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Training enables substantial decoupling of visual attention and saccade preparation

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A B S T R A C T

Visual attention is typically shifted toward the targets of upcoming saccadic eye movements. This observation is commonly interpreted in terms of an obligatory coupling between attentional selection and oculomotor programming. Here, we investigated whether this coupling is facilitated by a habitual expectation of spatial congruence between visual and motor targets. To this end, we conducted a dual-task (i.e., concurrent saccade task and visual discrimination task) experiment in which male and female participants were trained to either anticipate spatial congruence or incongruence between a saccade target and an attention probe stimulus. To assess training-induced effects of expectation on premotor attention allocation, participants subsequently completed a test phase in which the attention probe position was randomized. Results revealed that discrimination performance was systematically biased toward the expected attention probe position, irrespective of whether this position matched the saccade target or not. Overall, our findings demonstrate that visual attention can be substantially decoupled from ongoing oculomotor programming and suggest an important role of habitual expectations in the attention-action coupling.

1. Introduction

The visual information falling on our retinae at any given moment by far exceeds the limited processing capacity of our brain. Efficient visual perception is therefore contingent on selective processing. A means to this end are saccadic eye movements. We typically execute three to four saccades per second (Findlay & Gilchrist, 2003), allowing us to sequentially foveate locations or objects of interest and thereby process their content at highest visual acuity. However, perceptual selection can also be achieved through another mechanism, namely via covert shifts of visual attention. By shifting attention covertly in space, relevant visual information can be selected and processed in detail without concurrent movement of the eyes. Influential theories of visual attention postulate a tight and obligatory link between the mechanisms underlying the deployment of visual attention and the programming of motor actions. The premotor theory of attention (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994) states that covert attention shifts originate directly from activity in the motor system and are merely a by-product of programming goal-directed actions. The visual attention model (Schneider, 1995; Schneider & Deubel, 2002) assumes that attentional selection is a prerequisite for motor preparation, with covert attention shifts being linked to the selection of targets for upcoming actions. Although there is disagreement about the causal relationship of the attention-action link, both theories postulate that the programming of goal-directed actions, such as saccades or manual movements, is inevitably accompanied by an attention shift toward the motor target.

Indeed, a large number of studies have provided evidence for the assumption that processes of attentional selection and motor preparation are closely intertwined. For instance, neurophysiological studies have shown that saccade programming and covert attention shifting elicit largely overlapping neural activation in frontal and parietal regions of the human brain (Corbetta et al., 1998; de Haan, Morgan, & Rorden, 2008). Also, subthreshold stimulation of oculomotor brain regions of non-human primates, such as the frontal eye fields (FEF) and the superior colliculus (SC), has been found to improve visual performance at the position to which gaze would have been shifted at a higher stimulation level (Moore & Fallah, 2004; Müller, Philiastides, & Newsome, 2005). At the behavioral level, evidence in favor of an obligatory attention-action coupling has come primarily from psychophysical dual-task studies requiring participants to perform goal-directed actions

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toward cued placeholder stimuli, while premotor attention allocation is probed by flashing a discrimination target either at the motor target or at a different position. A consistent finding of these studies was that discrimination performance is selectively enhanced when the attention probe and the target of a saccade (Deubel, 2008; Deubel & Schneider, 1996, 2003; Hoffman & Subramaniam, 1995; Jonikaitis & Deubel, 2011) or manual movement (Deubel, Schneider, & Paprotta, 1998; Jonikaitis & Deubel, 2011; Schiegg, Deubel, & Schneider, 2003) spatially coincide compared to when they diverge. Notably, this spatial congruency effect was still observed when experimental conditions provided an incentive to withdraw attention from the motor target (Deubel, 2008; Deubel & Schneider, 1996; Deubel, Schneider, & Paprotta, 1998; Schiegg, Deubel, & Schneider, 2003), indicating that attention allocation toward targets of upcoming goal-directed movements is mandatory. Indeed, a very recent dual-task study (Hanning et al., 2022) affirmed these earlier observations by demonstrating that attention can be deployed to distinct eye and hand movement targets in parallel and without cost, whereas the preparation of these movements cumulatively deteriorates the capacity to attend to movement-irrelevant, yet highly task-relevant, objects.

Even though the evidence for an obligatory attention-action link is compelling, there are also findings that cast doubt on the notion that visual attention shifts are inextricably coupled to processes of motor preparation (see Smith & Schenk, 2012, for an overview). For example, studies in non-human primates have shown that only the activity of visually responsive subpopulations of FEF neurons, but not the activity of saccade-related movement neurons, is modulated by covert attention (Gregoriou, Gotts, & Desimone, 2012; Thompson, Biscoe, & Sato, 2005), suggesting that oculomotor preparation and shifts of visual attention rely on distinct mechanisms. Consistent with this observation, a temporal dissociation between covert attention and saccade preparation has been demonstrated for the human FEF using transcranial magnetic stimulation (Juan et al., 2008). Moreover, there is evidence from psychophysical dual-task studies suggesting a less strict attention-action link. For instance, it has been found that some attentional resources can be diverted from the target of an upcoming saccade (Born, Ansorge, & Kerzel, 2013; Kowler et al., 1995; Moehler & Fiehler, 2014; Montagnini & Castet, 2007), a finding that is difficult to reconcile with the assumption that covert attention is merely a by-product of motor programming activity (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994). Likewise, it was recently demonstrated that visual discrimination performance is not enhanced at the endpoint of imminent averaging saccades landing in between two competing stimuli (Van der Stigchel & de Vries, 2015; Wollenberg, Deubel, & Szinte, 2018, 2019; Wollenberg, Hanning, & Deubel, 2020), arguing against a strict dependence of attention allocation on the spatial parameters of subsequently executed saccades. Also, there is evidence that unexecuted saccadic programs are not accompanied by an attention shift to the motor target (Born, Mottet, & Kerzel, 2014), which shows that saccade preparation does not always entail a spatially congruent allocation of attentional resources.

Given the conflicting evidence regarding the link between attention and action, it is important to point out that under natural conditions, goal-directed movements are generally directed toward targets of high behavioral relevance, and thus shifting attention to the target of an upcoming movement is beneficial in most situations. Accordingly, the commonly observed shift of attention toward motor targets might not necessarily reflect an inherent property of motor programming, but potentially a stubborn habit-driven phenomenon (Posner, Snyder, & Davidson, 1980) that is difficult to overcome without sufficient training (Dignath et al., 2019; Reeves & McLellan, 2020). This assumption was recently examined by Reeves and McLellan (2020) in a rapid serial visual presentation (RSVP) task requiring participants to shift attention from a letter stream to a proximal numeral stream from which the first items had to be reported. Importantly, participants were trained to perform this attention shift either while simultaneously saccading from the letter stream to the numeral stream (pro-shift) or vice versa (anti-shift). Results showed that after several hours of training, the majority of participants achieved similar levels of task performance (in terms of reaction time and numeral report measures) in anti-shift and pro-shift trials, suggesting that attentional selection can operate independently of saccade preparation. However, some caution should be exercised in interpreting these findings as evidence against an obligatory attention-action coupling, since participants foveated the numeral stream in anti-shift trials before saccade execution. Thus, it is possible that successful performance of anti-shift trials did not result from decoupling of attention and saccade preparation, but instead from strategic exploitation of high-acuity foveal vision.

Furthermore, to investigate the role of habitual processes in the attention-action link, it is crucial to determine to what extent and at what stage within the motor preparation phase attentional resources can be decoupled from the motor target. Therefore, the more commonly used discrimination task (e.g., Deubel & Schneider, 1996) appears to be a more suitable tool to study the attention-action link than an RSVP task, as it allows attention allocation to be probed at different positions competing for attentional resources and at different time points relative to movement execution. Using a discrimination task, Dignath et al. (2019) recently demonstrated for pointing movements that a learned expectation of spatial congruence or incongruence between a discrimination and a motor target can modulate the attention-action link. Specifically, they showed that after training, participants directed attention toward an anticipated discrimination target position, regardless of whether it matched or diverged from the motor target. However, this was only shown in a delayed pointing task that potentially allowed for pre-programming of movements (cf. Deubel & Schneider, 2003), rendering it unclear whether these findings also hold for the critical stage of motor preparation. To answer this question, we recently conducted an adapted version of the experiment of Dignath et al. (2019) in which participants completed a training of a concurrent attention probing and pointing task (Topfstedt, Wollenberg, & Schenk, 2023). By manipulating the attention probe position, participants learned to expect the probe at the same or opposite position of a cued pointing target. In addition, we varied the time of movement delays (i.e., time between a movement cue and a movement go-signal) to examine potential training effects on attention allocation at different stages of the motor preparation phase. Results of a subsequent test phase showed that attention was markedly biased toward the anticipated probe position, even when it diverged from the motor target position. Moreover, these findings were not affected by the time available for movement preparation, suggesting that decoupling attentional resources from the motor target is not limited to pre-programmed movements, but can be achieved during ongoing movement programming. These results imply that, at least for manual movements, habitual processes may play a more important role regarding the attention-action coupling than previously assumed.

