The role of habitual learning in premotor attention allocation

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Dual-task studies have demonstrated that goal-directed actions are typically preceded by a premotor shift of visual attention toward the movement goal location. This finding is often taken as evidence for an obligatory coupling between attention and motor preparation. Here, we examined whether this coupling entails a habitual component relating to an expectation of spatial congruence between visual and motor targets. In two experiments, participants had to identify a visual discrimination target (DT) while preparing variably delayed pointing movements to a motor target (MT). To induce distinct expectations regarding the DT position, different groups of participants performed a training phase in which the DT either always appeared at MT, opposite to MT, or at an unpredictable position. In a subsequent test phase, the DT position was randomized to assess the impact of learned expectancy on premotor attention allocation. Although we applied individually determined DT presentation times in the test phase of Experiment 1, a fixed DT presentation time was used in Experiment 2. Both experiments yielded evidence for attentional enhancement at the expected DT position. Although interpretability of this effect was limited in Experiment 1 because of between-group differences in DT presentation time, results of Experiment 2 were much clearer. Specifically, a marked discrimination benefit was observed at the position opposite to MT in participants anticipating the DT at this position, whereas no statistically significant benefit was found at MT. Crucially, this was observed at short movement delays, demonstrating that expectation of spatial incongruence between visual and motor targets allows for decoupling of attentional resources from ongoing motor preparation. Based on our findings, we suggest that premotor attention shifts entail a considerable habitual component rather than being the sole result of motor programming.

Introduction

Visual attention is the mechanism that enables our visual system to cope with its limited capacity to process the vast amount of available visual information in our environment. It allows us to select behaviorally relevant aspects or locations of the visual scene for prioritized processing while other information is ignored (Carrasco, 2011). Attentional selection is not only assumed as crucial for optimal processing of visual input information (selection-for-perception) but also to provide the motor system with visuospatial information required to generate goal-directed movements such as reaches, grasps, or saccadic eye movements (selection-for-action; Allport, 1987). More specifically, a goal-directed action is typically directed toward only one of several available targets in our visual surroundings. For this reason, information selection has been claimed to be a prerequisite for movement planning to supply the motor system with the spatial parameters of the target (Neumann, 1987) and to inhibit signals from competing movement goals (Allport, 1987).

Several theories of visual attention emphasize the close link between visual attention shifts and goal-directed actions and further suggest that the two processes are mandatorily coupled to one another. For instance, the Visual Attention Model (VAM; Schneider, 1995; Schneider & Deubel, 2002) states that selection-for-perception and selection-for-action are bound together by a common attentional mechanism. More precisely, VAM assumes that attentional selection of an object in the visual scene leads to prioritized processing of this information in both the ventral stream for object recognition and the dorsal stream for

setting up motor programs towards the selected target. In contrast, the authors of the Premotor Theory of Attention (Rizzolatti, Riggio, Dascola, & Umiltá, 1987; Rizzolatti, Riggio, & Sheliga, 1994) argued against the notion of separate processing mechanisms for movement preparation and visual attention. Rather, the theory states that both endogenous (i.e., top-down) and exogenous (i.e., bottom-up) attention shifts are the direct consequence of motor programming activity. However, despite these different views on the neural underpinnings of the attention-action link, both theories propose a similar behavioral consequence of this coupling: Planning a goal-directed movement is mandatorily accompanied by a covert attention shift towards the movement goal, and vice versa (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994; Schneider, 1995; Schneider & Deubel, 2002).

Support for the claim of an obligatory coupling between motor planning and attention shifts came from several studies using a dual-task paradigm in which participants prepare a goal-directed movement toward an endogenously cued location whereas attention allocation is probed by presenting a discrimination target (DT) either at the movement target (MT) or at a different location. These studies consistently showed that single saccades (Deubel, 2008; Deubel & Schneider, 1996; Deubel & Schneider, 2003; Hoffman & Subramaniam, 1995; Jonikaitis & Deubel, 2011) and single pointing movements (Deubel, Schneider, & Paprotta, 1998; Jonikaitis & Deubel, 2011; Hanning, Wollenberg, Jonikaitis, & Deubel, 2022) are preceded by a premotor shift of attention toward the movement goal location, as indicated by enhanced discrimination performance at the MT compared to other locations. Similarly, attentional facilitation was found at the to-be-grasped parts of the target object of an upcoming grasping movement (Schiegg, Deubel, & Schneider, 2003). Moreover, these premotor attention shifts are not restricted to the preparation of single goal-directed movements. When sequences of saccades or reaches are planned, separate foci of attention are deployed to all target locations in parallel (Baldauf & Deubel, 2008; Baldauf, Wolf, & Deubel, 2006; Godijn & Theeuwes, 2003). Importantly, attentional facilitation at the movement goal location persists even in conditions in which participants are encouraged to direct attention away from the MT (Deubel, 2008; Deubel & Schneider, 1996; Deubel et al., 1998; Hanning et al., 2022; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Schiegg et al., 2003), suggesting that the link between motor planning and visual attention is mandatory.

Consistent with these findings, other behavioral studies have shown that covert attention allocation leads to deviations in saccade trajectories when the attended location and the target of an oculomotor program diverge (Moehler & Fiehler, 2014; Sheliga, Riggio, &

Rizzolatti, 1994; Sheliga, Riggio, & Rizzolatti, 1995; Van der Stigchel & Theeuwes, 2007). Furthermore, electrophysiological studies provided evidence in support of the notion of an obligatory attention-action coupling. For example, studies of nonhuman primates have shown that subthreshold microstimulation of brain regions involved in the generation of saccades, such as the frontal eye field (FEF) and the superior colliculus (SC), leads to attentional facilitation at the motor field location of the stimulated neurons (Moore & Fallah, 2001, 2004; Müller, Philiastides, & Newsome, 2005). Correspondingly, it was found that attention-associated components of event-related potentials (ERPs) are enhanced in human participants when visual stimuli are presented at movement-relevant locations during the preparation phase of saccades and manual movements (Baldauf & Deubel, 2009; Eimer, Forster, Van Velzen, & Prabhu, 2005; Eimer, Van Velzen, Gherri, & Press, 2006; Gherri & Eimer, 2010).

