Perception and action in a far-aiming task: Inhibition demands and the functionality of the Quiet Eye in motor performance

André Klostermann

University of Bern, Switzerland

Correspondence to:
André Klostermann
University of Bern
Institute of Sport Science
Bremgartenstrasse 145
CH - 3012 Bern
Switzerland
Tel. +41 (0) 31 631 5102
andre.klostermann@ispw.unibe.ch

In everyday activities as well as in sports, visual perception must be coupled with motor action to successfully solve tasks. For example, when preparing food, our eye movements are tightly linked to our hand movements in order to provide visual information for movement planning and control. Moreover, only a few irrelevant eye movements can be found, substantiating gaze behavior as an integral component rather than simply a by-product of motor behavior (Land & Hayhoe, 2001). Furthermore, it has been found in sports and particularly in elite sports that gaze behavior and perception-action coupling substantially predict performance on an intra-individual level (e.g., successful vs. unsuccessful decisions) as well as on an inter-individual level (e.g., expert vs. intermediate athletes) (e.g., Mann, Williams, Ward, & Janelle, 2007). For example, expert athletes have shown economized search behaviors (also termed expert-like gaze behavior, e.g., Wilson, et al., 2011). By simultaneously processing task-relevant visual information during on-going actions, expert athletes obtain the right information at the right time.

Thus, perception-action coupling is tightly linked to motor performance, and the Quiet Eye (QE, Vickers, 2007) is one of the most influential phenomena elucidating this relation. In Vickers's seminal study, expert basketball players were found to show distinctive fixations – i.e., relatively stable gaze that enables the processing of visual information – just before the initiation of the shooting movement in basketball free throws. The better free-throw shooters had nearly twice as long QE durations as the worse free-throw shooters. Moreover, the better free-throw shooters showed even longer QE durations when they performed successfully than unsuccessfully (Vickers, 1996). Since then, the QE phenomenon has been studied in many sports and professional tasks (for an overview, e.g., Vickers, 2016), and the original findings have been replicated multiple times as summarized by the meta-analysis of Lebeau et al. (2016).

Interestingly, the relation between the QE and motor behavior is not only unidirectional as sketched in the findings above. On the one hand, longer QE durations are related to better motor performance (see also Klostermann, Kredel, & Hossner, 2013 who provided evidence for a causal relation by experimentally varying QE durations) and longer QE durations are related to higher motor expertise. On the other hand, task demands have also been shown to influence QE durations. This bi-directionality was exemplified by Williams, Singer, and Frehlich (2002) in billiards. With varying complexities of billiards tasks – e.g., the object ball could be hit directly vs. indirectly and the cue ball had to be played with spin vs. without spin –players exhibited different QE durations that were related to the degree of task complexity, i.e., the more difficult the task the longer the QE duration. Likewise, Walters-Symons, Wilson, Klostermann, and Vine (2018) revealed similar results in a golf-putting task by experimentally varying, e.g., the surface size of the putter and the distance to the hole. In sum, these findings are perfectly in line with the suggestion that visual perception and (motor) action are mutually coupled.

When investigating the functionality – and possible mechanisms – of this coupling, three main hypotheses have been proposed that relate the QE phenomenon to: information processing (e.g., Williams et al., 2002; Vickers, 1996), optimal attentional control (e.g., Vine, Moore, & Wilson, 2014) and mediation of other phenomena like the focus-of-attention effect (e.g., Rienhoff, Fischer, Strauss, & Baker, 2015) (for an overview on discussed QE mechanisms, Gonzales et al., 2017). Vickers (1996, 2007) and Williams et al. (2002) suggested that long QE durations facilitate information processing over response selection and parameter fine-tuning. Williams et al. (2002) empirically supported this idea by showing that more complex motor tasks that demand greater parameter fine-tuning in turn require longer QE durations (see also, e.g., Horn, Okomura, Alexander, Gardin, & Sylvester, 2012; Klostermann et al., 2013, Experiment 2). Neurophysiological evidence was provided by Mann, Coombes, Mousseau, and Janelle (2011) who found relations between the Bereitschaftspotential (‘readiness potential’ as index of motor planning, e.g., Shibasaki & Hallet, 2006) and the QE period in expert and intermediate golf players. In addition, the studies by Vine and colleagues (e.g., Vine & Wilson,

2011) suggest that the QE supports optimal attentional control, as evidenced by QE-trained learners' resistance to experimentally evoked pressure in testing conditions. Thus, by applying the "QE-technique", top-down attentional control is facilitated and internal as well as external distractions (evoked by bottom-up attentional processes) that harm motor performance can be avoided. Finally, evidence has been provided relating the QE period to the focus-of-attention phenomenon – albeit without directly addressing possible QE mechanisms. It has been suggested that an external focus of attention (i.e., mentally focusing movement effects, for an overview see Wulf, 2013) occurs during the QE period, which facilitates motor control and performance (e.g., Rienhoff et al., 2015).

Taken together, the aforementioned hypotheses provide an apt explanation for the functionality of the QE in motor performance: top-down attentional control requires less cognitive resources that, in turn, can be allocated to response programming, resulting in improved parameter fine-tuning. However, the functionality of the QE in motor expertise remains unclear, as improved information processing and attentional control can hardly explain why experts require longer QE durations "when efficiency is paramount" (so-called "efficiency paradox", e.g., Mann, Wright, & Janelle, 2016, p. 3). Consequently, over the last years, advancements to the existing models have been proposed. Among others, it was proposed that the QE functions to shield for an optimal movement variant during response selection and motor control (Klostermann, Kredel, & Hossner, 2014; see also Klostermann & Hossner, 2018). This so-called inhibition hypothesis builds upon the assumption that for solving a given task, several potential actions are being planned in parallel (e.g., Cisek, 2012; Cisek & Kalaska, 2010). For example, when picking one apple from a tree full of apples, at one point in time one apple needs to be selected and the selection of other apples needs to be decoupled from the reaching action (Allport, 1987). However, this requires to inhibit alternative actions "to avoid the behavioural chaos that would result from an attempt to simultaneously perform all possible actions for which sufficient causes exist” (Neumann, 1987, p. 374).

Among other, empirical evidence for this inhibition mechanism stems from studies investigating the effect of distractors in manual reaching-to-grasp movements. In classical studies (e.g., Howard & Tipper, 1997) participants had to reach for and grasp wooden cubes. Together with these targets, e.g. in the form of light emitting diodes, non-targets were presented. When analyzing hand paths, it is generally found the presence of the non-targets to affect the hand trajectories. For example, Howard and Tippert (1997) showed that if the non-targets were presented in spatially close distance to the responding hand, the hand deviates further away as compared to if the non-target was presented more far away from the responding hand. Moreover, Welsh and Eliott (2004) replicated the non-target effect both in vision and no-vision conditions in Experiment 1 and showed a temporal dependence of this effect in Experiment 2 such that movements were drawn to the non-target stimulus only if the non-target stimuli were presented just before or at the same time with the target stimuli. Thus, “if more than one response is in an active state, then the initial response will be composed of characteristics of the competing responses” (Welsh & Eliott, 2004, p. 1055) which results in interfered movement behavior (i.e., the response activation model).

In line with these thoughts, the inhibition hypothesis suggests that by optimally synchronizing movement execution with a stabilizing gaze on one task-relevant cue, the selection of one and, in turn, the inhibition of further potential actions is facilitated. A first empirical test of the relation between the QE and the inhibition of multiple potential actions comes from Klostermann (2018). In this study, response-selection demands were manipulated in a far-aiming task that required balls to be thrown as precisely as possible at virtual target disks. In a yoked-control design, the group with high response-selection demands always had to select one out of four possible targets during movement preparation. In contrast, the group with low response-selection demands had to throw at one pre-selected target, which was determined based on the selection of the yoked participant from the high response-selection demand group. Thus, both groups had to throw balls at exactly the same target positions, which controlled for task difficulty. The only difference regarded response-selection demands. The results were perfectly in line with the inhibition hypothesis; the group with high response-selection demands showed more than 25 % longer QE durations than the group with low response-selection demands, while there were no differences in throwing performance.