Although our previous findings in pointing movements suggest that the attention-action link is substantially modulated by habitual top-down processes (Topfstedt, Wollenberg, & Schenk, 2023), it remains unclear whether this also applies to saccadic eye movements. For instance, it has been shown that attention can be diverted from a reach target, but not from a saccade target, when sufficient time (>300 ms) is available for motor preparation (Deubel & Schneider, 2003), suggesting that the nature of the attention-action link might differ depending on the type of goal-directed movement. The present study was designed to address this open question. Similar to previous studies involving manual pointing movements (Dignath et al., 2019; Topfstedt, Wollenberg, & Schenk, 2023), we investigated whether and, if so, to what extent, habitual processes contribute to the commonly observed presaccadic shift of attention. To this end, we conducted an experiment that allowed us to test the possibility of a decoupling of visual attention from saccade programming. Please note that we use the term *decoupling* to refer to an instance in which attentional resources are allocated to positions other than the target a of concurrently programmed saccade, without necessarily implying the complete absence of attentional facilitation at the saccade target. We asked participants to complete a training and a test session of a dual-task consisting of an attention probing and a saccade task. The initial training session (Attention Training) included a manipulation of the attention probe position. Participants learned anticipating that the probe will always appear either at the saccade target position (*Training Same*), at a position defined relative to the saccade target (*Training Relative*), or at a fixed position independent of the saccade target (*Training Fixed*). In the subsequent test session (Test Phase), however, the attention probe appeared equally likely at one out of several placeholder positions. Thus, based on probe discrimination data obtained in the Test Phase, it was possible to examine whether the expectation of spatial congruence or incongruence of attention probe and saccade target positions modulates presaccadic attention allocation. If the attention-action link is mainly the result of habitual processes, we should find that participants shift attention only toward the anticipated probe position, regardless of whether this position corresponds to the saccade target or not. In contrast, if visual attention is a mere by-product of processes of motor preparation (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994), attention should only be shifted to the saccade target, regardless of an expectation of spatial congruence or incongruence of positions. However, a third possibility would be that an anticipation of spatial incongruence leads to attentional facilitation at both the saccade target and the expected probe position. At first glance, such a finding would be in line with the assumption that the preparation of a goal-directed movement requires attentional selection of its target (Schneider, 1995; Schneider & Deubel, 2002). However, in previous studies (Dignath et al., 2019; Topfstedt, Wollenberg, & Schenk, 2023), participants were trained to expect an attention probe at a spatial position defined relative to the motor target (i.e., the position opposite the motor target). In this case, an observation of a retention of attentional resources at the motor target position could also be explained by the fact that attention was (initially) shifted to the motor target because it served as a spatial reference to identify the position of the attention probe (in the current study, we refer to this as the "spatial reference hypothesis"). Our study design allowed us to test this hypothesis by comparing presaccadic attention allocation in a training condition in which the attention probe was anticipated to appear at a position relative to the saccade target (*Training Relative*) to a training condition in which the probe was expected at a position not defined relative to the saccade target (*Training Fixed*). In addition, we wanted to examine whether potential top-down modulations of attention depend on the time available for motor preparation. Similar to our previous study (Topfstedt, Wollenberg, & Schenk, 2023), we thus varied the time of movement delays (i.e., stimulus onset asynchrony, SOA, between a movement cue and a movement go-signal of either 0 ms or 1000 ms) in the saccade task so that attention allocation was probed either within or after the assumed phase of motor programming. If the attention-action coupling is at least in part the result of habitual processes, prior training should affect attention allocation in a later task and the effect of this training should not be limited to long movement delays (i.e., delays during which movement pre-programming becomes possible).

2. Methods

2.1. Participants

Forty-one healthy students (aged 18–42 years; 28 females) with normal or corrected-to-normal vision gave written informed consent and participated in the experiment for monetary compensation or course credits. All participants were unaware of the purpose of the experiment. The experiment was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki.

The present study aimed to test whether it is possible to decouple attentional resources from the targets of imminent saccades. Evidence for such a decoupling was recently reported in a very similar dual-task study on pointing movements (Topfstedt, Wollenberg, & Schenk, 2023). More specifically, this study demonstrated a significant advantage in discrimination performance at a movement-irrelevant position where participants were trained to expect an attention probe compared to the upcoming motor target position. This performance benefit had an effect size of $d_z = 4.72$ (calculated on the basis of the original data, but not reported in Topfstedt, Wollenberg, & Schenk, 2023). However, as mentioned in the Introduction, it is conceivable that the decoupling of attention and action is more difficult to overcome in saccades (Deubel & Schneider, 2003), so that the effect might be less pronounced in saccades compared to pointing movements. Accordingly, in the current study, we aimed for a final sample size (see Section 2.4.) of at least ten participants per condition, as this allows us to detect effects with a size of $d_z \geq 1.00$ with an a priori power of 80 % (calculated using G*Power for a matched pairs two-tailed t test with $\alpha = .05$).

2.2. Apparatus

Participants sat in a dimly illuminated room viewing a one-way mirror with their head positioned on a chin rest. The mirror reflected the image of a downward facing computer monitor (Acer XB271HUA; 120 Hz; 2560 × 1440 pixels; screen size: 59.67 × 33.57 cm) mounted at the top of the experimental setup. The distance between participants' eyes and the center of the stimulus presentation was 56.0 cm. We recorded the gaze position of participants' right eye with a temporal resolution of 1000 Hz using an EyeLink 1000 Plus eye-tracking system (SR Research Ltd., Ottawa, Ontario, Canada). To ensure high tracking accuracy throughout the experiment, the eye-tracker was calibrated prior to each experimental session (see Section 2.3.) and whenever necessary due to participants taking a short break or noticeable head movement. Manual responses were recorded with a standard numeric keypad.

2.3. Design and procedure

Fig. 1 illustrates the time course of a typical trial. Stimuli were displayed on a uniform grey background. Each trial began with the presentation of a central black fixation cross (size: $0.5^\circ \times 0.5^\circ$) and four black premask characters (seven-segment "8"; size: $0.9^\circ \times 1.4^\circ$) positioned equidistant from each other at an eccentricity of 7.2° relative to the fixation cross. To start a trial, participants had to maintain gaze within a 2.0° radius around the fixation cross. After 1000–1300 ms (randomly selected in steps of 25 ms), the fixation cross was replaced by an arrow cue (size: $1.5^\circ \times 1.5^\circ$) that indicated the saccade target (ST) by pointing in the direction of one of the premask characters with equal probability. After a stimulus onset asynchrony (SOA) of 0 ms (*SOA-0* condition) or 1000 ms (*SOA-1000* condition), an acoustical go-signal (440 Hz tone) was presented. Note that an SOA of 0 ms required immediate saccade preparation while an SOA of 1000 ms allowed for extended movement preparation time and thus the possibility for movement pre-programming. Participants were instructed to make a rapid and accurate saccade to the indicated ST as soon as the go-signal tone was played. They were also asked to avoid blinking throughout the trial. After a delay of 100–150 ms (randomly selected in steps of 25 ms) relative to go-signal onset, the premask characters were replaced by an attention probe (seven-segment "3" or "E") and three distractors (seven-segment "2" or "5"). Accordingly, depending on the movement delay, the attention probe appeared either during ongoing motor programming (*SOA-0*) or once the programming phase was presumably complete (*SOA-1000*). The probe display was shown for 83 ms and then masked again. After movement execution, participants reported the identity of the attention probe ("3" vs. "E") in a non-speeded manner by manually pressing one of two buttons (left vs. right) on the keypad. They received acoustical feedback about discrimination performance after each trial of the Discrimination Only task and Attention Training but not on trials of the Test Phase (see further below).