Although a close link between movement programming and covert attention has been widely demonstrated, the obligatory nature of this coupling remains controversial (for a review, see Smith & Schenk, 2012). For instance, physiological studies have shown that overt and covert orienting are controlled by distinct neuronal populations within the FEF (Sato & Schall, 2003; Thompson, Biscoe, & Sato, 2005) and that both processes are temporally dissociated (Juan et al., 2008; Juan, Shorter-Jacobi, & Schall, 2004). Consistent with this finding, behavioral dual-task studies demonstrated a spatial dissociation between the endpoint of so-called averaging saccades and the locus of visual attention (Van der Stigchel & de Vries, 2015; Wollenberg, Deubel, & Szinte, 2018, 2019; Wollenberg, Hanning, & Deubel, 2020). Furthermore, there is evidence that endogenous attentional control in particular does not depend on motor preparation. Studies with neuropsychological patients have shown that an impairment in executing goal-directed eye movements is associated with deficits in exogenous attention but that the ability to shift attention endogenously in space is unaffected (Gabay, Henik, & Gradstein, 2010; Smith, Rorden, & Jackson, 2004). Likewise, exogenous but not endogenous attention shifts of healthy participants were found to be limited to areas in the visual field within the range of eye movements (Smith, Schenk, & Rorden, 2012; but see Hanning & Deubel, 2020). In addition, studies using a dual-task paradigm have shown that top-down processes can modulate the attention-action coupling. Kowler et al. (1995, Experiment 4), for example, observed that when following the instruction to avoid a prioritization of either the perceptual or the saccade task, participants were capable of withdrawing some attentional resources from the movement goal without costs in saccade latency or accuracy. Similarly, Montagnini and Castet (2007) showed that attention can be deployed endogenously to locations other than a

saccade target, but that this ability diminished shortly before movement onset.

One way to account for the contradictory evidence regarding the nature of the attention-action link would be to consider the typical premotor attention shift towards a movement goal location as a merely habitual process (Posner, Snyder, & Davidson, 1980), because the target of a goal-directed movement is of highest behavioral relevance in most everyday situations. If so, a prerequisite to decouple covert attention from the target of an upcoming goal-directed movement might be extensive training (Reeves & McLellan, 2020). To date, very few studies have investigated how training to shift attention toward a non-movement target affects the attention-action coupling. Song and Bédard (2013) found that participants directed attentional resources equally well to both a visual and a reach target when they had learned to spatially dissociate both target locations through visuomotor adaptation. Also, Reeves and McLellan (2020) showed that learning affects covert attentional deployment. Specifically, they observed that the majority of their participants were capable of executing a simultaneous shift of gaze and of attention in opposite directions, but that learning this skill required up to 10 hours of practice. However, both studies (Reeves & McLellan, 2020; Song & Bédard, 2013) used a Rapid Serial Visual Presentation (RSVP) task to measure attention allocation, which has several weaknesses when studying top-down modulations of premotor attention shifts compared to the more commonly used discrimination task (Deubel & Schneider, 1996). First, participants are aware of the spatial position of the attention test (i.e., the RSVP stream), which facilitates the use of explicit strategies to solve the task. Second, the task requires sustained maintenance of attention at the position of the RSVP stream, making it difficult to test attention allocation at varying time points relative to the onset of the movement. This would be crucial, however, to examine at which stage of movement preparation attentional resources can be decoupled from the movement goal location. Third, an RSVP stream is a highly salient event and thus does not allow us to distinguish whether attentional facilitation at that position is caused by attentional capture of the stream itself (exogenous attention) or by top-down modulations of attention (endogenous attention).

In contrast, Dignath, Herbort, Pieczykolan, Huestegge, and Kiesel (2019) recently used a discrimination task to test whether the learned anticipation of spatial congruence or incongruence of a visual and a motor target modulates the link between visual attention and motor preparation. Specifically, they asked participants to accomplish training in which a DT was presented either at the target of a pointing movement or at a position opposite to this target. Results showed that attention is strictly tied to the movement goal location when participants had learned that a DT position always coincides with the MT. In contrast, learning to expect the DT at the position opposite the MT caused participants to shift attentional resources only towards that location, suggesting that it is possible to overcome the attention-action link through practice. However, there are reasons to be cautious in taking these results as evidence against an obligatory coupling between covert attention shifts and processes of motor preparation. First, the pointing task of Dignath et al. (2019) contained a movement delay (i.e., stimulus onset asynchrony [SOA] between a movement cue and a go-signal for movement initiation) that was relatively long (i.e., 612–799 ms). Thus it is possible that those participants, who had learned to decouple the locus of attention from the movement goal location, did so only after the movement had been fully programmed. This would be in line with the findings of Deubel and Schneider (2003), who showed that attention can be withdrawn from a reach target but only if the movement is delayed by more than 300 ms, indicating that these movements can be "performed 'off-line,' that is, without attention" (p. 295). Second, the discrimination task of Dignath et al. (2019) consisted of only two placeholder positions at which the DT could appear (i.e., at or opposite the MT). However, the use of only two placeholders makes the discrimination task relatively simple, which could lead to insufficient sensitivity of the attention test (i.e., attention is no longer necessary for DT identification). In such a case, certain outcomes of the discrimination task do not permit unambiguous conclusions to be drawn, particularly when no task-irrelevant control position is available as a baseline condition. For instance, if discrimination performance is observed to be equally well at both positions, it is not possible to tell whether attention was directed towards both positions or whether the task allowed probe identification without attention. Dignath et al. (2019) reported exactly such a pattern of equivalent performance at both available positions for one control group in which participants had not learned to anticipate the DT at a specific position. It is in this case possible that the sensitivity of the discrimination task of Dignath et al. (2019) was actually too low to still serve as a reliable measure of attention allocation. This means that it cannot be determined whether the training effects reported by Dignath et al. (2019) were driven by processes of attentional selection or whether they were rather a consequence of a low difficulty of the discrimination task. In summary, it is still unclear (1) whether the anticipation of spatial incongruence of a visual target and a movement goal location can modulate the attention-action coupling and, if so, (2) whether these top-down effects on attention allocation can occur even when the critical movement programming phase is still in progress.