However, as already noted by Klostermann (2018), response-selection demands were not manipulated within participants, possibly confounding results. Thus, although well controlled, the effect could simply be explained by sampling. Therefore, in the current series of experiments, this shortcoming was addressed by applying within-subject designs. Moreover, in Experiment 1, we further examined whether the response-selection effect can indeed be explained by the number of potential actions (4 vs. 1 targets), or whether the distance between potential targets evokes different inhibition demands and, in turn, varying QE durations. Building on Experiment 1, Experiment 2 aimed to further disentangle whether the observed effect is influenced by demands during response selection, movement control or both.

Experiment 1

In Experiment 1, participants performed a far-aiming task that required a ball to be thrown at one target disk as precisely as possible. Before movement initiation, participants selected either one out of four or one out of two possible targets, which were grouped with either small or large distances between targets. Based on an earlier study (Klostermann, 2018), both the number of targets and target distances would allow for predictions of longer QE durations with a large vs. small number of targets as well as small vs. large target distances. However, based on the results of a more recent motor learning study (Klostermann & Hossner, 2018), it was expected that smaller distances between potential targets – but not simply higher number of potential targets – would require longer QE durations. As for throwing performance, participants were expected to show increased performance in long vs. short QE duration trials and similar performance across all target number and target distance conditions (cf. Klostermann, 2018).

Methods

Participants

Fourteen male (age: $M = 24.0 \pm 3.6$ years) and twelve female (age: $M = 20.9 \pm 3.6$ years) sport science students participated in the experiment and received course credits in return. For the predicted target distance main effect, an optimal sample size of $n = 26$ was calculated a-priori with the expectation of a medium to large effect size ($d = 0.75$, cf. Klostermann, 2018) with a power (1-β) of .95. The significance level was set at $\alpha = .05$. For two participants, there were technical problems with the eye-tracking calibration and re-calibration. Thus, data acquisition was not finished, and the participants had to be removed from further analyses. Participants reported normal vision or corrected-normal vision by wearing lenses and were right-handed. 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.

Apparatus

Participants stood in front of a life-sized, white screen (width: 320 cm, height: 220 cm), on which the virtual target disks (diameter: 22.5 cm) were projected by an LCD projector (Epson H271B LCD Projector, Nagano, Japan). All data were collected with a 3D motion-capture system (VICON T20, VICON Motion Systems Limited, Oxford, United Kingdom, 200 Hz). The eye tracker (EyeSeeCam, EyeSeeTec GmbH, Fürstenfeldbruck, Germany, 220 Hz) was integrated in the VICON system and connected via an active FireWire extension (GOF-Repeater 800, Unibrain, San Ramon, CA, USA) to a MacBook Air (Apple, Cupertino, CA, USA), on which the EyeSeeCam software was used only for calibrating the eye tracker. The internal loudspeaker of the control PC (HP Z230 Tower-Workstation, Hewlett Packard, Palo Alto, CA, USA) played the audio signals.

Throwing movement and ball flight were assessed by passive retro-reflective markers mounted to a marker cluster (diameter: 14 mm) and retro-reflective balls (diameter: 50 mm), respectively. The marker cluster was attached to a fingerless glove on the throwing hand by use of Velcro tape. The EyeSeeCam assessed rotational angles of the left eye by means of an optical tracking of the corneal reflections from infra-red light. The rotational angles of the eye were streamed in real time via Ethernet to the control Pc, which additionally received synchronized positional and rotational head data via the retro-reflective markers attached to the EyeSeeCam. With these data, a custom Matlab (Matlab 2016a, The MathWorks, Natick, MA, USA) software application calculated the three-dimensional gaze vector in the laboratory reference frame. 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. (cf. Kredel, Klostermann, & Hossner, 2015).

The visual stimuli were programmed with Matlab, 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. Data analyses were conducted with Mathworks Matlab 2016a, Microsoft Excel 2016 (Microsoft, Redmond, WA, USA), and IBM SPSS Statistics 24 (IBM, Armonk, NY, USA).

Procedure

The experiment was conducted in individual sessions in the institute's sensorimotor laboratory. Upon arrival, participants received instructions and provided informed consent. Before testing, participants were equipped with the VICON marker cluster as well as the EyeSeeCam and performed an 8-trial warm up block. The EyeSeeCam was then calibrated, which required participants to consecutively fixate 5 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 points of the calibration grid, which was checked after every eighth test trial.

In 12 test blocks with 16 trials each, participants threw retro-reflective balls with their dominant hand at one target disk as precisely as possible *after* an auditory start signal (i.e., start of the throw attempt). The throwing position was 260 cm from the center of the screen. Several balls were kept in a box that was positioned at hip height next to the participant. At the beginning of each trial, one ball was taken in the non-dominant hand. Followingly, participants fixated a fixation cross in the center of the screen until the start of the throw attempt. After 1'500 ms, 16 targets were displayed, with four targets in each quadrant of the screen and in randomly changing positions from trial to trial. Next, either 2 or 4 targets (number of targets conditions) were visually highlighted. These targets were either all in one quadrant (small-distance condition) or spatially separated in different quadrants (large-distance condition). Thus, participants had to perceive the highlighted targets peripherally as after the auditory signal the highlighting disappeared. The auditory start signal was played at a random interval between 2'500 ms and 3'500 ms. Followingly, participants had to throw the ball at one of the previously highlighted targets in four different experimental conditions: (1) small-number/small-distance, (2) small-number/large-distance, (3) large-number/small-distance, and (4) large-number/large-distance. After 7'000 ms, numbers were presented in the target center and the participants had to name the target number that was selected and thrown at. All stimuli disappeared after 10’000 ms, and the next trial began by displaying the following trial number (see also Klostermann, 2018).

All four conditions were equally presented in all four quadrants in a quasi-randomized order, such that the same condition and the same quadrant were not presented more than two times in a row. The testing lasted about 60 minutes. At the end the participants were thanked and debriefed on the aims of the study.

<<< Insert Figure 1 about here >>>

Measures

Before aggregating the dependent variable measures, all trials in which participants fixated the targets too early or did not wait for the starting cue were removed from further analyses, respectively (*M* = 18.4 % of all trials, *SD* = 22.2 % of all trials). Trials without QE or with technical problems in data acquisition were additionally removed (*M* = 20.7 % of all trials, *SD* = 21.7 % of all trials). A closer look at the data revealed that some participants either did not follow the fixation instruction or had a high amount of no-QE trials. Thus, in order to keep the number of test trials per condition as high as possible, participants who did not had at least 16 valid trials per condition – i.e., with more than 45 % of test trials missing (*n* = 8) – were removed from further analyses. Therefore, the final sample consisted of 16 participants with on average 72.3 % ± 7.0 % valid test trials (*n* ~139 test trials). The descriptive data and the inferential statistics of the full sample in Experiment 1 are reported in the Appendix Table A1, Table A2, and Table A3, respectively. The average number of missing test trials was evenly distributed among the experimental conditions: (1) small-number/small-distance condition: 6.6 % of all trials, (2) small-number/large-distance condition: 7.0 % of all trials, (3) large-number/small-distance condition: 6.6% of all trials, and (4) large-number/large-distance condition: 7.4 % of all trials.