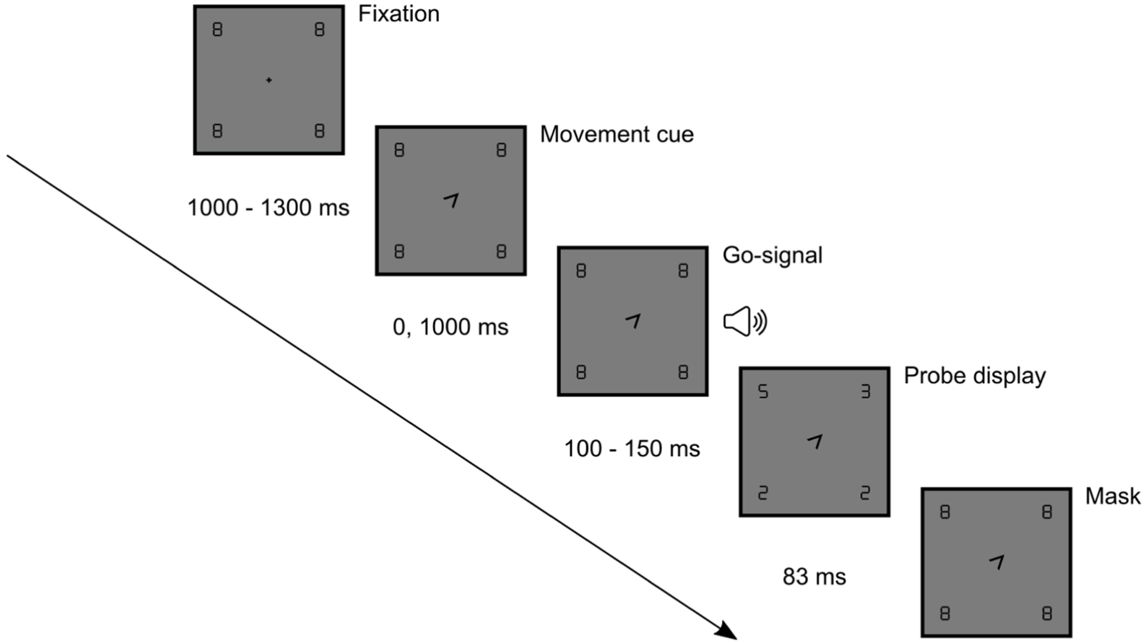

Fig. 1. Typical trial sequence. Participants started a trial by fixating a central fixation cross that was presented together with four placeholder characters ("8″). Shortly afterwards, a movement cue (an arrow pointing in the direction of one of the four placeholders) was presented to indicate the saccade target (ST) of the current trial. Participants were instructed to execute a saccade as quickly and accurately as possible to ST upon presentation of an acoustical go-signal, played either 0 ms or 1000 ms after movement cue presentation. Presaccadic attention allocation was measured by presenting an attention probe ("3" or "E") along with three distractors ("2" or "5") during saccade preparation (i.e., in the time between go-signal and saccade onset). This probe display was subsequently masked. After saccade execution, participants indicated the identity of the attention probe by manual key press.

Fig. 2 summarizes the main differences between experimental phases and experimental conditions. Each participant completed two experimental sessions, taking place on two consecutive days. The first session started with four blocks of 30 trials of the saccade task (Saccade Only). In these practice trials, no probe display (cf. Fig. 1) was presented. Participants received visual feedback about task performance after their response saccade (see Section 2.4.) had landed. To train participants to perform fast saccades, a central green circle was presented when the saccade had been initiated between 0 and 400 ms after go-signal onset. A central yellow circle was presented when a blink had been detected after the movement cue presentation. A central red circle with the label "too early" was presented when the saccade had been initiated before the go-signal, and with the label "too late" when saccade latency exceeded 400 ms.

Next, participants completed eight blocks of 30 trials of the discrimination task (Discrimination Only). In these trials, no movement cue and no go-signal was presented (cf. Fig. 1) and participants were asked to keep fixation throughout a trial. The attention probe was presented in 80 % of trials at a specific placeholder position. In the remaining 20 % of trials, the probe was presented with equal probability at one of the remaining placeholder positions. The likely position of the probe was randomly selected and held constant for each trial block. Participants were informed about the likely probe position by displaying the position (e.g., "Position: 1" for the upper right position) above the stimulus configuration. The Discrimination Only task of the first experimental session served as a screening phase to ensure that participants were capable of reliably discriminating the probe stimulus at a position toward which attention was deployed. For this purpose, discrimination performance (see Section 2.4.) was calculated for probes at the likely probe position in the last two trial blocks of this task. Participants continued the experiment only if this value exceeded 60 %. The last two trial blocks of the Discrimination Only task were also used to compute probe discrimination measures for *attended* positions (containing the probe with a high probability) and *unattended* positions (containing the probe with a low probability) in the absence of a concurrent saccade task. By computing corresponding measures for an identical Discrimination Only task performed at the very end of the experiment (see further below), we were able to assess potential overall improvements in probe discrimination capacities across the experiment.

The initial Discrimination Only task was followed by a training of the dual-task (Attention Training) in which participants performed the saccade and discrimination task simultaneously. For the Attention Training, participants were randomly assigned to one of three training groups, differing from each other in the placeholder position at which the attention probe was presented. In *Training Same*, the probe was presented in 100 % of trials at the cued ST. In *Training Relative*, the probe was always presented at one specific placeholder position relative to ST, namely either at the placeholder 90°, 180°, or 270° clockwise to ST (but never at ST). The selection of this relative probe position was counterbalanced (e.g., participant 1: placeholder 90° clockwise to ST, participant 2: placeholder 180° clockwise to ST, participant 3: placeholder 270° clockwise to ST, etc.). In *Training Fixed*, the probe was always displayed at a fixed spatial position (i.e., either at the upper right, bottom right, bottom left, or upper left placeholder position), regardless of the current ST position. Again, this fixed probe position was counterbalanced across participants of the *Training Fixed* group (e.g., participant 1: upper right placeholder, participant 2: lower right placeholder, participant 3: lower left placeholder, participant 4: upper left placeholder, etc.). Prior to the start of the Attention Training, participants of all training groups were informed about the respective position at which the probe would appear in 100 % of trials. In the first experimental session, participants completed 24 blocks of 30 trials of the Attention Training.

At the beginning of the second session, participants completed another set of six blocks (30 trials each) of the Attention Training. For each participant, probe contingencies were identical to the Attention Training of the first session. The continuation of the Attention Training in the second session served to refresh potential group-specific learning effects from the previous day.

Next, to assess such training-induced learning effects on presaccadic

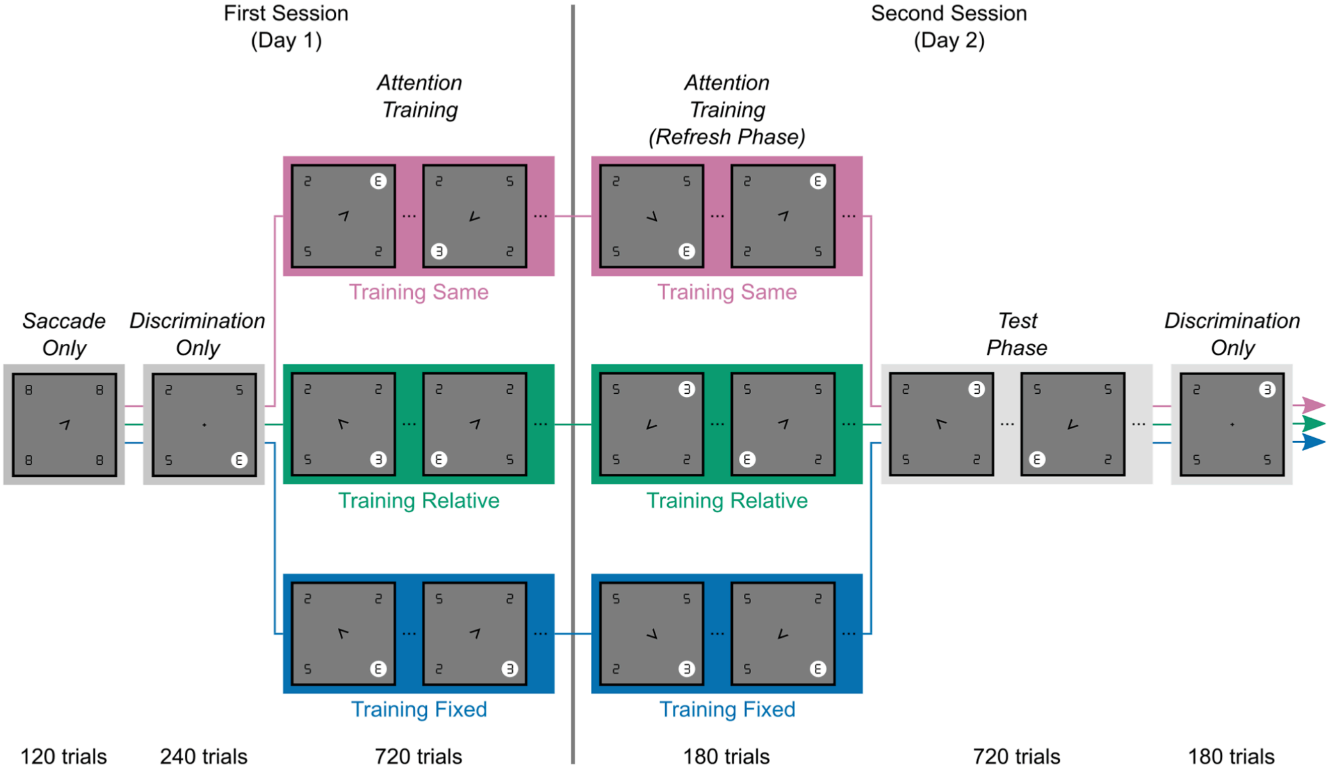

Fig. 2. Experimental phases and conditions. The first session began with a training of the saccade task (Saccade Only), in which saccades were performed to a centrally cued saccade target (ST) whose position varied randomly across trials. Next, participants completed a training of the discrimination task (Discrimination Only) in which they discriminated a probe stimulus ("3″ vs. "E"; highlighted in white for illustration purposes only) presented with 80% probability at a specific placeholder position that was held constant over a trial block. Then, participants completed one of three Attention Training conditions in which they performed the saccade and discrimination task in parallel. In *Training Same* (upper panels), the attention probe was always presented at ST. In *Training Relative* (central panels), the probe always appeared at a specific position relative to ST (e.g., at the opposite position). In *Training Fixed* (lower panels), the probe was always displayed at a fixed spatial position (e.g., at the bottom right position), regardless of the ST position. The second session began with a refresh phase of the Attention Training, followed by a Test Phase in which the probe was presented at a random placeholder position. The second session was concluded with another series of trial blocks of the Discrimination Only task.