In the current study, we aimed to address these open questions by conducting two experiments (Experiments 1 and 2) with a modified version of the dual-task paradigm used by Deubel and Schneider (2003) and Dignath et al. (2019). Similar to these previous studies, the dual-task in both experiments consisted of a delayed pointing task, in which participants had to prepare a pointing movement toward an endogenously cued MT, and a discrimination task, in which they had to indicate the identity of a DT that was presented before movement execution. However, we doubled the number of placeholder positions compared to the study by Dignath et al. (2019). This allowed us, on the one hand, to increase the difficulty of the discrimination task and, on the other hand, to measure discrimination performance at task-irrelevant control positions. By introducing this baseline condition, we were able to directly test whether the sensitivity of our attention test was sufficiently high to reliably measure relative differences in the spatial allocation of attention.

In Experiment 1, we asked participants to perform a training session that was similar to the one of the study of Dignath et al. (2019). Participants either learned that a DT always appears at the same position as a MT, always at a position opposite a MT, or at a randomly chosen position. As in the study of Dignath et al. (2019), we adjusted presentation times of the DT for each participant over the course of the training phase to account for interindividual differences in discrimination performance. In a subsequent test phase, putative training effects on the attention-action coupling were examined by presenting the DT with equal probability at one of the placeholder positions. To test whether the previously found effects of learned spatial congruence and incongruence (Dignath et al., 2019) can be generalized to the movement preparation phase, we varied the time between the presentation of the movement cue and go-signal to initiate the pointing movement (movement delay). If learning can modulate the attention-action link both before and after the completion of movement preparation, similar effects on attention allocation should be found for short and long movement delays.

Experiment 1 revealed differences between training conditions in the length of adjusted presentation times of the attention probe (DT). Although these differences offered insights into the difficulty of establishing a learned spatial congruence or incongruence between positions during the training phase, they made it difficult to compare training effects on attention allocation between training conditions in the subsequent test phase. We therefore conducted a second experiment (Experiment 2) that was similar to Experiment 1, except that we used a fixed probe presentation time in the discrimination task. This allowed for improved intergroup comparison of results and additional examination of whether training effects observed in

Experiment 1 were modulated by probe presentation time.

Experiment 1

Methods

Participants

Sixty-nine healthy participants (45 females; 10 left-handed; average age: 24.1 years; age range 19–37 years) took part in Experiment 1, including one author (C.E.T.). All participants had normal or corrected-to-normal vision and normal motor behavior. Except C.E.T., participants were naïve to the purpose of the experiment. Two of them had participated in a previous study on attention allocation. Participants gave informed consent to participate in the study. The experiment was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki.

Apparatus

Figure 1 depicts the experimental setup. Participants were seated in front of a one-way mirror with their head positioned on a chin rest. A computer monitor (Acer XB271HUA; Acer, New Taipei City, Taiwan) at the top of the setup presented visual stimuli at a frame rate of 120 Hz and a resolution of 1600 × 1440 pixels (size of the used screen area: 37.3 × 33.6 cm). The opposite inclination of the monitor and the mirror allowed the projection of visual stimuli onto a virtual pointing plane beneath the mirror. Thereby, participants were able to execute pointing movements toward visually presented movement targets without seeing their reaching hand. The viewing distance to the center of the monitor was 56.4 cm. Gaze fixation was controlled by tracking participants' right eye at 1000 Hz using an EyeLink 1000 Plus eye tracking system (SR Research Ltd., Mississauga, Ontario, Canada). Pointing movements were recorded by a robotic haptic device (Phantom Premium 1.5.; 3D Systems, Rock Hill, SC, USA) with a temporal resolution of 1000 Hz. Participants positioned the tip of their right index finger in a thimble attachment mounted at the end effector of haptic device. To ensure that participants were not able to move their index finger through the pointing plane, a haptic feedback in the form of a resisting force was applied at the pointing plane's position. A cursor (red bar) was presented before and after movement execution to provide visual feedback of the current finger position. Because of technical constraints of the experimental setup, the cursor was displayed with a constant vertical offset of approximately 3.0° beneath
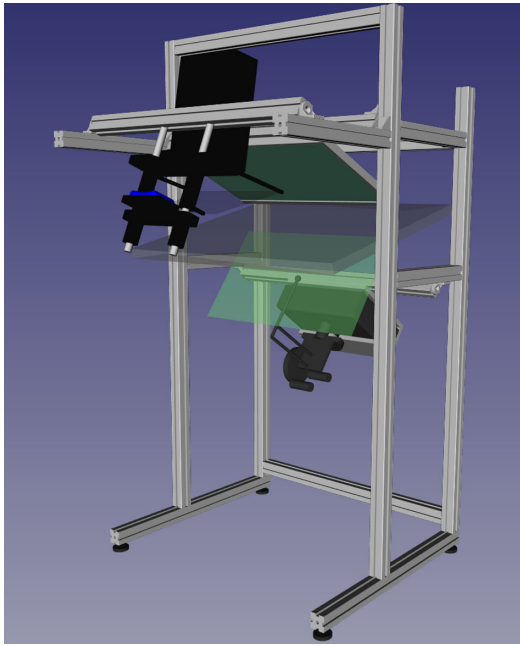
Figure 1. Sketch of the experimental setup. Participants positioned their head on a chin rest (marked in blue) facing towards a one-way mirror (depicted transparently for illustration only). A monitor (marked in dark green) projected movement targets on a virtual pointing plane (marked in bright green). The index finger of the reaching hand was positioned in a thimble attachment at the end effector (illustrated as a black sphere) of a haptic device. Thereby, participants were able to perform pointing movements toward visually presented movement targets without seeing their reaching hand.