Quiet Eye

The gaze data were analyzed using the dispersion-based algorithm by Nyström and Holmqvist (2009), in which a fixation is detected as soon as the point of gaze becomes 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 the initiation of the 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 the initiation of the forward swing. Thus, negative values represent moments in time before swing initiation, whereas positive values represent moments in time after the swing initiation. The QE duration was calculated as time interval between QE onset and QE offset. The initiation of the forward swing was determined as the VICON frame in which the average position of the hand marker cluster moved forward after reaching its backmost position (cf. Klostermann et al., 2013). QE onset, offset and duration were separately aggregated for the 2 (number of targets) times 2 (target distance) experimental conditions. Moreover, median splits of QE duration were performed to assess effects of short vs. long QE durations on throwing performance (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 screen frame of reference. The deviation of the ball from the target center at the moment of ball impact could then be calculated. The throwing performance was separately aggregated for the 2 (number of targets) times 2 (target distance) experimental conditions as well as for long vs. short QE-duration trials.

Statistical Analyses

QE duration, QE onset, QE offset, and throwing performance were analyzed with 2 (number of targets) x 2 (target distance) ANOVAs with repeated measures on both factors. In addition, QE duration and throwing performance were analyzed with one-sided dependent t-tests to compare long vs. short QE duration trials, with the prediction of better throwing performance in long vs. short QE-duration trials (e.g., Vickers, 2016). A posteriori effect sizes were computed as Cohen's *d*-values and partial eta squared, η_p^2. In addition to the averaged QE data, the distribution of the QE data is presented as boxplots in the figures A4-A6.

Results

Quiet Eye

As depicted in Figure 2a, QE onset exhibited a significant main effect for target distance, $F(1,15) = 12.77$, $p = .003$, $\eta_p^2 = .46$, with earlier QE onsets in small-distance ($M = -459.8$ ms, $SE = 36.2$ ms) vs. large-distance conditions ($M = -435.0$ ms, $SE = 34.9$ ms). The main effect for number of targets, $F(1,15) = 1.11$, $p = .31$, $\eta_p^2 = .07$, and the interaction target distance x number of targets, $F(1,15) = 2.18$, $p = .16$, $\eta_p^2 = .13$, were non-significant. Likewise, ANOVAs for QE offset, $F(1,15) = 6.49$, $p = .02$, $\eta_p^2 = .30$, and QE duration (Figure 2b), $F(1,15) = 11.15$, $p = .004$, $\eta_p^2 = .43$, showed significant main effects for target distance. The remaining tests all failed to reach the pre-determined level of significance (all *p*s > .31, all $\eta_p^2 < .07$).

<<< Insert Figure 2 about here >>>

Throwing performance

Participants were most accurate in the large-number/small-distance condition (*M* = 142.3 mm, *SD* = 27.9 mm), followed by the large-number/large-distance condition (*M* = 143.7 mm, *SD* = 23.8 mm), the small-number/large-distance condition (*M* = 145.2 mm, *SD* = 30.6 mm), and the small-number/small-distance condition (*M* = 148.6 mm, *SD* = 29.9 mm). However, neither the main effects for target distance, $F(1,15) = 0.06$, $p = .82$, $\eta_p^2 < .01$, and number of targets, $F(1,15) = 2.37$, $p = .14$, $\eta_p^2 = .14$, nor the interaction, $F(1,15) = 0.36$, $p = .56$, $\eta_p^2 = .02$, were statistically significant.

QE median split

After performing a median split based on QE durations, trials were classified as long (*M*= 1241.7 ms, *SD* = 599.2 ms) or short (*M*= 463.8 ms, *SD* = 273.7 ms) QE-duration trials, $t(15) = 6.64$, $p < .01$, $d = 1.64$. In long QE-duration trials, participants showed descriptively better throwing performance (*M* = 142.2 mm, *SD* = 27.8 mm) when compared to short QE-duration trials (*M* = 146.1 mm, *SD* = 28.5 mm), $t(15) = 1.03$, $p = .16$, $d = 0.25$.

Discussion

The aim of Experiment 1 was twofold: first, to replicate the findings of Klostermann (2018) in a within-subject design, and second to gain further insights into the effect of response-selection demands. To this end, in a far-aiming task, participants' response-selection was experimentally manipulated by presenting two or four optional targets that were positioned at either small or large distances to each other. It was predicted that the small distance conditions would evoke longer QE durations as a function of the increased inhibition demands.

Whereas throwing performance did not differ among conditions – confirming similar task difficulty – clear differences in QE as a function of the response-selection manipulation were revealed. As in Klostermann (2018), increased response-selection demands resulted in increased QE periods and in particular, earlier QE onsets and longer QE durations. Therefore, the results replicate earlier findings and further rule out possible confounding due to the within-subject design. Moreover, the current results provided further insights, as the distance between the targets but not the number of targets affected the QE. This suggests, as already noted by Klostermann & Hossner (2018), that particularly higher densities of potential actions require prolonged QE durations. Thus, the more similar the potential actions (e.g., hitting targets with similar coordinates in three-dimensional space) and the more similar the resulting parametrization of these different movement variants (e.g., similar release angles), the higher the inhibition demands that require longer QE periods.

The results further indicate that the number of potential actions might matter as well, however the interaction effects suggest influences only in the small-distance conditions. This claim is highlighted by more pronounced number effects at small distance with even longer QE durations in the large-number ($M_{Difference}$ = 35.1 ms) vs. the small-number conditions ($M_{Difference}$ = 14.5 ms). Similarly, the earliest QE onsets in the large-number/small-distance condition (M = -469.9 ms, SE = -36.9 ms). However, if the potential targets were widely spread (i.e., high-distance conditions), it did not matter whether participants had to select one target out of a small or large number of targets (see Figure 2a). This suggests that the planning of optional actions – at least in the context of far-aiming tasks – requires increased inhibition only if these actions are within the proximity of the visual (and / or attentional) focus.

In sum, Experiment 1 corroborated the response-selection effect and further provided greater insights into dependencies of the QE. Interestingly, in both the current study and that of Klostermann (2018), the response-selection manipulation affected not only the QE onset and QE duration, but also the QE offset. This suggests that the experimentally evoked demands similarly affect the movement control phase in addition to the response selection phase. Research shows that inhibition demands extend throughout the movement control phase (e.g., Cisek & Kalaska, 2005) and that longer QE periods advance movement preparation (e.g., Vickers, 1996) and movement control (e.g., Klostermann et al., 2014). Accordingly, the QE offset results correspond to the inhibition function. However, to get an idea about the actual mechanisms, further research is required. Consequently, Experiment 2 addressed this research question more explicitly by manipulating inhibition demands during response selection and movement control.

Experiment 2

In Experiment 2, a similar experimental paradigm was used as in Experiment 1. However, instead of manipulating inhibition demands only during response selection, inhibition demands were additionally manipulated during movement control by varying target-distractor discriminability. Thus, different to Experiment 1 in which the number of potential targets was highlighted during the initial preparation phase only (i.e., until the auditory start signal), in Experiment 2, the potential alternative targets were visually highlighted during the full trial. Further, the discriminability of these targets was manipulated by introducing same or different colors (e.g., Olk, Dinu, Zielinski, and Kopper, 2018). Consequently, selecting and maintaining this selection was either more demanding or less demanding. Moreover, as in Klostermann (2018) either one out of one target (small number of targets) or one out of four targets (large number of targets) had to be selected. As in Experiment 1, it was expected that the experimental manipulations would not affect overall throwing performance. However, manipulations during response selection were expected to affect the QE period as in the previous studies, i.e., longer QE durations with high vs. low response-selection demands (cf. Klostermann, 2018) and small vs. high distance, respectively. With regards to the manipulation during movement control, not such clear-cut predictions were apparent. Yet based on the QE offset findings in the previous studies, an additive rather than interaction effect was hypothesized.