attention allocation, participants completed a Test Phase (24 blocks of 30 trials), in which the attention probe was displayed with equal probability at one of the four placeholder positions. Yet, to prevent potential training-induced effects on attention allocation from being quickly unlearned, participants were not informed about the randomized presentation of the attention probe prior to the Test Phase. They were only informed that they would no longer receive feedback about the correctness of their discrimination response. The randomization of the probe position in the Test Phase led to different trial types with regard to the spatial relationship between the position at which participants had been trained to expect the probe in the Attention Training (trained position), the actual (randomly drawn) probe position, and the ST position. Specifically, there were four distinct trial types in the Test Phase: *ST/trained* trials in which the probe appeared at the ST position matching the trained position, *ST/non-trained* trials in which the probe appeared at the ST position not matching the trained position, *non-ST/trained* trials in which the probe appeared at the trained position not matching the ST position, and *neutral* trials in which the probe appeared at a position neither matching the trained position nor the ST position. However, by design, not all of these trial types were included in the Test Phase of each training group. *Training Fixed* included all four trial types in equal numbers: 180 *ST/trained* trials, 180 *ST/non-trained* trials, 180 *non-ST/trained* trials and 180 *neutral* trials. In *Training Relative*, there were 180 *ST/non-trained* trials, 180 *non-ST/trained* trials, and 360 *neutral* trials (i.e., no *ST/trained* trials). In *Training Same*, there were 180 *ST/trained* trials and 540 *neutral* trials (i.e., no *ST/non-trained* trials and no *non-ST/trained* trials).

At the end of the second session, participants performed another six blocks of 30 trials of the Discrimination Only task. As mentioned above, this final phase served to assess possible overall learning effects regarding discrimination performance.

2.4. *Data analysis*

Preprocessing of behavioral and eye-tracking raw data was performed in MATLAB (Mathworks, Natick, MA). Saccadic eye movements were detected offline using the velocity-based approach proposed by Engbert and Mergenthaler (2006) with a detection threshold parameter $\lambda = 5$ and a minimum saccade duration of 15 ms. The first saccade that landed outside a radius of 2.5° from fixation was defined as the response saccade, which was subjected to further analyses. Saccade latency was calculated relative to go-signal onset.

For offline analyses of all experimental phases that included the saccade task, we discarded trials if no saccade was detected (No saccade), if an anticipatory response saccade (saccade latency < 80 ms; for an identical approach, see for example: Born, Ansorge, & Kerzel, 2013; Born, Mottet, & Kerzel, 2014) was detected (Saccade too early), if the latency of the response saccade deviated from participant's median by more than three times the median absolute deviation (Leys et al., 2013; Saccade latency outlier), if a blink occurred after movement cue onset (Blink violation), if the response saccade did not land within a radius of 2.5° relative to ST (Saccade inaccurate), or if the attention probe was still displayed after saccade onset (Saccade before probe offset). For data analysis of the Discrimination Only task, we excluded trials if gaze was not maintained within 2.5° from fixation (Fixation violation) or if a blink occurred (Blink violation).

Four participants were excluded from the experiment because they did not reach the threshold of discrimination performance in the screening phase of the initial Discrimination Only task (see Section 2.3.). Of the remaining sample ($N = 37$ out of 41), we discarded the data set of one participant of the *Training Same* group, three participants of the *Training Relative* group, and one participant of the *Training Fixed* group from the analyses because more than 45 % of the trials (for an identical approach, see Arkesteijn et al., 2019) of the Test Phase had to be rejected after applying the exclusion criteria described in the previous paragraph. The final sample ($N = 32$) comprised 11 participants in *Training Same*, 10 participants in *Training Relative*, and 11 participants in *Training Fixed*. A summary of the proportion of Test Phase trials rejected based on the applied exclusion criteria is presented for each training group in the Appendix (see Table S1 under "Supplementary Table").

Statistical data analyses were carried out with JASP version 0.17.3 (JASP Team). For all statistical tests performed, a p-value ≤ 0.05 was used as the threshold for statistical significance. Reported mean values represent the grand mean across single-subject means for a given experimental condition, with corresponding measures of dispersion (standard error of the mean, standard deviation) being computed relative to the grand mean based on single-subject means. Performance in the discrimination task was expressed as the percentage of correct manual responses regarding the identity ("3″ vs. "E") of the attention probe (discrimination performance). For analysis of performance in the Discrimination Only task, we conducted a repeated measures analysis of variance (ANOVA) with factors probe position (*attended* position vs. *unattended* position) and session (first session vs. second session). To ensure that only trials with stable task performance were included, we only analyzed the data of the last two trial blocks from the first experimental session. From the second session, all trials of the Discrimination Only task were included. For analysis of the Test Phase, we computed discrimination performance separately for each training group (*Training Same* vs. *Training Relative* vs. *Training Fixed*) and for each combination of SOA condition (*SOA-0* vs. *SOA-1000*) and probe position. As described at the end of Section 2.3., the number of levels of factor probe position (i.e., the number of distinct trial types) in the Test Phase differed between training groups: *Training Fixed* (*ST/trained* vs. *ST/non*-trained vs. *non-ST/trained* vs. *neutral*), *Training Relative* (*ST/non*-trained vs. *non-ST/trained* vs. *neutral*), *Training Same* (*ST/trained* vs. *neutral*). Due to these differences in the number of trial types, we analyzed discrimination performance separately for each training group by means of repeated measures ANOVAs with factors SOA and probe position. In case of sphericity violations, Greenhouse-Geisser corrections were applied. Post-hoc pairwise comparisons were Bonferroni-adjusted. Note that we further explored specific aspects of our data by performing several additional analyses, which are described in detail in Section 3.3.

3. Results

To examine expectancy-driven top-down modulations on pre-saccadic attention allocation (as induced in the Attention Training), we analyzed eye movement data (as assessed via the saccade task) and discrimination performance data (as assessed via the attention probing task) obtained in the Test Phase.

3.1. Saccade performance

We first investigated whether saccade performance within the Test Phase, defined as saccade latency (i.e., time between go-signal onset and saccade onset) and saccade accuracy (i.e., distance between the endpoint of the response saccade and the target position), was affected by SOA (*SOA-0* vs. *SOA-1000*) and training condition (*Training Same* vs. *Training Relative* vs. *Training Fixed*). Descriptive results of saccade performance are shown in Table 1.

Table 1
Test Phase data of saccade latency in ms and saccade accuracy in visual degrees for each training condition (*Training Same* vs. *Training Relative* vs. *Training Fixed*) and stimulus onset asynchrony (SOA; 0 ms vs. 1000 ms). Data are presented as mean ± SD.

	Training Same	*Training Relative*	*Training Fixed*
Latency: *SOA-0*	388 ± 51	420 ± 61	379 ± 39
Latency: *SOA-1000*	337 ± 49	367 ± 59	327 ± 42
Accuracy: *SOA-0*	1.1 ± 0.2	1.2 ± 0.2	1.1 ± 0.1
Accuracy: *SOA-1000*	1.0 ± 0.2	1.2 ± 0.2	1.0 ± 0.1

Inspection of descriptive results suggests that *Training Relative* was associated with longer saccade latencies than *Training Same* and *Training Fixed* in each SOA condition. However, results of an analysis of variance (ANOVA) showed no significant main effect of training condition, $F(2, 29) = 1.93$, $p = 0.163$, $\eta_p^2 = 0.12$, and no significant interaction between training and SOA condition, $F(2, 29) = 0.01$, $p = 0.986$, $\eta_p^2 < 0.01$, for saccade latency. In contrast, saccade latencies were significantly affected by SOA condition, $F(1, 29) = 122.71$, $p < 0.001$, $\eta_p^2 = 0.81$, indicating shorter latencies across training groups in *SOA-1000* trials ($M = 343$ ms, $SD = 52$ ms) than in *SOA-0* trials ($M = 395$ ms, $SD = 52$ ms). This suggests that, as expected, the *SOA-1000* trials permitted at least some pre-programming of saccades. Yet, latencies were still relatively high in *SOA-1000* trials, which at first glance seems to contradict the assumption that these trials allowed for completion of motor preparation prior to the go-signal. However, this can probably be attributed to the fact that *SOA-1000* trials required participants to suppress saccade execution for an extended period of time (i.e., 1000 ms). Thus, participants probably had to overcome initial motor inhibition before they could execute the saccade in response to the go-signal. Moreover, in our recent study on pointing movements (Topfstedt, Wollenberg, & Schenk, 2023) we observed longer movement latencies in a task including both short and long delays compared to a task comprising only one short movement delay. This suggests that the use of variable movement delays generally slows down movement initiation by inducing temporal uncertainty (i.e., uncertainty as to whether movement execution has to be withheld or not). Since we used two different movement delays in the current study, this type of uncertainty could also explain (or contribute to) the relatively long saccade latencies in *SOA-1000* trials.