the tip of the index finger (please note that vertical deviations between the endpoint of the pointing movements and the motor target's position were close to zero in each part of the experiment [i.e., all $M < 0.13°$, all $SD < 0.40°$], indicating that participants adapted the pointing movements right from the start of the experiment).

Design and procedure

The time course of a typical trial is depicted in Figure 2. At the beginning of each trial, a white circular button (radius 0.75°) consisting of a black frame and a central black fixation cross (size 0.5° × 0.5°) was presented on a uniform grey background. The button was surrounded by four black premask characters (seven-segment character "8"; size 0.9° × 1.4°) presented at a distance of 7.2° from fixation. At this stage, the cursor was visible. Participants were instructed to position the cursor on the white button while fixating the central fixation cross with their eyes. They were asked to maintain gaze fixation throughout the trial. By touching the white button with the cursor, the background color of the button changed to a

uniform gray, and, simultaneously, the cursor was turned off. After a delay of 500 to 800 ms, the button was replaced by a movement cue (black arrow) that pointed with equal probability toward one of the four premask characters. After an SOA of 100 or 800 ms (movement delay), a tone (440 Hz) was presented for 50 ms serving as a go-signal to point as quickly and accurately as possible toward the cued MT. To perform the movement, participants were instructed to lift their finger off the pointing plane. With go-signal offset, one of the four premask characters was replaced by a DT (seven-segment character "E" or "3"), while distractors (seven-segment character "2" or "5") were presented at the three remaining placeholder positions. After an individual presentation time (see section Staircase procedure), the DT and the distractors were masked again. Feedback of pointing accuracy was given by presenting the cursor again after movement execution. At the end of a trial, participants reported the identity of the DT by pressing one of two buttons on a keyboard with their left hand. Participants received acoustical feedback about the discrimination performance after each trial of the training phase but not of the test phase (see next paragraph).

The experiment consisted of a training and a test session, which took place on two consecutive days. In the training session, participants were assigned to one of four training groups. Training conditions differed from each other in the adjustment of individual probe presentation times (see section Staircase procedure) and the relative positions of the DT and MT. In the Training Same group, the DT was always presented at the location of the MT. In the Training Opposite group, the DT always appeared at the location opposite to the MT. We had two control groups (Control Same and Control Opposite). The reason for using two control groups will be explained in the next section (Staircase procedure). In both control groups, the DT was presented with equal probability at one of the four placeholder positions. Participants were not informed about the relative positions of the DT and MT in any of the four conditions. The training session started with two blocks of 32 practice trials of the pointing task only (latency training). In these trials, participants were informed by a visual feedback signal (red [indicates an error] vs. green [indicates an acceptable movement] circle) whether the movement had been initiated too early (i.e., before go-signal onset), too late (>350 ms), or sufficiently fast (≤350 ms). Participants then completed two blocks of 32 practice trials of the dual-task in which they performed the pointing task and the discrimination task in parallel (dual-task training). In these trials, participants received acoustical feedback about discrimination performance after each trial. The probe display was presented for 408 ms. The subsequent training phase consisted of 12 blocks of 32 trials.
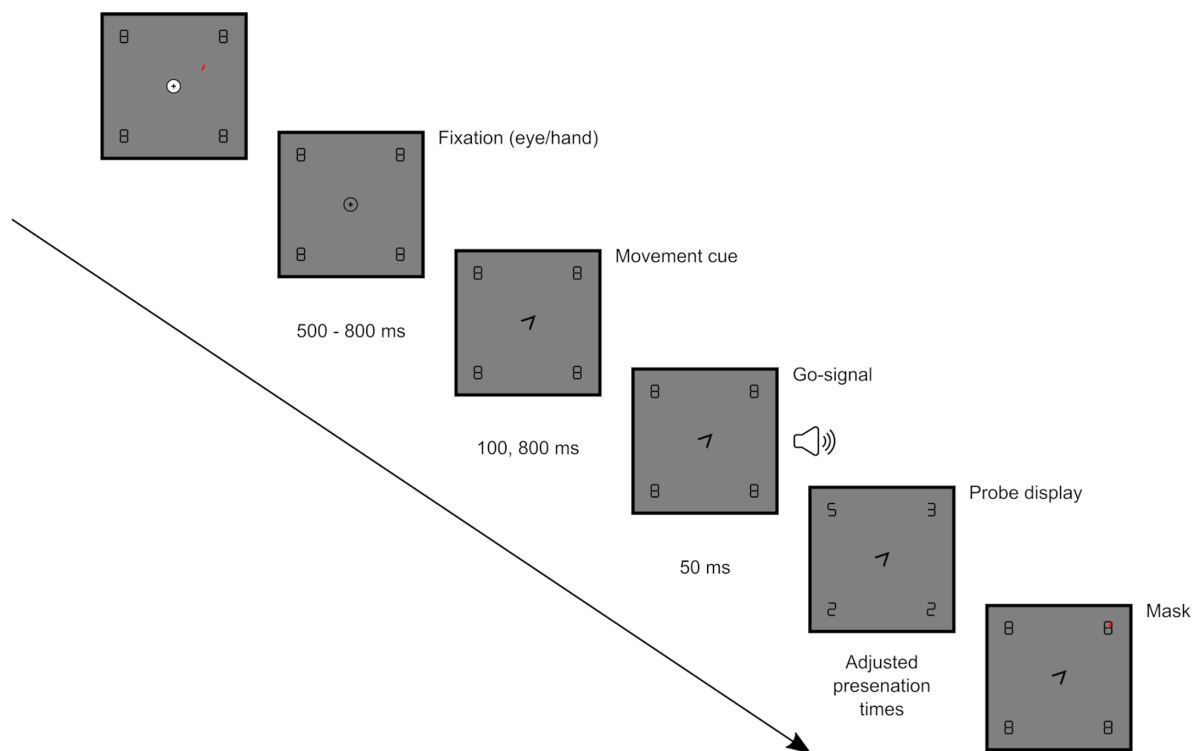
Figure 2. Time course of a typical trial. Participants positioned a red cursor on a central white button with their right index finger. Eye fixation was maintained throughout the trial. An arrow cue indicated the pointing target. After presentation of a go-signal, participants executed a pointing movement toward the cued location. At 50 ms after go-signal onset, a probe display was presented consisting of a DT (seven-segment character "E" or "3") and three distractors (seven-segment character "2" or "5"). Participants reported the identity of the DT after movement execution.