Methods

Participants

Experiment 2 included 26 sports science students who had not participated in Experiment 1. The sample consisted of 22 males (age: $M = 20.7 \pm 1.2$ years) and 4 females (age: $M = 20.0$ years ± 1.2 years). For one participant, technical problems occurred with the eye-tracking system, and thus the participant was excluded from data collection. All participants were unaware of the research question and reported normal or corrected-to-normal vision. The study 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.

Apparatus

The same apparatus were used as in Experiment 1.

Procedure

The experimental task and the procedure were similar to that of Experiment 1, but different visual stimuli were used and the number of test trials was reduced.

After being provided with instructions, participants signed informed consent. Followingly, the EyeSeeCam was calibrated and participants performed a warm-up block of 8 practice trials in which all four experimental conditions were practiced twice. The first of 8 blocks of 16 test trials then began. In the beginning of each test trial, a fixation cross was presented. After 1’500 ms, 16 targets appeared in the four quadrants of the screen. Next, four targets in one of the quadrants were colored after 2’000 ms. In the low-inhibition condition, the four targets were colored green, blue, brown, and red. In contrast, in the high-inhibition condition, all four targets were colored in red. Thus, in the condition with high target-discriminability, all four targets in one quadrant were of different colors and thereby easier to discriminate and in the condition with low target-discriminability, all four targets in one quadrant shared the same color and were thus more difficult to discriminate (e.g., Olk et al., 2018). This means that in the low target-discriminability condition, maintaining the initial target selection should require less inhibition and thus shorter QE duration and earlier QE offsets, respectively. In contrast, in the high target-discriminability condition, in which all potential targets share multiple features (like the apples in the apple tree, Allport, 1987) increased inhibition is required to maintain the initial selection over movement control. After 2’500 ms, either 1 (small number of targets) or all 4 (large number of targets) colored targets were visually highlighted by flashing for a duration of 1’500 ms. The participants, while still fixating the fixation cross, were instructed to select one of the highlighted targets. Followingly, the fixation cross disappeared, and an auditory start signal indicated that participants were free to throw the ball at the selected target as centrally as possible. As in Experiment 1, the targets were replaced by numbers after 7’000 ms and participants had to name the number of the selected target. Each trial ended after 10’000 ms and the next test trial started with the presentation of the following trial number. All four experimental conditions were equally presented in all four quadrants in a quasi-randomized order, such that the same condition and the same quadrant were not presented more than two times in a row. The calibration of the EyeSeeCam was checked after every 8 test trials and was re-calibrated if necessary. At the end, participants were thanked and debriefed about the aims of the study. Each session lasted about 45 minutes.

Measures

The same measures were obtained, and the same analyses were run as in Experiment 1. Moreover, as in Experiment 1, after data aggregation, a number of participants (*n* = 3) were removed due to a large number of missing test trials (i.e., not having at least 16 valid test trials per condition)[1]. Thus, the final sample consisted of 22 participants with on average 74.9 % ± 9.8 % valid test trials (*n* ~96 test trials). The descriptive data and the inferential statistics of the full sample in Experiment 2 are reported in the Appendix Table A1, Table A2, and Table A3, respectively. The average number of missing test trials was evenly distributed among the experimental conditions: (1) small-number / high-discriminability condition: 5.3 % of all trials, (2) small-number / low-discriminability condition: 7.1 % of all trials, (3) large-number / high-discriminability condition: 6.1% of all trials, and (4) large-number / low-discriminability condition: 6.4 % of all trials.

QE onset, offset, and duration as well as throwing performance were separately aggregated for the 2 (number of targets) times 2 (target discriminability) experimental conditions.

Moreover, QE duration and throwing performance were further aggregated for trials with short and long QE durations.

Statistical Analyses

QE duration, QE onset, QE offset, and throwing performance were analyzed with 2 (number of targets) x 2 (target discriminability) ANOVAs with repeated measures on both factors. In addition, QE duration and throwing performance were analyzed with one-sided dependent t-tests to compare long vs. short QE duration trials. A posteriori effect sizes were computed as Cohen's *d*-values and partial eta squared, η_p^2. As in Experiment 1, the distribution of the QE data is presented as boxplots in the figures A7-A9 to be found in the Appendix.

Results

Quiet Eye

The results of the QE analyses are depicted in Figure 3. Regarding the number of targets, longer QE durations, $F(1, 21) = 5.19, p < .05, \eta_p^2 = .19$, and earlier QE onsets, $F(1, 21) = 10.61$, $p < .05$, $\eta_p^2 = .34$, were found in large vs. small target-number conditions. Similarly regarding target discriminability, QE duration, $F(1, 21) = 4.01, p = .058, \eta_p^2 = .16$, and QE onset, $F(1, 21) = 3.88$, $p = .062$, $\eta_p^2 = .16$, revealed main effects with descriptively longer QE durations and earlier onsets in low vs. high target-discriminability conditions. Neither significant interactions (all *p*s > .58, all $\eta_p^2 < .01$) nor significant main effects were found for QE offset (response selection: $F(1, 21) = 0.47$, $p = .49$, $\eta_p^2 = .02$; target discriminability: $F(1, 21) = 2.28$, $p = .14$, $\eta_p^2 = .09$).

<<< Insert Figure 3 about here >>>

Throwing performance

For throwing performance, a significant main effect for target discriminability was revealed, $F(1, 21) = 4.72$, $p < .05$, $\eta_p^2 = .18$. Participants were more accurate in low ($M = 193.3$ mm, $SD = 48.6$ mm) vs. high ($M = 203.0$ mm, $SD = 57.2$ mm) target-discriminability conditions. The main effect for number of targets, $F(1, 21) = 0.18$, $p = .67$, $\eta_p^2 = .01$, and the interaction, $F(1, 21) = 2.95$, $p = .10$, $\eta_p^2 = .12$, were non-significant.

QE-median split

A median split resulted in trials with long ($M = 1534.6$ ms, $SD = 693.7$ ms) vs. short ($M = 573.1$ ms, $SD = 347.8$ ms) QE durations, $t(21) = 9.69$, $p < .01$, $d = 2.51$. Moreover, participants were more accurate in long QE-duration trials ($M = 198.4$ mm, $SD = 59.6$ mm) when compared to short QE-duration trials ($M =207.3$ mm, $SD = 54.2$ mm), $t(21) = 2.15$, $p < .05$, $d = 0.25$.

Discussion

In Experiment 2, the processes behind the inhibition function of long QE durations in a far-aiming task were further investigated. In addition to number of targets (1 vs. 4 potential targets), inhibition demands during movement control were manipulated by varying target discriminability (multicolored vs. unicolored). Based on earlier findings, an additive effect was expected with the shortest QE durations in the condition with the lowest inhibition demands (i.e., small number of targets / high target discriminability) and the longest QE duration in the condition with the highest inhibition demands (large number of targets / low target discriminability).

When first examining the manipulation check, throwing performance unexpectedly differed as a function of the experimental manipulations. Larger performance errors occurred in the high vs. low target-discriminability conditions. This suggests that participants had increased difficulties when throwing balls at multicolored as opposed to unicolored targets. A profound explanation for such is not apparent. However, when referring back to our main questions, this finding does not raise problems since the performance difference does not reflect the feasible task-difficulty differences evoked by the experimental manipulations, i.e. highest demands with low target discriminability. Moreover, throwing performance does not coincide as expected with the QE patterns, since the longest QE durations occurred with the greatest performance error. Therefore, the QE data can be exclusively discussed as a function of the experimental manipulation.

As can be seen in Figure 3b, two main effects were revealed, elucidating that QE duration increased with increasing inhibition demands. The QE duration effect was mainly driven by respective differences in QE onset (see Figure 3a). As opposed to earlier studies, we did not find any significant differences in QE offset that might be explained by ceiling effects. Nonetheless, participants expectedly showed descriptively later QE offsets in those conditions which required inhibition during movement control due to more difficult target discriminability. Thus, experimentally confirming earlier findings, the inhibition function prevails during response selection and movement control, which corroborates the idea of a continuous perception-action cycle in motor behavior.