Regarding saccade accuracy, descriptive results indicate slightly less accurate saccades in *Training Relative* than in *Training Same* and *Training Fixed* in each SOA condition. However, ANOVA results showed no significant main effect of SOA, $F(1, 29) = 2.57$, $p = 0.120$, $\eta_p^2 = 0.08$, no significant main effect of training condition, $F(2, 29) = 3.01$, $p = 0.065$, $\eta_p^2 = 0.17$, and no significant interaction between SOA and training condition, $F(2, 29) = 2.39$, $p = 0.110$, $\eta_p^2 = 0.14$.

In sum, we observed no statistically reliable evidence that oculomotor performance differed between training conditions. Thus, overall, our results provide no indication for the assumption that participants used different strategies to perform the saccade task depending on the training condition (which is relevant regarding the interpretation of discrimination performance data, see Section 3.2.). However, at the descriptive level, there was a tendency toward slightly increased saccade latency and reduced saccade accuracy in *Training Relative* compared to the other two training groups. Since it is possible that this between-group difference might have reached statistical significance in a larger sample, we addressed this aspect in the context of the discrimination performance data in Section 3.3.2. In addition, we provide and discuss the results of further analyses comparing saccade latency and accuracy measures within each training group as a function of the probe position (i.e., trial type) in the Appendix (see "Supplementary Saccade Performance Results"). However, the results of these complementary analyses do not suggest that the probe position pronouncedly affected saccade parameters.

3.2. *Discrimination performance*

In order to detect and quantify potential overall learning effects across the experiment, we used average discrimination performance at *attended* (i.e., likely) and *unattended* (i.e., unlikely) probe positions to compare performance between the first and second Discrimination Only task (i.e., last two trial blocks of first session vs. trial blocks of second session). A visual depiction of the results of this analysis can be found in the Appendix (see Fig. S1 under "Supplementary Figure"). In the first session, mean discrimination performance was 96.0 % ($SD = 6.2$ %) at *attended* positions and 59.2 % ($SD = 15.7$ %) at *unattended* positions. Relative to the first session, performance in the second session barely changed at *attended* positions ($M = 96.4$ %, $SD = 2.3$ %), whereas performance at *unattended* positions ($M = 66.2$ %, $SD = 15.0$ %) increased slightly. However, results of a mixed ANOVA only showed a significant main effect of probe position (*attended* vs. *unattended* positions), $F(1, 31) = 259.41$, $p < 0.001$, $\eta_p^2 = 0.89$, but a non-significant main effect of session, $F(1, 31) = 4.01$, $p = 0.054$, $\eta_p^2 = 0.12$, and no significant interaction between session and probe position, $F(1, 31) = 3.59$, $p = 0.068$, $\eta_p^2 = 0.10$. Accordingly, it can be concluded that discrimination performance without concurrent saccadic eye movements was enhanced at *attended* compared to *unattended* positions, while we found no statistical evidence for a reliable change across the experiment in the overall capacity to discriminate the attention probe.

Next, we analyzed discrimination performance for each training condition in the Test Phase to examine possible effects of learned spatial congruence or incongruence between the attention probe and the saccade target (ST) on presaccadic attention allocation (Fig. 3). This was done by subjecting discrimination performance data of each training condition to separate repeated measures ANOVAs with factors SOA (*SOA-0* vs. *SOA-1000*) and probe position (*Training Same*: *ST/trained* vs. *neutral; Training Relative*: *ST/non*-trained vs. *non-ST/trained* vs. *neutral; Training Fixed*: *ST/trained* vs. *ST/non*-trained vs. *non-ST/trained* vs. *neutral*).

For *Training Same*, ANOVA results showed a significant main effect of probe position, $F(1, 10) = 134.64$, $p < 0.001$, $\eta_p^2 = 0.93$, indicating enhanced discrimination performance across SOA conditions at the *ST/trained* position ($M = 97.4$ %, $SD = 2.8$ %) compared to performance at neutral probe positions ($M = 58.0$ %, $SD = 10.9$ %). The main effect of SOA, $F(1, 10) = 0.07$, $p = 0.804$, $\eta_p^2 = 0.01$, and the interaction between SOA and probe position, $F(1, 10) = 1.36$, $p = 0.271$, $\eta_p^2 = 0.12$, were not significant. These results suggest that participants directed attention to the saccade target position at which they also expected the attention probe to appear. We found no evidence to suggest that this effect

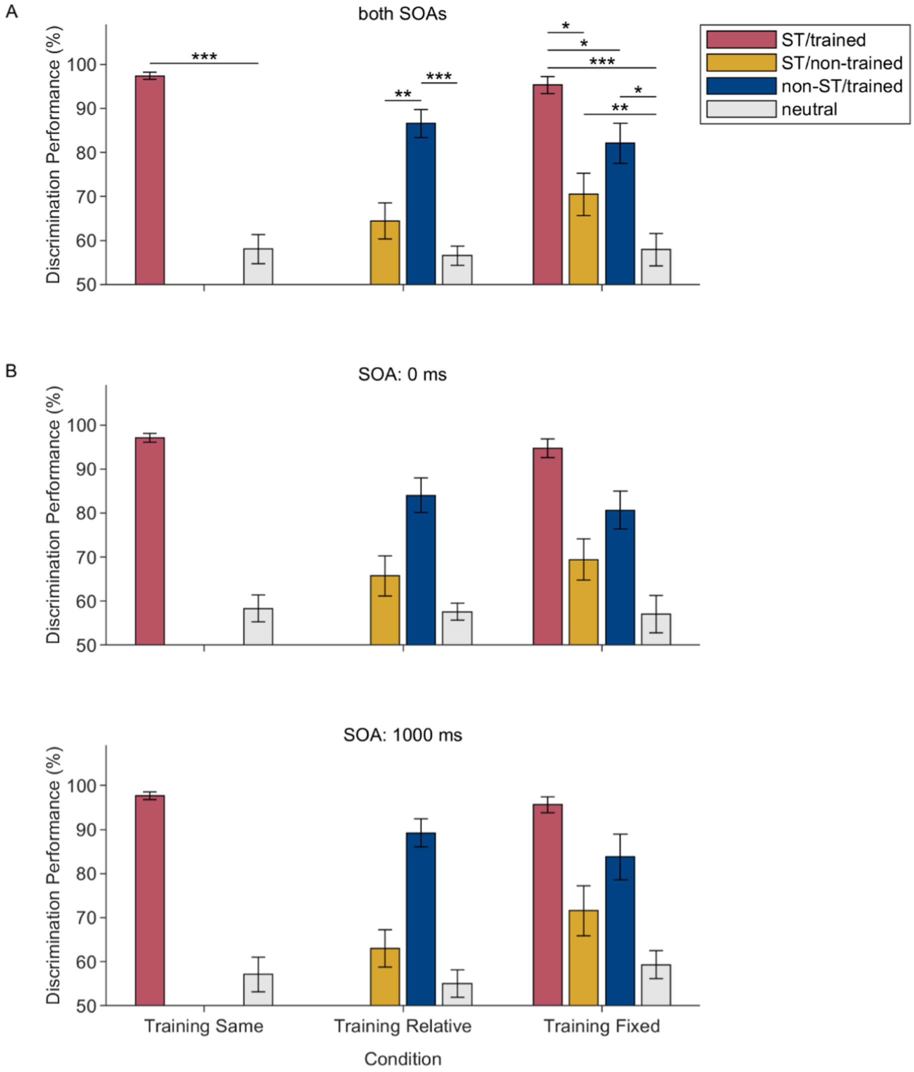

Fig. 3. Discrimination performance in Test Phase. Graphs depict mean discrimination performance for each training condition as a function of probe position. (A) Mean discrimination performance pooled across *SOA-0* and *SOA-1000* conditions. Asterisks indicate statistical significance of pairwise comparisons between probe positions within a given training condition (* $p \leq .05$; ** $p \leq .01$; *** $p \leq .001$). (B) Mean discrimination performance plotted separately for *SOA-0* condition (upper panel) and *SOA-1000* condition (lower panel). Error bars represent standard error of the mean (SEM).

depends on the time available for motor preparation.

For *Training Relative*, we found that discrimination performance differed significantly between probe positions, $F(2, 18) = 25.50$, $p < 0.001$, $\eta_p^2 = 0.74$. However, there was no significant main effect of SOA condition, $F(1, 9) < 0.01$, $p = 0.986$, $\eta_p^2 < 0.01$, and no significant interaction between SOA and probe position, $F(2, 18) = 1.99$, $p = 0.166$, $\eta_p^2 = 0.18$. Post-hoc pairwise comparisons revealed that discrimination performance across SOAs was significantly enhanced at the *non-ST/trained* position ($M = 86.6$ %, $SD = 10.1$ %) compared to both the *ST/non-trained* position ($M = 64.4$ %, $SD = 13.0$ %, $t(9) = -3.95$, $p = 0.010$, $d_z = -1.95$) and neutral positions ($M = 56.6$ %, $SD = 6.9$ %, $t(9) = 9.13$, $p < 0.001$, $d_z = 2.66$). Moreover, there was no significant difference in performance between the *ST/non-trained* position and neutral positions ($t(9) = 2.07$, $p = 0.207$, $d_z = 0.71$). Taken together, these results demonstrate that participants learned to shift attention to the expected probe position, even though this position did not coincide with the saccade target. This pattern of results was not significantly affected by the time available for motor preparation.