	Training same	Training opposite	Control same	Control opposite
Training phase				
Performance feedback	Yes	Yes	Yes	Yes
DT position	MT	Opposite MT	Random	Random
DT condition used for individual presentation time adjustments	MT	Opposite MT	MT	Opposite MT
Number of trials	384	384	384	384
Test phase				
Performance feedback	No	No	No	No
DT position	Random	Random	Random	Random
DT presentation time	Individually adjusted	Individually adjusted	Individually adjusted	Individually adjusted
Number of trials	512	512	512	512

Table 1. Main differences in experimental conditions between training groups and between the training phase and test phase.

In the test session, participants first performed two blocks of 32 trials of the latency training and two blocks of 32 trials of the dual-task training. The procedure of the practice trials was similar to the training session, except that individual presentation times of the probe display (see section Staircase procedure) were used in the dual-task training. Then, each participant performed 16 blocks of 32 experimental trials in which the DT was presented with equal probability at one of the four placeholder positions (test phase). To discourage quick unlearning of potential attentional biases acquired during training, no feedback about discrimination performance was given during the test phase. Table 1 summarizes the most important differences between the training groups and between the training phase and test phase.

Staircase procedure

Similar to Dignath et al. (2019), the presentation time of the probe display was adjusted individually over the course of the training phase. We applied a 3-down 1-up staircase procedure, which converges to a 79.4% performance level. At the beginning of the training phase, the DT presentation time was set to 250 ms. The step size of adjustments after each direction reversal varied across the training phase: 66.67 ms for reversals 1–3, 33.33 ms for reversals 4–6, 16.67 ms for reversals 7–9, and 8.33 ms for the remaining reversals. The minimum presentation time was 8.33 ms. Trials were not included in the staircase calculations if an eye fixation violation (see section Data analysis) was detected or if the pointing movement was not initiated within 350 ms after go-signal onset. After completion of the training phase, individual presentation times were determined by averaging presentation times calculated at the last four reversals.

The type of trials included in the computations of the threshold (i.e., adjusted probe presentation time) differed between training groups (see Table 1). In Training Same and Training Opposite, all training phase trials could potentially be included in the threshold calculations, since the probe was consistently presented at only one specific position (Training Same: MT position; Training Opposite: opposite position) in the training phase of these two groups. However, the question of which trials to use to calculate the threshold in control conditions with varying probe positions was less straightforward, since inclusion of all trials (regardless of probe position) would likely lead to a ceiling effect, making the task no longer sensitive enough to measure attention allocation in the subsequent test phase. For this reason, we also restricted threshold calculations in control conditions to one specific probe position. In addition, we aimed at consistency between threshold calculations in Training Same and Training Opposite and threshold calculations in control conditions. To this end, we used two control groups. In Control Same, only trials in which the DT was presented at the MT position were included in the threshold computations. In Control Opposite, only trials in which the DT was presented opposite the MT position were used to calculate the threshold. Given that this approach resulted in a group difference in the number of potential trials (Training Same and Training Opposite: 100% of training phase trials; Control Same and Control Opposite: 25% of training phase trials) included in the threshold computations, we set a minimum number of staircase reversals (i.e., 14 reversals) that had to be reached in the training phase to proceed with the experiment (see also section Data analysis). This ensured that the threshold was calculated with sufficient accuracy in all training groups.

Data analysis

Recordings of pointing movements and gaze behavior were analyzed with MATLAB R2021b (MathWorks, Inc., Natick, MA, USA). We defined the onset of pointing movements as the first point in time when velocity exceeded a threshold of 0.02 m/s for a duration of at least 150 ms. Because participants were instructed to lift the finger to perform the movement, movement offset was measured as the first point in time the pointing plane was touched again. Pointing movement duration was defined as the time between movement onset and movement offset.