General Discussion

In the current series of studies, an underlying mechanism of the perception-action variable QE was further investigated. The suggested inhibition hypothesis explains the functionality of the QE with a shielding mechanism, which facilitates the selection and parametrization of the most optimal movement variant over that of alternative, less optimal movement variants. This mechanism was tested by manipulating demands during response selection and movement control. Causalities between the QE and (inhibition) demands were shown in both experiments, further replicating earlier findings (Klostermann, 2018).

Both experiments revealed that the relation between the QE and inhibition demands was driven by the structure of the effect space rather than (or at least to lesser degree), e.g., the number of potential actions within the effect space. This means that the more similar the potential actions and thus their resulting parametrizations, the longer the QE duration. This result applied to spatial similarity (target distance in Experiment 1) as well as feature similarity (target discriminability in Experiment 2). Importantly, this effect is not simply explained by (visual) processing demands since, e.g., in Experiment 1 the visual-information load did not differ between the conditions (see also Klostermann, 2018). Rather, it was the functional distinction in Experiment 2 (target vs. non-target in Experiment 2) that mattered, though cannot be explained by present feasible QE mechanisms. Consequently, the inhibition hypothesis introduces the necessary *functional* mechanism behind the QE-motor response relation, which adeptly extends the cognitive approaches introduced by Vickers (1996) and Williams et al. (2002) as well as by Vine, Wilson, and colleagues (e.g., Vine et al. 2015).

When discussing the QE - motor performance relation, both studies revealed very similar performance effects with more accurate throws in long vs. short QE-duration trials. However, in contrast to earlier studies (e.g., Causer, Hayes, Hooper, & Benett, 2017), only small effect sizes were found, though still within the range of the expected effect sizes (cf. Lebeau et al., 2016). Nevertheless, future studies should further investigate the relation between the performance-enhancing effect of the QE and the suggested inhibition mechanism. Based on the current and earlier findings (Klostermann et al., 2013), similar functional dependencies between the QE, motor performance, and inhibition demands would be expected. This means that experimentally controlled long vs. short QE durations should particularly affect motor performance in high inhibition-demand conditions. Whereas in cases of low inhibition demands, a smaller or even no dependency would be predicted for motor performance with little to no functionality of long QE durations.

Over data analysis, a number of test trials were excluded because of missing QE detection (e.g., Kostermann et al., 2013) and tainted conditions in which participants fixated the selected target too early. Although we tried to overcome this issue by warning participants that trials failing to follow protocol would be detected and repeated at the end, this caution was unfortunately not effective for all participants (Experiment 1: n = 8, Experiment 2: n = 3). Nonetheless, with an average of 36 trials per condition in Experiment 1 and 24 trials per condition in Experiment 2, the number of repeated measures is still beyond the average number of repeated measures in QE research (see Lebeau et al., 2016). Therefore, reliability and validity issues should not be assumed. In addition, it should be noted that the inferential statistics of the full sample sizes (see Tables A1-A3) closely replicated the effect sizes found for the reduced sample sizes. Nevertheless, in future studies we plan to implement an automatized detection of the final fixation as well as an automatic repetition of erroneous trials to overcome such issues.

Finally, it must be acknowledged that with the current method, it cannot be ruled out that participants occasionally did not report their initial target selection, but instead the target they had thrown at. However, besides taking care that participants strictly followed our instructions, both the current performance errors as well as the successful replication of Klostermann

(2018) rather speak up against this potential issue. First, the average radial error in both experiments is clearly larger than the radius of the targets (i.e., 112.5 mm), thus on average participants did not hit the targets. If, indeed, the participants would have selected the target they had thrown at, smaller radial errors with balls hitting the targets should be expected. Second, the current results replicated the finding by Klostermann et al (2018) in which a yoked-control design was applied to manipulate response-selection demands. To repeat, it was just the difference in response selection (either selecting one out of four targets vs. to taking the selection of the yoked participant) which affected the QE duration. Therefore, in sum the selection issue cannot be fully ruled out. However, the current data rather speak against that.

In conclusion, this series of studies provides further insights into the underlying mechanism of the QE phenomenon. By showing tight relations between response-selection demands over movement preparation and control, the suggested inhibition hypothesis, as an extension of the present cognitive approaches, was supported. However, some shortcomings were recognized and require further studies, in particular, to address the QE-performance relation more directly. Moreover, motor-learning studies are necessary to directly tackle the efficiency paradox which might also transfer into sport practice. Such studies are planned in the near future.

Acknowledgments

The author wishes to thank Catherine Haber for proof-reading the manuscript. The work of the author was financially supported by the SNSF foundation (grant number 100014_178879).

References

Allport, A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action* (pp. 395-419). Hillsdale, NJ: Lawrence Erlbaum.

Causer, J., Hayes, S. J., Hooper, J. M., & Bennett, S. J. (2017). Quiet eye facilitates sensorimotor preprograming and online control of precision aiming in golf putting. *Cognitive Processing*, *18*, 47-54.

Gonzalez, C. C., Causer, J., Miall, R. C., Grey, M. J., Humphreys, G., & Williams, A. M. (2017). Identifying the causal mechanisms of the quiet eye. *European Journal of Sport Science*, *17*, 74-84.

Horn, R. R., Okumura, M. S., Alexander, M. G., Gardin, F. A., & Sylvester, C. T. (2012). Quiet eye duration is responsive to variability of practice and to the axis of target changes. *Research Quarterly for Exercise and Sport*, *83*, 204-211.

Howard, L. A., & Tipper, S. P. (1997). Hand deviations away from visual cues: indirect evidence for inhibition. Experimental Brain Research, *113*, 144-152.

Klostermann, A. (2018). Picking an apple from a tree: Response-selection demands, inhibition requirements, and the functionality of the Quiet Eye in a far-aiming task. *Quarterly Journal of Experimental Psychology*. Advance online publication. doi: 10.1177/1747021818786223

Klostermann, A., & Hossner, E. J. (2018). The Quiet Eye and motor expertise: Explaining the “efficiency paradox”. *Frontiers in Psychology*, *9*: *104*.

Klostermann, A., Kredel, R., & Hossner, E. J. (2013). The “quiet eye” and motor performance: Task demands matter!. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 1270-1278.

Klostermann, A., Kredel, R., & Hossner, E. J. (2014). On the interaction of attentional focus and gaze: the quiet eye inhibits focus-related performance decrements. *Journal of Sport and Exercise Psychology*, *36*, 392-400.

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities?. *Vision Research*, *41*, 3559-3565.

Lebeau, J. C., Liu, S., Sáenz-Moncaleano, C., Sanduvete-Chaves, S., Chacón-Moscoso, S., Becker, B. J., & Tenenbaum, G. (2016). Quiet eye and performance in sport: a meta-analysis. *Journal of Sport and Exercise Psychology*, *38*, 441-457.

Mann, D. T., Coombes, S. A., Mousseau, M. B., & Janelle, C. M. (2011). Quiet eye and the Bereitschaftspotential: visuomotor mechanisms of expert motor performance. *Cognitive Processing*, *12*, 223-234.

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology*, *29*, 457-478.

Mann, D. T., Wright, A., & Janelle, C. M. (2016). Quiet Eye: The efficiency paradox–comment on Vickers. *Current Issues in Sport Science (CISS)*, *1*, 111-114. doi: 10.15203/CISS-2016.111

Neumann, O. (1987). Beyond capacity: A functional view of attention. *Perspectives on Perception and Action*, *14*, 361-394.