Regarding *Training Fixed*, ANOVA results showed a significant main effect of probe position on discrimination performance, $F(1.20, 11.96) = 15.06$, $p = 0.002$, $\eta_p^2 = 0.60$. The main effect of SOA, $F(1, 10) = 2.75$, $p = 0.128$, $\eta_p^2 = 0.22$, and the interaction between SOA and probe position, $F(3, 30) = 0.15$, $p = 0.932$, $\eta_p^2 = 0.01$, were not significant. Post-hoc pairwise comparisons showed that overall discrimination performance at the *ST/trained* position ($M = 95.3$ %, $SD = 6.3$ %) was significantly enhanced relative to performance at all remaining probe positions (*ST/non-trained*: $M = 70.5$ %, $SD = 16.1$ %, $t(10) = 4.04$, $p = 0.014$, $d_z = 1.81$; *non-ST/trained*: $M = 82.1$ %, $SD = 15.0$ %, $t(10) = 3.69$, $p = 0.025$, $d_z = 0.95$; neutral positions: $M = 57.9$ %, $SD = 12.2$ %, $t(10) = 8.19$, $p < 0.001$, $d_z = 2.71$). Moreover, performance at the *non-ST/trained* position was significantly higher compared to performance at neutral probe positions, $t(10) = 3.62$, $p = 0.028$, $d_z = 1.76$. In contrast to *Training Relative*, discrimination performance at the *ST/non-trained* position was significantly higher than performance at neutral positions, $t(10) = 4.36$, $p = 0.009$, $d_z = 0.90$, and did not differ compared to performance at the *non-ST/trained* position, $t(10) = -1.33$, $p > 0.999$, $d_z = -0.86$. These results suggest that participants directed attention to both the expected probe position and the saccade target. Furthermore, the finding of enhanced discrimination performance at the *ST/trained* position compared to all other probe positions in this condition provides evidence for an additive attentional enhancement effect when saccade target and expected probe position spatially coincide.

3.3. *Results of further analyses*

3.3.1. *No evidence for a spatial reference hypothesis*

In addition to examining the possibility of a decoupling of attentional resources from targets of forthcoming saccades through training, we aimed at investigating whether the feasibility of such decoupling during ongoing oculomotor programming depends on the spatial relationship between visual and saccadic targets (spatial reference hypothesis; see Introduction). To this end, we computed, separately for the *Training Relative* and *Training Fixed* condition, an index of the training-induced decoupling effect in *SOA-0* trials by subtracting discrimination performance at the *ST/non-trained* position from performance at the *non-ST/trained* position. We then performed an unpaired *t*-test to statistically compare this decoupling index between *Training Relative* and *Training Fixed*. Surprisingly, other than predicted by a spatial reference hypothesis, we found no significant difference between training conditions, $t(19) = -0.68$, $p = 0.504$, $d = -0.30$. Thus, our data do not provide evidence to suggest that the capacity to decouple attention from motor targets depends on the specific spatial relationship between a motor target and a task-relevant visual target.

3.3.2. *Attention decoupling does not rely on compromised oculomotor performance*

As reported in Section 3.1., there was a tendency toward increased saccade latency and reduced saccade accuracy for both SOAs in *Training Relative* compared to the other two training conditions. Even though we observed no statistically reliable modulation of these two saccade parameters across groups, this indication of reduced saccadic speed and accuracy leaves open the possibility that the observed attention decoupling in *Training Relative* was achieved only by compromising oculomotor performance. Put differently, the discrimination performance results in this condition may have resulted from a prioritization of the discrimination task over the saccade task rather than being indicative of a genuine decoupling of attention from saccade programming. To resolve this ambiguity, we re-examined discrimination performance data of *Training Relative* in an exploratory analysis including only trials indicative of fairly uncompromised saccadic control. This entailed the following steps. For each participant of *Training Relative*, we first performed, separately for each SOA condition, a median-split on the saccade latency data and selected the subset of trials with comparably fast (i.e., below median latency) saccades. For each resulting dataset, we then calculated the median saccade accuracy and used it to select only those trials representing comparably accurate (i.e., above median accuracy) saccades. Thus, the final datasets comprised only the most accurate among the fastest saccades of each SOA condition, which were subjected to a repeated measures ANOVA with factors probe position and SOA, using discrimination performance as the dependent variable. Note that we performed two additional variants of this exploratory analysis with different subsets of uncompromised saccade trials to ensure that the statistical results reported here did not depend on the specific method used for trial selection. Details of these analyses and corresponding results are described in the Appendix (see "Supplementary Discrimination Performance Results"). If attentional decoupling depends on compromising saccadic speed or accuracy, there should be no discrimination benefit at non-saccade targets in uncompromised saccade trials. In contrast, if true attentional decoupling is possible, a discrimination benefit at non-saccade targets should be observed in this subset of trials.

For the *Training Relative* data included in this analysis, mean saccade latency was 378 ms ($SD = 55$ ms) in *SOA-0* trials and 321 ms ($SD = 53$ ms) in *SOA-1000* trials. Mean saccade accuracy was 0.7° ($SD = 0.2°$) in *SOA-0* trials and 0.7° ($SD = 0.2°$) in *SOA-1000* trials. Thus, for both SOAs, oculomotor performance in this subset of trials was even better than that of *Training Same* and *Training Fixed* in our main analysis (cf. Table 1). Accordingly, possible attentional effects observed in the current data cannot be attributed to a strategy that involves compromising saccadic speed or accuracy. In fact, we found that the pattern of discrimination performance (see Fig. 4) was highly similar to that observed in the main analysis including the full data set of the *Training Relative* condition (cf. Fig. 3). ANOVA results revealed a significant main effect of probe position on discrimination performance, $F(2, 18) = 18.93$, $p < 0.001$, $\eta_p^2 = 0.68$, whereas the main effect of SOA, $F(1, 9) = 0.66$, $p = 0.439$, $\eta_p^2 = 0.07$, and the interaction SOA by probe position, $F(2, 18) = 0.55$, $p = 0.588$, $\eta_p^2 = 0.06$, were non-significant. Moreover, post-hoc pairwise comparisons showed that discrimination performance across SOAs was significantly enhanced at the *non-ST/trained* position compared to the *ST/non-trained* position, $t(9) = -3.62$, $p = 0.017$, $d_z = -1.61$, and neutral positions, $t(9) = 8.92$, $p < 0.001$, $d_z = 2.17$. The difference in performance between the *ST/non-trained* position and neutral positions was not significant, $t(9) = 1.45$, $p = 0.542$, $d_z = 0.55$. Hence, even in trials with uncompromised saccade performance, the largest discrimination benefit was still observed at a movement-irrelevant position. This suggests that the attention decoupling observed in *Training Relative* (as reported in our main analysis) did not merely reflect the consequence of compromised oculomotor performance.

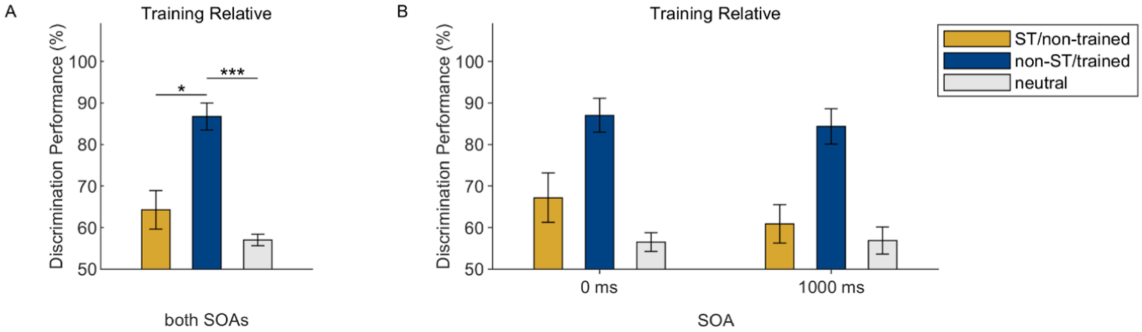

Fig. 4. Discrimination performance for subset of Test Phase trials representing the most accurate among the fastest saccades in *Training Relative* condition. Graphs depict mean discrimination performance as a function of probe position. (A) Mean discrimination performance pooled across trial subsets of both SOA conditions. Asterisks indicate statistical significance of pairwise comparisons between probe positions (* $p \leq .05$; *** $p \leq .001$). (B) Mean discrimination performance plotted separately for *SOA-0* and *SOA-1000* condition trial subsets. Error bars represent standard error of the mean (SEM).

