficient to maintain performance in incompatible trials, the current data do not support this assumption, as there was no statistically relevant performance-enhancing effect of long QE durations in any condition. Therefore, future experimental manipulations of the QE duration might provide an answer.

Attentional explanation of the QE effect

With these additional analyses the proposed interpretation of the data was strengthened in so far as, in line with our expectations, larger effects sizes for the QE-compatibility effect in the HC were found if the QE was calculated relative to the reaction time (i.e., QE_{RT}). Thus, cognitive interference evoked over response selection was reflected in the onset and the duration of the QE. This finding is remarkable as the Simon effect has been shown to clearly interfere with the eye movements (see also Lugli et al., 2016) and the throwing movement (see also Buetti & Kerzel, 2009). However, in the HC these interferences were compensated by an optimal coupling between perception and action – i.e., prolonged phases of stable eye movements to the support of the ongoing movement parametrization – which might have permitted maintenance in motor performance. Vine et al. (2014) as well as Klostermann et al. (2014) suggested that the QE reflects underlying attentional control processes. The longer, – or the more optimal (e.g., Behan & Wilson, 2008; but see also Klostermann et al., 2018) – the QE duration, the better the visuo-motor system is thought to be attuned towards the goal of the current action (cf. Harris et al., 2021). Exactly this functionality was shown in the current study, as the conflict in response selection evoked by the Simon manipulation (cf., Hommel, 2019) required an optimization of the attentional processes, as indicated by the earlier onsets and longer QE durations, in the incompatible stimulus-response-mapping trials. Indeed, the findings additionally indicate that – due to different QE-compatibility effects in the HC vs. the TC conditions – this optimization might be better explained with the inhibition mechanism (see also Klostermann, et al., 2020) as it assumes functionality on the level of motor control. Yet, overall, these results are too inconclusive to allow such a further differentiation.

Limitations of the study

As a potential study limitation, there was a rather high number of participants who could not be included in final data analyses. However, as already observed in pilot studies, this problem is entailed by the Simon paradigm. Unfortunately, as there is a large Simon effect on visuo-motor control, it was not possible to calculate a sufficient number of trials with a valid QE detection (i.e., a fixation at the target before onset of the critical movement phase) for a number of participants. Therefore, to maintain a valid and reliable aggregation of the gaze and the movement data, after the data check, these participants had to be removed. To overcome this issue, one must optimize current experimental paradigms in such a way that invalid QE detections are being detected online and repeated later in the test session. At the moment, we are working exactly on such procedures to be implemented in future experiments. Nonetheless, it has to be noted that, in this study, both the number of participants – see also the result of our a-priori sample size calculations – and the number of valid trial data per condition-compatibility combination (on average more than 40 trials), was well in line with previous QE research.

Conclusion

In summary, to the best of our knowledge, this is the first study that shows the well-studied Simon effect in a far-aiming task, extending the scope of this phenomenon to more complex motor tasks. Crucially, this successful replication allowed further insights into the underlying mechanism of the QE by revealing the tight relationship between cognitive interferences over response selection and respective QE parameters (onset and duration).