Olk, B., Dinu, A., Zielinski, D. J., & Kopper, R. (2018). Measuring visual search and distraction in immersive virtual reality. *Royal Society Open Science*, *5*: 172331. doi: 10.1098/rsos.172331

Rienhoff, R., Fischer, L., Strauss, B., Baker, J., & Schorer, J. (2015). Focus of attention influences quiet-eye behavior: An exploratory investigation of different skill levels in female basketball players. *Sport, Exercise, and Performance Psychology*, *4*, 62-74.

Shibasaki, H., & Hallett, M. (2006). What is the Bereitschaftspotential?. *Clinical Neurophysiology*, *117*, 2341-2356.

Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 342-354.

Vickers, J. N. (2007). *Perception, cognition, and decision training: The quiet eye in action*. Champaign, IL: Human Kinetics.

Vickers, J. N. (2016). Origins and current issues in Quiet Eye research. *Current Issues in Sport Science (CISS)*, *1:101*, doi: 10.15203/CISS_2016.10

Vine, S. J., Moore, L. J., & Wilson, M. R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. *European Journal of Sport Science*, *14*, 235-242.

Walters-Symons, R., Wilson, M., Klostermann, A., & Vine, S. (2018). Examining the response programming function of the Quiet Eye: Do tougher shots need a quieter eye?. *Cognitive Processing*, *19*, 47-52.

Welsh, T. N., & Elliott, D. (2004). Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. *The Quarterly Journal of Experimental Psychology Section A*, *57*, 1031-1057.

Williams, A. M., Singer, R. N., & Frehlich, S. G. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behavior*, *34*, 197-207.

Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S., Defriend, D., & McGrath, J. S. (2011). Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: a randomized, controlled study. *Surgical Endoscopy and Other Interventional Techniques*, *25*, 3731-3739.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, *6*, 77-104.

Figures

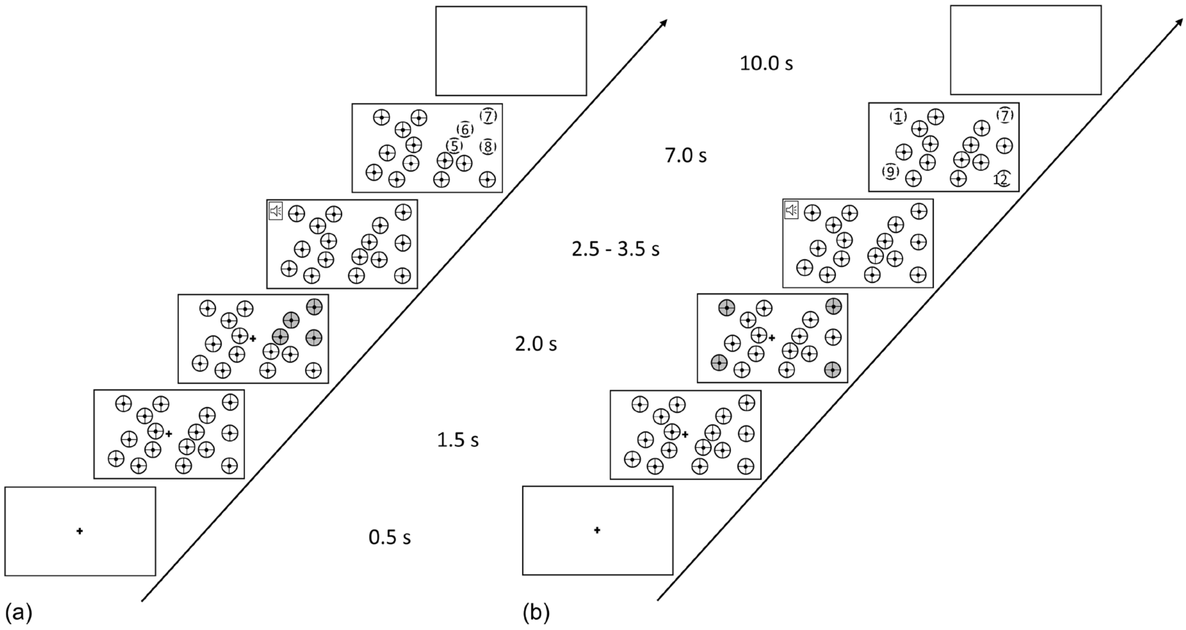

Figure 1. Timeline of the Experiment for the 4-target condition at small (a) vs. large (b) distance. Example: After the presentation of the fixation cross, all 16 targets appeared in four quadrants. Thereafter, either all four targets of the top-right quadrant (a) or all four targets in all four quadrants (b) were visually highlighted. With the presentation of the auditory start stimulus, the fixations cross and the highlighting patches disappeared, and the participants had to throw at one of the four targets highlighted. At the end of each trial, the participants had to name the number of the selected target disk.

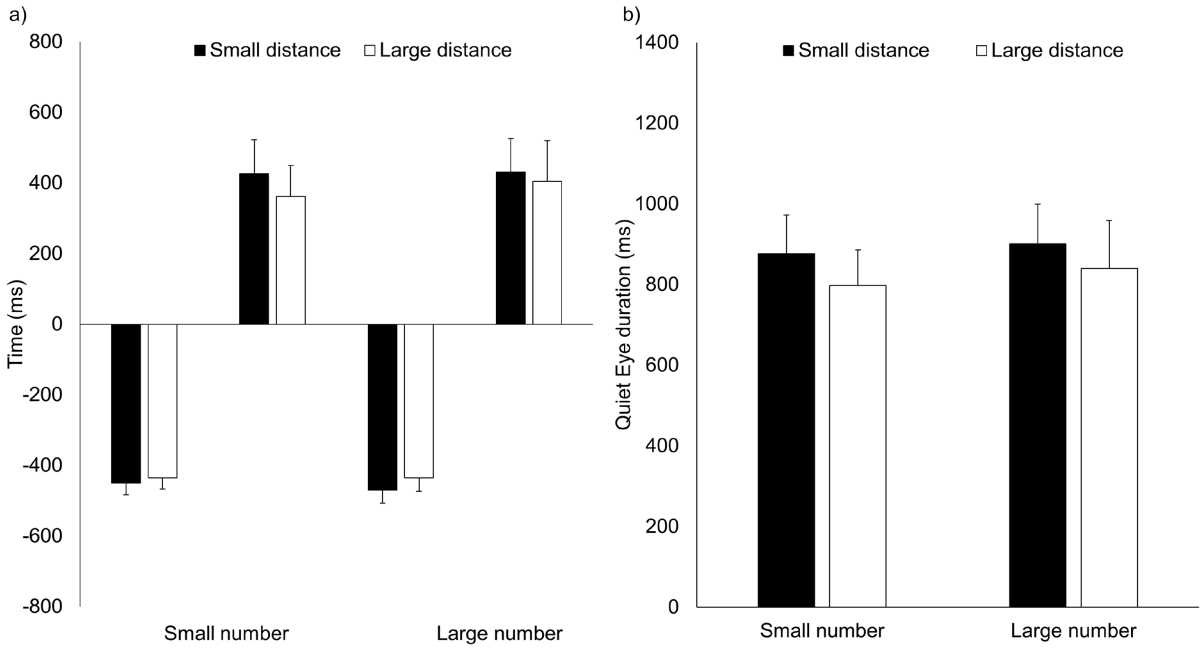

Figure 2. Average Quiet Eye onset and offset relative to the moment of movement initiation (a) as well as Quiet Eye duration (b) as a function of number of targets (small vs. large) and distance (small vs. large). The error bars represent the standard error.