Three participants of the Control Same group and one participant of the Control Opposite reached less than 14 reversals in the staircase procedure and did not take part in the test session. We excluded participants when their adjusted probe presentation time deviated from the median of their training group by more than three times the median absolute deviation (Leys, Ley, Klein, Bernard, & Licata, 2013). This was true for four participants of the Training Opposite group and four participants of the Control Same group. For offline analyses of the test phase data of the remaining sample ($N = 57$ out of a total of 69), we discarded trials if one of the following exclusion criteria was met. Regarding gaze behavior, trials were excluded if gaze was not maintained within 2.5° from fixation (for a similar approach, see Hanning, Aagten-Murphy, & Deubel, 2018) between movement cue onset and mask onset (Fixation violation) or if a blink occurred within the same time interval (Blink violation). Regarding pointing behavior, we excluded trials if no pointing movement onset or offset was detected (No movement), if the movement was initiated before go-signal onset (Movement too early), or if the movement endpoint deviated from the center of the MT by more than 2.5° (Movement inaccurate; for a similar approach, see Hanning et al., 2018). Moreover, trials were discarded as an outlier if movement latencies differed from the participant's median by more than three times the median absolute deviation (Movement latency outlier). After applying the exclusion criteria for erroneous trials, we additionally discarded the data sets of participants when more than 45% of trials (for a similar approach, see Arkesteijn, Belopolsky, Smeets, & Donk, 2019) of the test phase were rejected. This was the case for one participant of the Training Same group, one participant of the Training Opposite group, one participant of the Control Same group, and two participants of the Control Opposite group. The final sample ($N = 52$) consisted of 14 participants in the Training Same group, 14 participants in the Training Opposite group, 11 participants in the Control Same group, and 13 participants in the Control Opposite group. Supplementary Table S1 provides a detailed overview of the proportion of trials rejected because

of the aforementioned exclusion criteria for the final sample of each group.

Statistical analyses were performed in JASP version 0.16.1 (JASP Team). To examine the movement parameters, we conducted mixed analyses of variance (ANOVAs) with within-participants factor SOA condition (100 ms vs. 800 ms) and between-participants factor training group. Adjusted presentation times were analyzed with a one-way ANOVA with factor training group or, in case of unequal variances, with a corresponding Welch ANOVA. Performance in the discrimination task was expressed as the percentage of correct decisions regarding the identity of the DT. For analyses of discrimination performance, we employed a repeated measures ANOVA with factors SOA condition and DT position (DT at MT vs. DT at neutral positions vs. DT at opposite position) separately for each training group. Greenhouse-Geisser corrections were applied when sphericity was violated. Unless stated otherwise, post hoc pairwise comparisons were Bonferroni corrected.

Results

We performed two analyses of the experimental data obtained in Experiment 1. The first data analysis included all experimental data after applying the exclusion criteria described in the Methods section. The results of this data analysis are presented in the following section (First analysis). However, the first analysis revealed that adjusted presentation times of the discrimination target (DT) were relatively long for some of the participants, so that in some trials the DT was not yet masked at the time of movement onset. Thus it is possible that some of the effects observed in our first data analysis emerged only after movement onset. To rule out that post-onset probes confounded our results, we performed a second data analysis after discarding all trials from the dataset where the DT was still present after movement onset. The findings of the second analysis are presented in section Second analysis.

First analysis

Movement parameters: Regarding movement latencies (Table 2), we examined whether our manipulation of movement delays was successful in that motor preparation was still in progress after an SOA of 100 ms but completed after an SOA of 800 ms. If so, movement latencies should be longer in trials with an SOA of 100 ms than in trials with an SOA of 800 ms. As expected, a mixed ANOVA with factors training group and SOA condition revealed a significant main effect of SOA condition, $F(1, 48) = 159.55$, $p < 0.001$, $\eta_p^2 = 0.77$, suggesting that participants initiated pointing movements faster in trials with an SOA of 800 ms ($M = 275$ ms, $SD = 43$ ms) compared to trials with an SOA of 100 ms ($M = 308$ ms, $SD = 41$ ms). Neither the main effect of training group, $F(3, 48) = 0.99$, $p = 0.404$, $\eta_p^2 = 0.06$, nor the interaction, $F(3, 48) = 1.17$, $p = 0.332$, $\eta_p^2 = 0.07$, was significant. This indicates that an SOA of 100 ms required participants to first finalize motor preparation, whereas 800 ms were sufficient to release a completed motor program directly. However, pre-programming of the movement led to an average reduction in movement latencies of only 33 ms. Presumably, trials with an SOA of 800 ms required participants to initially suppress movement execution on movement cue presentation, resulting in the unexpectedly long movement latencies that were observed relative to the go-signal.

Movement duration across training groups was 325 ms ($SD = 96$ ms) in trials with an SOA of 100 ms and 330 ms ($SD = 92$ ms) in trials with an SOA of 800 ms. Moreover, Table 2 indicates that the difference in movement durations between an SOA of 800 ms and an SOA of 100 ms was larger in the Control Same group ($M = 21$ ms) compared to the remaining groups (Training Same: $M = -6$ ms; Training Opposite: $M = 0$ ms; Control Opposite: $M = 10$ ms). A mixed ANOVA with factors training group and SOA condition revealed a significant interaction between SOA and training group, $F(3, 48) = 2.88$, $p = 0.046$, $\eta_p^2 = 0.15$; however, neither the two main effects (main effect of SOA condition: $F(1, 48) = 3.70$, $p = 0.060$, $\eta_p^2 = 0.07$; main effect of training group: $F(3, 48) = 0.84$, $p = 0.477$, $\eta_p^2 = 0.05$) nor any post hoc comparisons of the data cells involved in the interaction reached significance (all $p > 0.169$).