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Figures

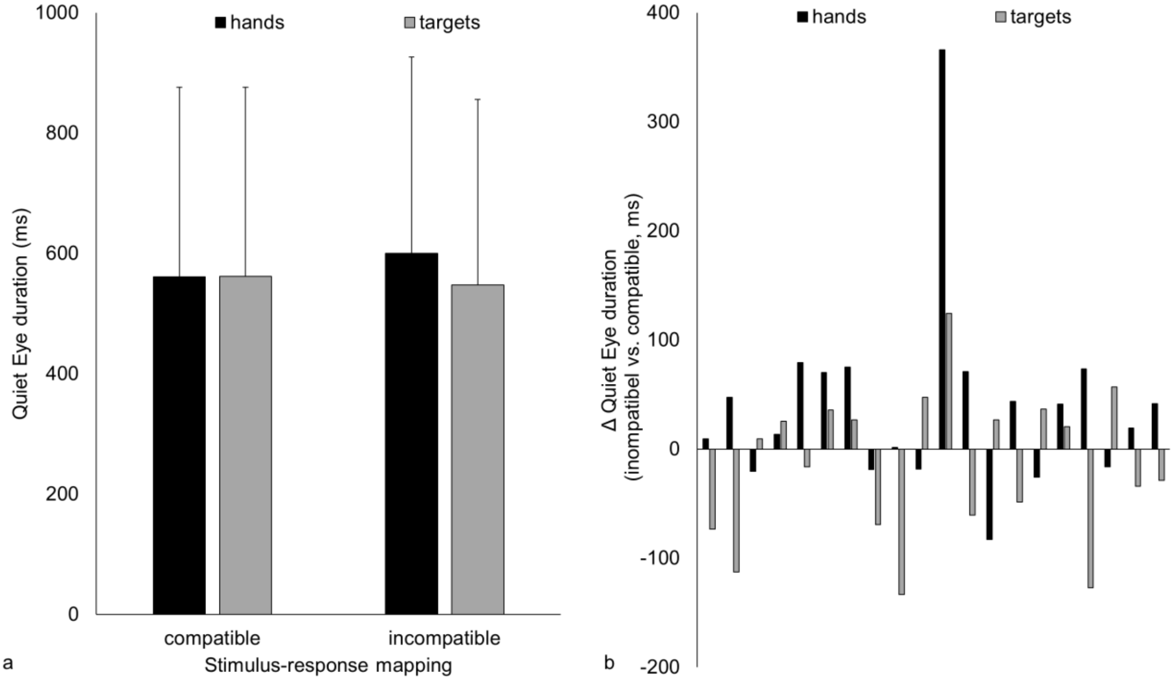

Figure 1. QE duration as a function of condition (hands vs. targets) and compatibility (compatible vs. incompatible stimulus-effect mappings) averaged over (a) the full sample and (b) the individual participants. It should be noted that in (b) positive values denote longer QE durations in incompatible vs. compatible trials.

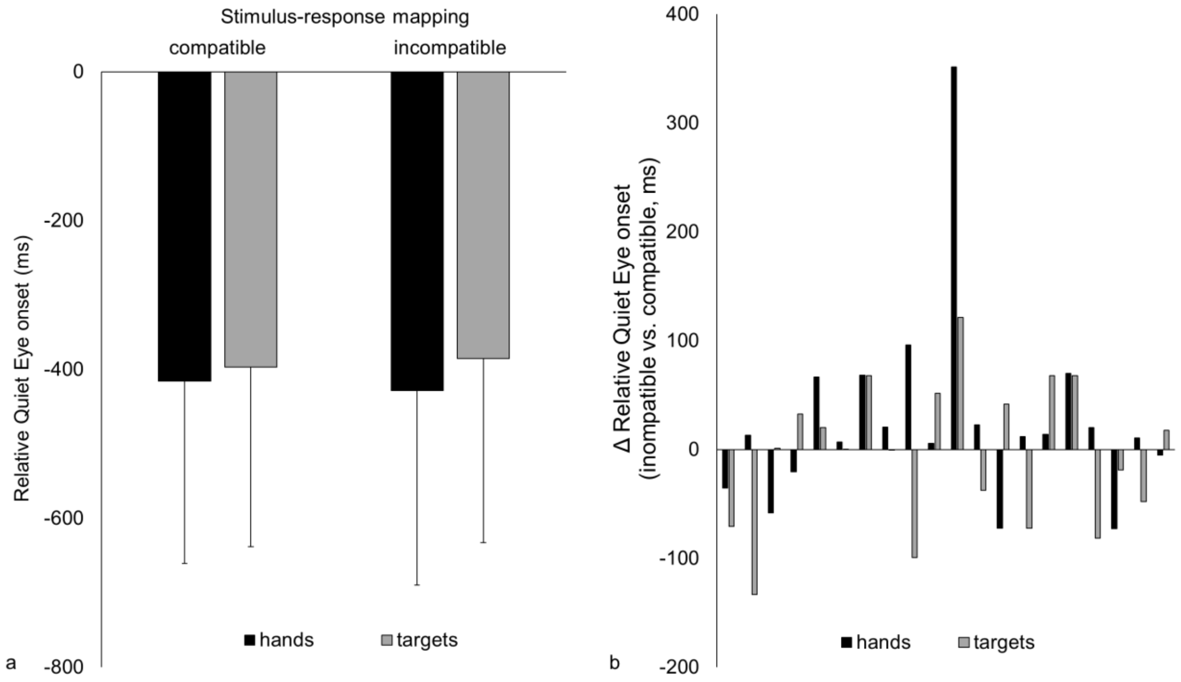

Figure 2. Relative QE onset as a function of condition (hands vs. targets) and compatibility (compatible vs. incompatible stimulus-response mappings) averaged over (a) the full sample and (b) the individual participants. It should be noted that in (a) negative values denote QE onsets before the moment of movement initiation. Furthermore, in (b) positive values denote earlier relative QE onsets in incompatible vs. compatible trials.