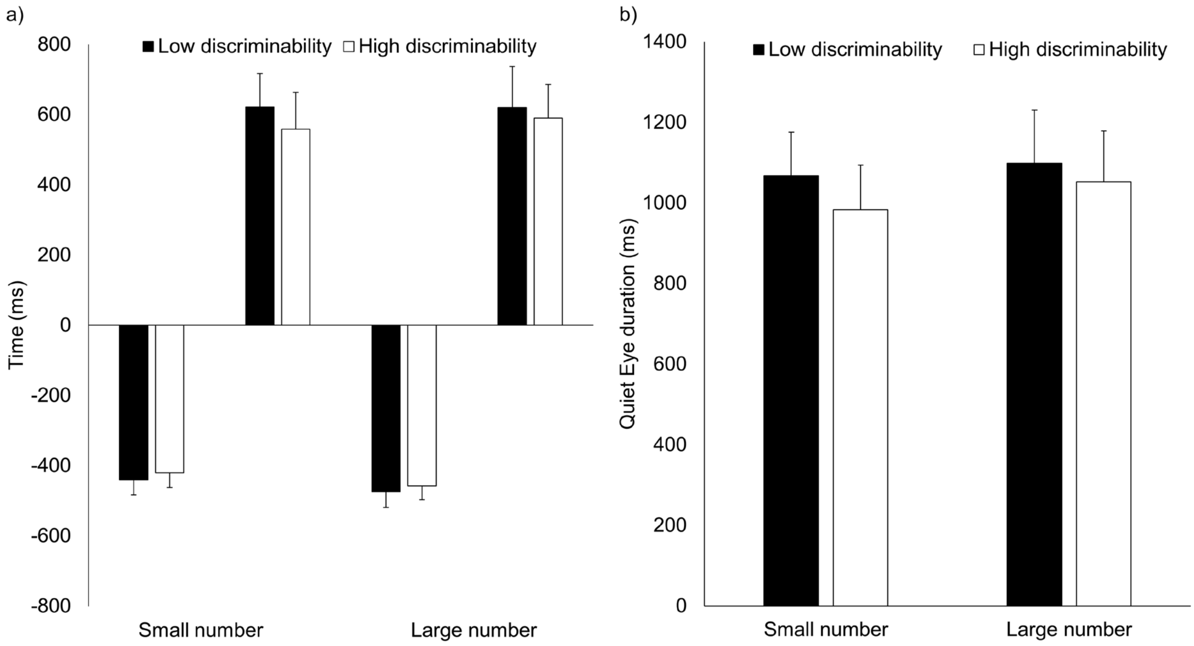

Figure 3. Average Quiet Eye onset and offset relative to the moment of movement initiation (a) as well as Quiet Eye duration (b) as a function of number of targets (small vs. large) and discriminability (low vs. high). The error bars represent the standard error.

Appendix

Table A1.

	Experiment 1 (*n* = 24)				Experiment 2 (*n* = 25)			
	Small-number/short-distance	Small-number/long-distance	Large-number/short-distance	Large-number/long-distance	Small-number/high-discriminability	Small-number/low-discriminability	Large-number/high-discriminability	Large-Number/low-discriminability
QE duration (ms)	M = 847.8 ms SD = 364.2 ms	M = 767.7 ms SD = 359.5 ms	M = 851.6 ms SD = 371.1 ms	M = 782.4 ms SD = 468.5 ms	M = 949.0 ms SD = 513.4 ms	M = 1011.1 ms SD = 479.0 ms	M = 1011.8 ms SD = 461.9 ms	M = 1069.5 ms SD = 549.3 ms
QE onset (ms)	M = -441.5 ms SD = 170.7 ms	M = -419.9 ms SD = 166.1 ms	M = -458.4 ms SD = 184.1 ms	M = -443.2 ms SD = 189.1 ms	M = -437.0 ms SD = 204.5 ms	M = -490.4 ms SD = 203.8 ms	M = -462.2 ms SD = 218.3 ms	M = -497.3 ms SD = 222.1 ms

QE offset (ms)	M = 406.3 ms SD = 339.2 ms	M = 347.8 ms SD = 312.0 ms	M = 393.2 ms SD = 330.3 ms	M = 339.2 ms SD = 410.7ms	M = 507.0 ms SD = 496.9 ms	M = 515.7 ms SD = 489.4 ms	M = 544.6 ms SD = 481.6 ms	M = 567.3 ms SD = 550.8 ms
Throwing performance (mm)	M = 151.1 mm SD = 41.8 mm	M = 149.9 mm SD = 38.0 mm	M = 139.5 mm SD = 30.2 mm	M = 149.7 mm SD = 38.4 mm	M = 204.1 mm SD = 63.9 mm	M = 189.9 mm SD = 51.5 mm	M = 185.8 mm SD = 50.9 mm	M = 189.3 mm SD = 48.3 mm

Table A2.

	Experiment 1 ($n = 24$)			Experiment 2 ($n = 25$)		
	Number of targets	Target distance	Interaction	Number of targets	Target discriminability	Interaction
QE duration (ms)	$F = 0.16$, $p = .69$, $\eta_p^2 = .01$	$F = 11.27$, $p < .01$, $\eta_p^2 = .33$	$F = 0.52$, $p = .82$, $\eta_p^2 < .01$	$F = 4.42$, $p = .04$, $\eta_p^2 = .17$	$F = 4.82$, $\mathrm{p} = .04$, $\eta_p^2 = .17$	$F = 0.04$, $p = .95$, $\eta_p^2 < .001$

QE onset (ms)	$F = 3.00$, $p = .09$ $\eta_p^2 = .12$	$F = 2.71$, p = .11 $\eta_p^2 = .11$	$F = 0.16$, $p = .69$ $\eta_p^2 = .01$	$F = 2.42$, $p = .13$, $\eta_p^2 = .09$	$F = 5.42$, $p = .03$, $\eta_p^2 = .18$	F = 0.32, $p = .58$, $\eta_p^2 = .01$
QE offset (ms)	$F = 0.21$, $p = .65$ $\eta_p^2 = .01$	$F = 9.19$, $p = .006$ $\eta_p^2 = .29$	$F = 0.01$, $p = .93$ $\eta_p^2 < .01$	$F = 2.59$, $p = .12$, $\eta_p^2 = .09$	$F = 0.53$, $p = .48$, $\eta_p^2 = .02$	$F = 0.05$, $p = .83$, $\eta_p^2 = .00$
Throwing performance (mm)	$F = 0.89$, $p = .36$ $\eta_p^2 = .04$	$F = 1.54$, p = .23 $\eta_p^2 = .06$	$F = 2.02$, $p = .17$ $\eta_p^2 = .08$	$F = 5.54$, $p = .03$, $\eta_p^2 = .19$	$F = 0.75$, $p = .39$, $\eta_p^2 = .03$	$F = 2.92$, $p = .10$, $\eta_p^2 = .11$

Table A3.

	Experiment 1 (*n* = 23)	Experiment 2 (*n*= 25)
Long QE-duration trials	*M* = 146.8 mm ± 36.4 mm	*M* = 194.4 mm ± 57.4 mm
Short QE-duration trials	*M* = 158.8 mm ± 44.4 mm	*M* = 200.0 mm ± 54.6 mm
Inferential statistics	*t*(23) = 1.37, *p* = .09, *d* = 0.28	*t*(24) = 1.31, *p* = .10, *d* = 0.26

Note. The QE-duration median split for the full sample could not be calculated for all participants because of missing cases.