Presentation times: As mentioned in the Methods section, presentation times of the DT were adjusted individually over the course of the training phase. To compute the threshold values for presentation times,

	Training same M ± SD	Training opposite M ± SD	Control same M ± SD	Control opposite M ± SD
Latency: SOA 100	308 ± 57	315 ± 38	290 ± 24	315 ± 32
Latency: SOA 800	269 ± 62	288 ± 41	260 ± 33	280 ± 24
Duration: SOA 100	343 ± 79	318 ± 86	345 ± 157	295 ± 43
Duration: SOA 800	337 ± 63	318 ± 83	366 ± 158	305 ± 43

Table 2. Movement latencies and movement durations for each training group and SOA (100 ms vs. 800 ms) in Experiment 1.
Note: Values in ms.

only the discrimination responses of a specific DT position were used within each of the training groups (Training Same, Control Same: MT position; Training Opposite, Control Opposite: opposite position). A side-effect of this method was that we were able to take the adjusted presentation times as a measure of how consistently participants of each training group allocated attention towards this DT position during the training phase. In particular, the comparison of presentation times between the Training Same and Training Opposite group was of high relevance for the analysis of training effects, because a group difference in presentation times would indicate a varying difficulty in establishing the implicitly learned spatial congruence (Training Same) or incongruence (Training Opposite) during the training phase. Moreover, a comparison of presentation times between the Training Same and Control Same group allowed to assess the contribution of learning in the allocation of attention at the MT position. Whereas shorter presentation times in the Training Same compared to the Control Same group would indicate that learning plays a crucial role in premotor attention allocation at the movement goal location, similar presentation times would suggest that premotor attention shifts towards this position are solely induced by processes of motor preparation.

Results of a Welch ANOVA revealed that presentation times (Figure 3A) differed considerably between training groups, $F(3, 24.56) = 8.20$, $p < 0.001$, $\eta_p^2 = 0.45$. Games-Howell post hoc comparisons showed that presentation times were shorter in the Training Same ($M = 90$ ms; $SD = 87$ ms) compared to the Training Opposite group ($M = 188$ ms, $SD = 44$ ms, $p = 0.007$), indicating that participants of the Training Same group directed attention more consistently toward the anticipated DT position (MT position) than participants of the Training Opposite group (opposite position). In other words, shifting attention toward the movement goal location (Training Same) was easier than learning to shift attention towards a non-movement target (Training Opposite). However, presentation times of the Training Same group were also shorter than those in the Control Same group ($M = 173$ ms, $SD = 57$ ms, $p = 0.891$). This shows that the expectation of spatial congruence between the DT and MT position in the Training Same group indeed facilitated attention shifts toward the MT position, which indicates that the attention-action coupling within this group was indeed modulated by top-down processes. Moreover, there was no difference in presentation times between the Training Opposite and Control Same group ($p = 0.891$), implying that task difficulty was comparable in these conditions. Furthermore, presentation times of the Control Opposite group ($M = 342$ ms, $SD = 178$ ms) were longer compared to the ones of the remaining training
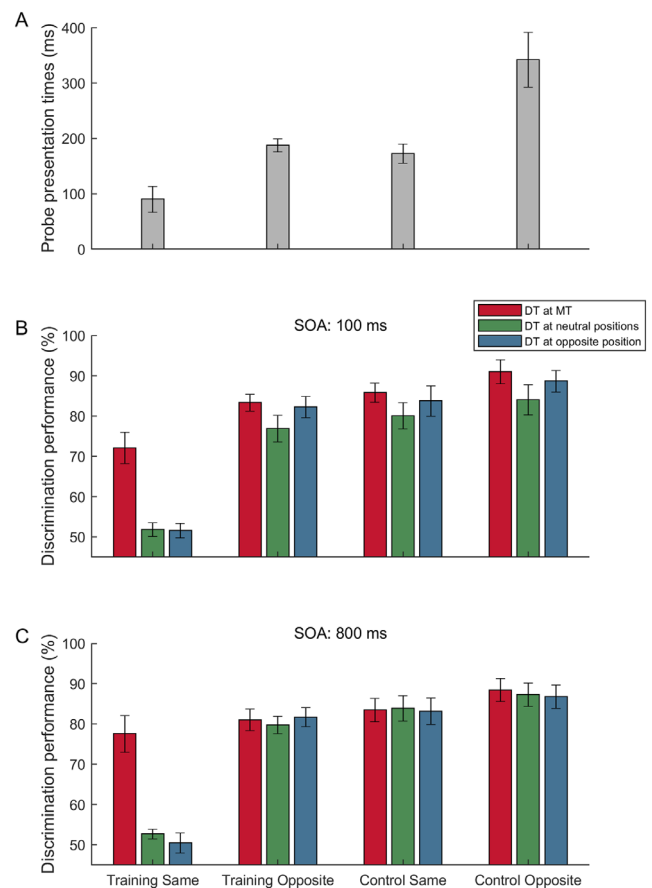

Figure 3. Adjusted presentation times of the DT of each training condition (A) in the first data analysis of Experiment 1. Mean discrimination performance of training and DT conditions in trials with a 100 ms (B) and 800 ms (C) SOA between movement cue onset and go-signal onset. Error bars indicate within-participants *SEM*.

groups (Control Opposite vs. Training Same: $p = 0.001$; Control Opposite vs. Training Opposite: $p = 0.040$; Control Opposite vs. Control Same: $p = 0.025$). This is not surprising because participants of this control condition were unaware of the DT's position, and thus there was no incentive to direct attention toward the opposite position. Presumably, an average presentation time of 342 ms may therefore reflect the time required to discriminate a probe stimulus at a position that is currently unattended. Moreover, presentation times in our experiments were longer than those reported by (Dignath et al., 2019; they reported a mean presentation time of 95 ms), indicating that our four-placeholder task was more difficult than the two-placeholder task used by Dignath and colleagues (2019).