3.3.3. Attention decoupling increases over the course of training

Finally, since results of *Training Relative* and *Training Fixed* demonstrated that an anticipation of spatial incongruence allowed participants to shift attentional resources to non-motor targets (i.e., the *non-ST/trained* position) in the Test Phase, we aimed at further exploring the temporal development of this capacity over the course of the Attention Training. To this end, we first divided data of the Attention Training (including the Refresh Phase) into five time-ordered trial bins, each consisting of 180 trials. Next, we computed, for each bin, separate measures of discrimination performance at the *non-ST/trained* position for the different training (*Training Relative* vs. *Training Fixed*) and SOA (*SOA-0* vs. *SOA-1000*) conditions. As highlighted in Fig. 5, discrimination performance in both *Training Relative* and *Training Fixed* was above chance level in the first trial bin, but increased over the course of the Attention Training without being considerably modulated by SOA. To test whether these training improvements were statistically significant, we subjected discrimination performance data of *Training Relative* and *Training Fixed* to separate repeated measures ANOVAs with factors SOA and trial bin (first vs. last). For *Training Relative*, results showed a non-significant main effect of SOA, $F(1, 9) = 0.73$, $p = 0.415$, $\eta_p^2 = 0.08$, and a non-significant interaction between SOA and trial bin, $F(1, 9) = 0.55$, $p = 0.477$, $\eta_p^2 = 0.06$. However, we observed a significant main effect of trial bin, $F(1, 9) = 7.54$, $p = 0.023$, $\eta_p^2 = 0.46$, affirming that performance reliably increased from the first bin ($M = 74.2$ %, $SD =$

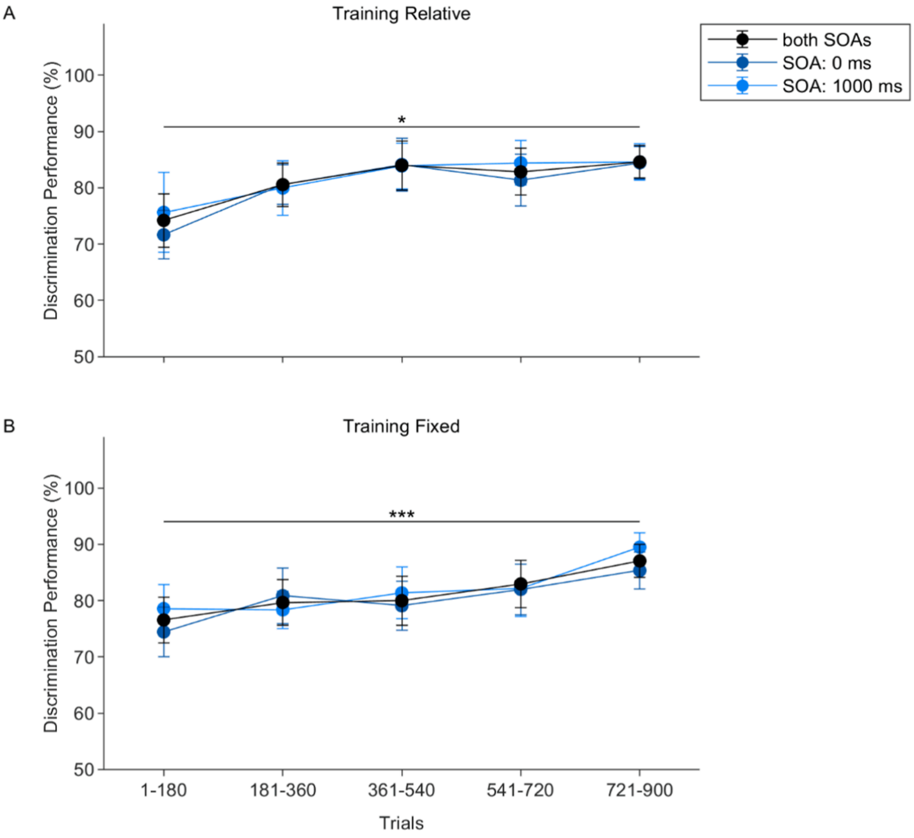

Fig. 5. Discrimination performance in Attention Training. Graphs depict mean discrimination performance at the *non-ST/trained* position for different trial bins (i.e., trials of Attention Training, including the Refresh Phase, divided into five equally sized bins of 180 trials each) in each SOA condition and pooled across SOA conditions. (A) Mean discrimination performance in *Training Relative* condition. (B) Mean discrimination performance in *Training Fixed* condition. Asterisks indicate statistical significance for the comparison between the first and last trial bin as observed for the data pooled across both SOA conditions (* $p \leq .05$; *** $p \leq .001$). Error bars represent standard error of the mean (SEM).

14.9 %) to the last bin (*M* = 84.6 %, *SD* = 9.1 %). Similarly, for *Training Fixed*, there was a non-significant main effect of SOA, F(1, 10) = 3.42, p = 0.094, $\eta_p^2 = 0.26$, a non-significant interaction, F(1, 10) < 0.01, p = 0.995, $\eta_p^2 < 0.01$, but a significant main effect of trial bin, F(1, 10) = 37.73, p < 0.001, $\eta_p^2 = 0.79$, suggesting enhanced performance in the last bin (*M* = 87.0 %, *SD* = 9.6 %) relative to the first bin (*M* = 76.6 %, *SD* = 13.5 %). Consequently, the pronounced discrimination benefits found at the *non-ST/trained* position for *Training Relative* and *Training Fixed* in the Test Phase indeed reflect training-induced improvements in the capacity to shift attention to non-movement targets.

4. Discussion

It has been widely demonstrated that programming a saccadic eye movement toward a given motor target is accompanied by a spatially congruent shift of visual attention, a finding often taken as evidence for an obligatory coupling between covert visual attention and processes of motor preparation. Here, we addressed the question whether this coupling is facilitated by top-down processes linked to an overlearned and therefore habitual expectation that behaviorally relevant visual and motor targets typically coincide in space. To this end, we asked participants to perform a dual-task (i.e., concurrent saccade and attention probing task) and tested whether expecting a mismatch of visual and motor targets can lead to a decoupling between attention and oculomotor programming. In an initial training phase, they learned to anticipate an attention probe either at the same position as a saccade target (ST; *Training Same*), at a specific position relative to ST (*Training Relative*), or at a fixed position not varying with ST (*Training Fixed*). In a subsequent Test Phase, the probe position was randomized, which allowed us to assess whether top-down expectation about the probe position modulated presaccadic attention allocation. In addition, we varied the duration of movement delays to probe attention either during or after the assumed phase of motor preparation. Thereby, it was possible to further examine whether potential training-induced attentional effects require saccade pre-programming or already emerge during ongoing saccade preparation.

Overall, our results demonstrate that presaccadic attention allocation was strongly biased by participants' expectations (see Section 3.2.). We found that a learned expectation of spatial congruence between the saccade target and the attention probe caused participants to selectively shift attention to the saccade target (i.e., *ST/trained* position in *Training Same*). In contrast, an expectation of spatial incongruence of positions allowed participants to deploy attentional resources to the anticipated probe position, regardless of whether it matched the saccade target (i.e., *ST/trained* position in *Training Fixed*) or diverged from it (i.e., *non-ST/trained* position in *Training Relative* and *Training Fixed*). Importantly, the robustness of the latter effect of attentional facilitation at positions other than the saccade target (relative to neutral control positions) is underscored by the fact that it was observed in two independent groups of participants (*Training Relative* and *Training Fixed*). Moreover, we found no evidence suggesting that the capacity to allocate attentional resources to movement-irrelevant positions was associated with a discernible impairment in saccade performance in these conditions (see Section 3.1.). There was only an indication of some (non-significant) costs in saccade performance specific to *Training Relative*. Importantly, as observed in an exploratory analysis (see Section 3.3.2.), a pronounced attentional benefit at the expected probe position (i.e., *non-ST/trained* position) was still present in this condition in trials without apparent costs in saccade performance (i.e., trials associated with relatively fast and accurate saccades). Our data therefore provide no indication that participants accomplished shifting attention away from saccadic targets by strategically prioritizing the discrimination task at the cost of the saccade task (Kowler et al., 1995). Similarly, as reported in Section 3.2., the results of the Discrimination Only task (which participants performed both before the Attention Training and after the Test Phase) revealed no statistical evidence that modulations of presaccadic attention allocation were caused by non-specific learning effects (e.g., an overall improvement in discrimination performance across the experiment). Rather, our data indicate that the observed attentional effects resulted from training-induced expectations about the probe position. Moreover, the observed top-down modulations of attention did not depend on the time available for movement preparation. Considering all of these aspects, the current results challenge the assumption that covert visual attention and processes of motor preparation are obligatorily coupled to each other and rely on the same mechanism (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994), thus complementing our previous findings on manual pointing movements (Topfstedt, Wollenberg, & Schenk, 2023).

Importantly, as can be seen in Fig. 3, discrimination performance at the expected probe position (i.e., *non-ST/trained* position) exceeded performance at the saccade target position (i.e., *ST/non-trained* position) in *Training Relative* and *Training Fixed*. In the former condition, we observed a significant performance benefit at the expected probe position compared to the saccade target position, supporting the idea that attentional resources were predominantly allocated toward a movement-irrelevant position rather than toward the motor target. Interestingly, despite showing a similar pattern, results of the latter condition did not reveal a significant relative performance enhancement at the expected probe position. Taken together, these findings therefore imply that, depending on the specific task, participants were capable of learning to allocate attentional resources to a movement-irrelevant position as efficiently as, or even more efficiently than, to the motor target itself.