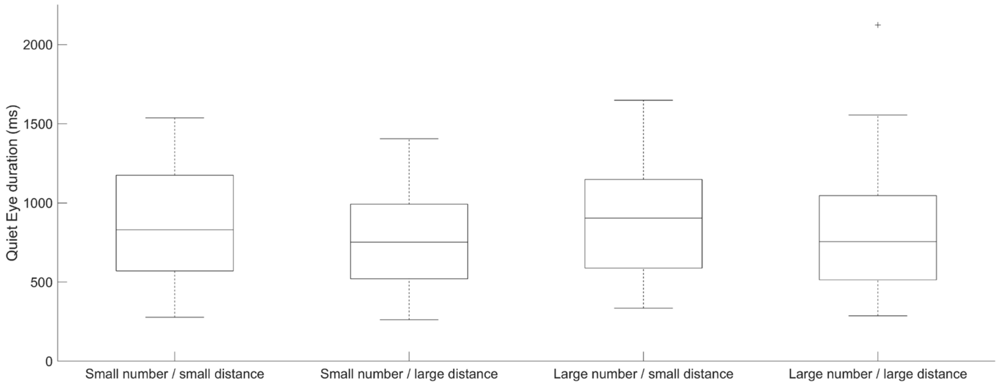

Figure A4. QE duration as a function of number of targets (small vs. large) and distance (small vs. large).

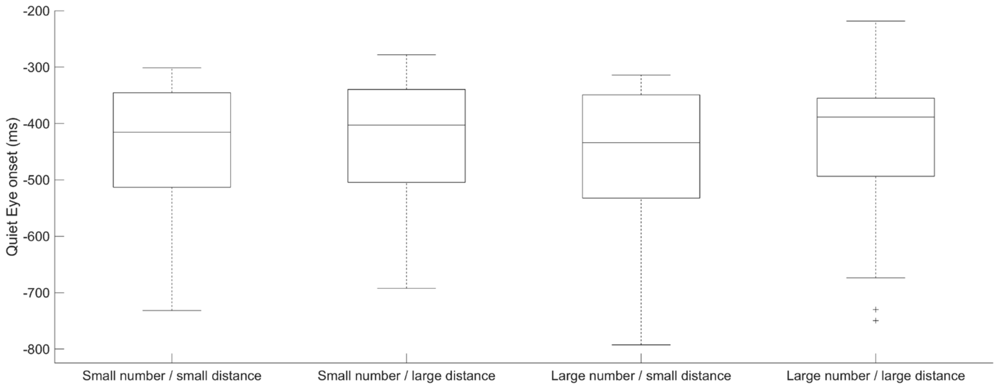

Figure A5. QE onset relative to the moment of movement initiation as a function of number of targets (small vs. large) and distance (small vs. large).

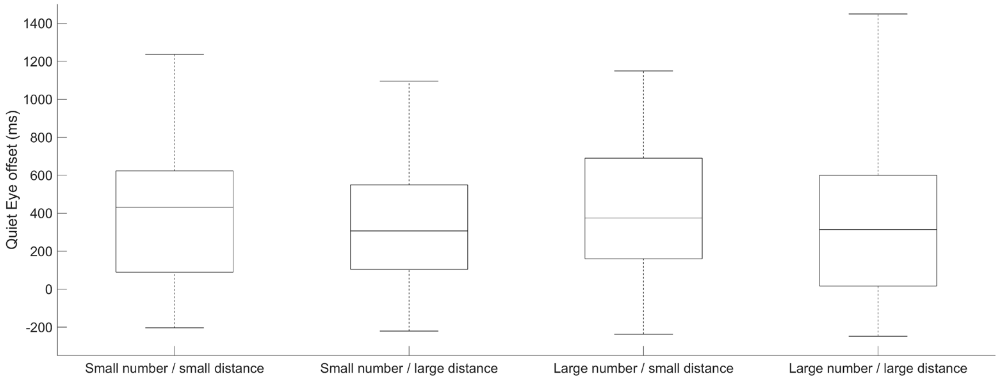

Figure A6. QE offset relative to the moment of movement initiation as a function of number of targets (small vs. large) and distance (small vs. large).

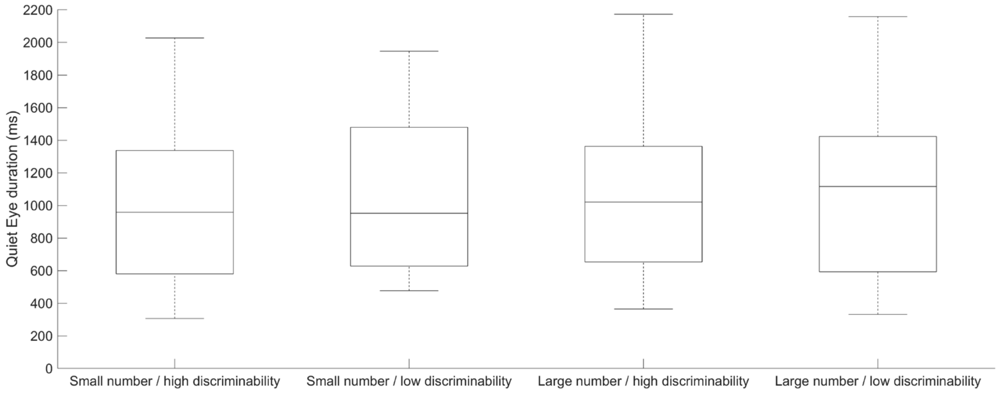

Figure A7. QE duration as a function of number of targets (small vs. large) and discriminability (high vs. low).

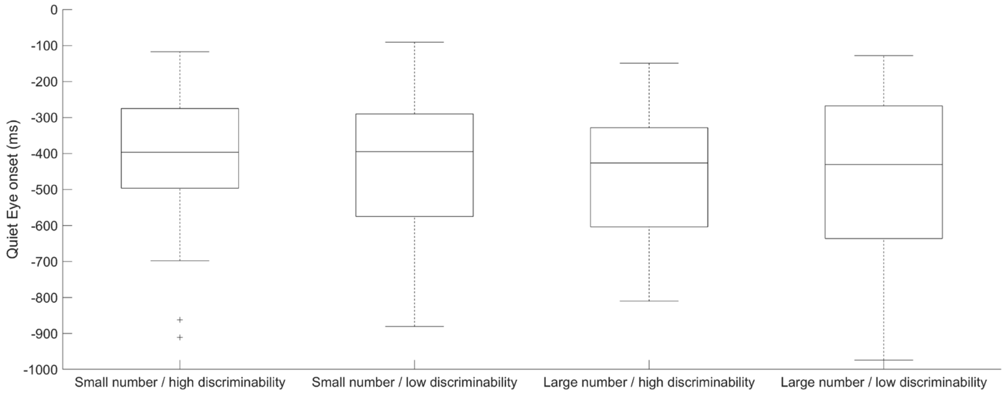

Figure A8. QE onset as a function of number of targets (small vs. large) and discriminability (high vs. low).

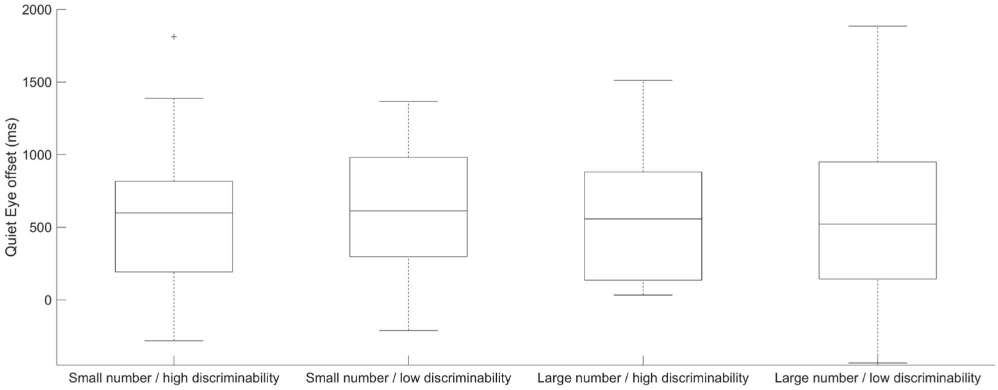

Figure A9. QE offset as a function of number of targets (small vs. large) and discriminability (high vs. low).