So far, the discussed results highlight the feasibility of a decoupling between attention and motor programming in terms of participants being able to direct attention to a considerable extent to a position other than the motor target. However, while this implies that attention is not restricted to the spatial parameters of upcoming motor actions, it does not allow to conclude that motor programming can occur in the absence of attentional selection. To assess whether this kind of complete decoupling (i.e., complete withdrawal of attentional resources from motor target) is possible, we compared discrimination performance between the saccade target (i.e., *ST/non-trained* position) and neutral control positions in *Training Relative* and *Training Fixed*. In the case of complete decoupling, no benefit in performance should be observed at the saccade target compared to neutral positions. Indeed, in *Training Relative*, we found no significant saccade target benefit. At first glance, this points toward the notion that endogenous (i.e., top-down) attentional control can operate independently of processes of motor preparation (Gabay, Henik, & Gradstein, 2010; Gregoriou, Gotts, & Desimone, 2012; Juan et al., 2008; Smith, Rorden, & Jackson, 2004; Smith, Schenk, & Rorden, 2012). However, inspection of data (see Fig. 3) suggests a small advantage in discrimination performance at the saccade target over the neutral positions, which might have potentially reached statistical significance with a larger sample size. Moreover, in *Training Fixed*, there was a small but significant enhancement in performance at the saccade target, suggesting that some attentional resources remained at this position. The present results therefore do not establish a sufficient basis for a definitive conclusion regarding the possibility of a complete decoupling between attention and action. Nonetheless, we found that performance at the saccade target was rather low in both conditions, which implies that saccade preparation requires at least fewer attentional resources than previously assumed (e.g., Deubel, 2008; Deubel & Schneider, 1996).

Similar to the present results, our earlier study on pointing movements (Topfstedt, Wollenberg, & Schenk, 2023) revealed that attention was substantially biased toward a non-movement target at which participants had learned to anticipate the attention probe. Notably, discrimination performance at the motor target did not differ significantly from performance at neutral control positions (see Topfstedt, Wollenberg & Schenk, 2023, Exp. 2). In our previous study, however, participants were exclusively trained to expect an attention probe at a position defined *relative* to the motor target. Thus, even if we had observed a significant performance benefit at the motor target, it would not have been possible to determine whether attention was shifted toward this position due to motor programming or because this position was required as a spatial reference to identify the expected probe position (spatial reference hypothesis, see also Introduction). To address this question in the present study, we therefore included not only a condition in which the expected probe position was defined relative to the saccade target (*Training Relative*), but also one in which the expected probe position did not depend on the saccade target position (*Training Fixed*). Interestingly, we observed exactly the opposite pattern of what would be expected under a spatial reference hypothesis (see Section 3.3.1.). As discussed above, a small but reliable performance benefit at the saccade target emerged in the condition in which the expected probe position was not defined relative to the saccade target (*Training Fixed*). In contrast, no reliable saccade target benefit was found when the expected probe position was defined relative to the saccade target (*Training Relative*). These findings contradict the assumption that attention had to be deployed at the motor target for probe position identification. Moreover, assuming that the spatial reference hypothesis holds, a larger attentional decoupling effect should be found in *Training Fixed* compared to *Training Relative*. However, we found no significant difference regarding the extent of attentional decoupling (measured as the difference in discrimination performance between the *non-ST/trained* position and the *ST/non-trained* position) during the preparation of undelayed saccades between these two conditions. In conclusion, our data therefore do not suggest that a spatial reference hypothesis provides a valid explanation for a possible retention of attentional resources at motor targets in the current study and similar previous training studies (Dignath et al., 2019; Topfstedt, Wollenberg, & Schenk, 2023) investigating a decoupling of attention and action.

In line with previous studies (Deubel, 2008; Deubel & Schneider, 1996, 2003; Hoffman & Subramaniam, 1995; Jonikaitis & Deubel, 2011), we observed a marked enhancement of visual discrimination performance at the saccade target position in *Training Same*. However, in *Training Same*, participants were trained to anticipate the attention probe at the saccade target. It is thus likely that the learned anticipation of spatial congruence between positions at least additionally facilitated attention shifts toward the motor target in this training condition. This assumption is supported by the results of *Training Fixed*, which showed that the attentional benefit caused either purely by top-down expectation (i.e., performance at *non-ST/trained* position) or saccade preparation (i.e., performance at *ST/non-trained* position) was smaller than the benefit found for a combination of these two components (i.e., performance at *ST/trained* position). Put differently, an additive attentional enhancement effect in *Training Fixed* was observed for trials in which the expected probe position and the saccade target coincided (i.e., those trials that effectively mirrored trials of *Training Same*). This indicates that top-down expectations led to similar additional attentional facilitation at the saccade target in *Training Same*. Consistent with this view, discrimination performance at the saccade target in *Training Same* (i.e., 97.4 %) was substantially higher than in similar previous studies (Deubel, 2008; Deubel & Schneider, 1996; Jonikaitis & Deubel, 2011).

Interestingly, contrary to the current results, similar previous dual-task studies have suggested that attention cannot be decoupled substantially from saccade targets during motor preparation (Deubel, 2008; Deubel & Schneider, 1996) or that saccade programming deteriorates the capacity to attend to movement-irrelevant objects (Hanning et al., 2022). While we can only speculate about the cause for this discrepancy, we believe that our study, in contrast to these previous studies, established optimal circumstances for a decoupling of attention from motor programming. First, our study involved a distinct phase in which participants were specifically trained to decouple attention from the motor target. Second, within a given training condition, the spatial characteristics of this decoupling were kept constant across trials. Third, as realized by means of an explicit instruction, the task-relevant probe position was made fully predictable. To our knowledge, none of the previous studies included all of these features, which might have rendered a decoupling of attention from motor preparation more difficult than in the current study. In particular, our results imply that the distinct training phase played an important role in the decoupling observed here. We found a significant improvement in discrimination performance at the anticipated (trained) probe position over the course of the training phase in *Training Relative* and *Training Fixed* (see Section 3.3.3.). Despite this temporal modulation, performance at these positions was already relatively high at the beginning of the Attention Training, presumably reflecting a general effect of probe predictability. An interesting endeavor for future research would therefore be to examine the preconditions for a successful decoupling of attentional and oculomotor control in more detail (e.g., via systematic and gradual variation of training duration and probe predictability).

In our study, we decided not to inform participants about probe randomization prior to the Test Phase. This was done to prevent training-induced top-down biases from rapidly decaying in this phase. In fact, advance knowledge of the randomized probing procedure would have likely abolished expectancy-driven attentional modulations in the Test Phase. Nonetheless, one might argue that concealment of the probe position randomization in the Test Phase constitutes a limitation of our study, as this may have led participants to perceptually ignore the saccade target. We believe, however, that this assumption is not warranted for three reasons. First, we observed a significant attentional benefit at the (non-trained) saccade target in *Training Fixed*, suggesting that participants did not ignore the saccade target in the discrimination task. Second, we found no evidence for impaired saccade performance in *Training Relative* and *Training Fixed* compared to *Training Same*. Therefore, we found no evidence to suggest that the attentional enhancement effect at the trained non-movement target (in *Training Relative* and *Training Fixed*) was achieved by ignoring the saccade target. Third, upon examination after the experiment, the majority of participants reported that they had noticed that the probe no longer always appeared at the expected (trained) position during the Test Phase, but sometimes at different positions. This indicates that participants were generally aware of the potential importance of positions other than the anticipated probe position. Taking all these aspects into account, we believe that the effects observed here are best accounted for in terms of specific training-induced and expectancy-driven top-down modulations of presaccadic attention allocation. Importantly, the very fact that participants can learn to perform accurate saccades while shifting attention away from the saccade target shows that motor preparation and covert attention shifts can be decoupled.

In summary, our results demonstrate that participants can be trained to decouple attentional resources from an upcoming movement target to a considerable extent. However, the data of one of our training conditions (*Training Fixed*) suggests that some attentional resources may remain locked to the saccade target even when observers have learned that the discrimination probe is most likely to appear at a different location. Accordingly, we do not claim that our findings refute the existence of a tight link between attentional control and motor programming. Rather, we advocate the idea that the attention-action link is at least partially consolidated through a habitual expectation that motor targets typically contain highly relevant visual information. To account for this expectation, attention is shifted to targets of forthcoming actions by default. Crucially, as demonstrated here, it is possible to modify this expectation through training and voluntarily shift attentional resources to movement-irrelevant, yet behaviorally relevant, positions or objects.

5. Conclusions

The data presented here demonstrate that the linkage of covert visual attention and saccadic eye movements is less strict than previously assumed. Whereas our results suggest that a learned anticipation of spatial congruence between a visual and a motor target boosts the commonly observed presaccadic shift of attention, a learned anticipation of spatial incongruence leads to a pronounced withdrawal of attentional resources from the target of imminent saccades. More specifically, top-down expectancy allows to flexibly allocate the greater part of attentional resources to task-relevant visual targets, even if they diverge from current motor targets. Importantly, these top-down modulations of presaccadic attention allocation are not limited to preprogrammed movements, but can occur during ongoing oculomotor preparation. This implies that habitual top-down processes may play an important and so far largely neglected role for the emergence of the well-established attention-action coupling in saccadic eye movements.

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CRediT authorship contribution statement

Christof Elias Topfstedt: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Wollenberg:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Thomas Schenk:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All raw data are publicly available at https://osf.io/x45dr

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2024.108424.

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