Discrimination performance: Because of the group differences in presentation times (for DT), we examined discrimination performance (Figures 3B, 3C) separately for each training group. For the Training Same group, a repeated measures ANOVA with factors DT position

and SOA condition revealed a large effect of DT position, $F(1.16, 15.07) = 25.56$, $p < 0.001$, $\eta_p^2 = 0.66$, on accuracy in the discrimination task. The main effect of SOA condition, $F(1, 13) = 1.39$, $p = 0.259$, $\eta_p^2 = 0.10$, and the interaction, $F(2, 26) = 1.72$, $p = 0.198$, $\eta_p^2 = 0.12$, was not significant. Post hoc comparisons showed that participants were significantly better in discriminating the DT at the MT ($M = 74.8\%$, $SD = 15.0\%$) compared to the neutral positions ($M = 52.2\%$, $SD = 5.0\%$, $p < 0.001$) and the opposite position ($M = 51.2\%$, $SD = 5.1\%$, $p < 0.001$). No differences in discrimination performance were found between the opposite and neutral positions ($p > 0.999$). These results indicate that the learned expectation of spatial congruence between a task-relevant stimulus and the movement goal locations caused participants to direct attention only toward the movement goal position, regardless of the length of movement delays.

In the Training Opposite group, average discrimination performance across SOA conditions was 82.2% ($SD = 8.2\%$) at the MT, 78.3% ($SD = 9.7\%$) at neutral positions, and 81.9% ($SD = 8.1$) at the opposite position. A repeated measures ANOVA indicated that discrimination performance differed between DT positions, $F(2, 26) = 4.63$, $p = 0.019$, $\eta_p^2 = 0.26$, but not between SOA conditions, $F(1, 13) < 0.01$, $p = 0.995$, $\eta_p^2 < 0.01$. Importantly, the interaction was also non-significant, $F(2, 26) = 1.50$, $p = 0.241$, $\eta_p^2 = 0.10$, suggesting that the length of SOAs was of no relevance for the deployment of attentional resources at DT positions. Post hoc comparisons revealed that overall discrimination performance was enhanced at the opposite position compared to the neutral positions ($p = 0.041$), but that performance did not differ between the MT and the opposite position ($p > 0.999$). This indicates that the learned expectation of spatial incongruence between positions allowed participants to direct some but not all attentional resources towards the opposite position. However, the difference in performance between the MT position and neutral DT positions did not reach significance ($p = 0.080$), suggesting a higher variation in performance differences than between the opposite and neutral positions.

Surprisingly, in the Control Same group, ANOVA results revealed that performance in the discrimination task was comparable irrespective of DT position, $F(1.15, 11.45) = 1.03$, $p = 0.344$, $\eta_p^2 = 0.09$, suggesting that there was no clear pattern of a premotor attention shift towards the movement goal location. The main effect of SOA was also not significant, $F(1, 10) = 0.12$, $p = 0.736$, $\eta_p^2 = 0.01$, but results showed a significant interaction, $F(2, 20) = 4.76$, $p = 0.020$, $\eta_p^2 = 0.32$. To examine this interaction, we employed a repeated measures ANOVA with factor DT position separately for each SOA condition. As Figure 3 suggests, performance differences between positions were more pronounced in trials with an SOA of 100 ms compared

to trials with an SOA of 800 ms. Nonetheless, there was neither a significant main effect of DT position for the SOA of 100 ms, $F(1.24, 12.39) = 2.78$, $p = 0.116$, $\eta_p^2 = 0.22$, nor for the SOA of 800 ms, $F(2, 20) = 0.09$, $p = 0.918$, $\eta_p^2 = 0.01$.

For the Control Opposite group, results showed a significant main effect of DT position, $F(2, 24) = 3.64$, $p = 0.042$, $\eta_p^2 = 0.23$, a significant interaction SOA condition × DT position, $F(1.28, 15.35) = 4.54$, $p = 0.042$, $\eta_p^2 = 0.27$, but a nonsignificant main effect of SOA condition, $F(1, 12) = 0.28$, $p = 0.607$, $\eta_p^2 = 0.02$. In contrast to the Control Same group, we found a significant effect of DT position in trials with an SOA of 100 ms, $F(2, 24) = 5.10$, $p = 0.014$, $\eta_p^2 = 0.30$. However, although Figure 3B suggests a trend towards enhanced discrimination performance at the MT and the opposite position compared to neutral DT positions, none of the post hoc pairwise comparisons reached significance (DT at MT vs. DT at neutral positions: $p = 0.064$; DT at neutral positions vs. DT at opposite position: $p = 0.096$; DT at MT vs. DT at opposite position: $p = 0.830$). For trials with an SOA of 800 ms, there was also no significant effect of DT position on discrimination performance, $F(2, 24) = 0.77$, $p = 0.474$, $\eta_p^2 = 0.06$.

Second analysis

The results of discrimination performance in our first analysis should be interpreted with caution because the duration of adjusted presentation times led to trials in which the DT was still present after movement onset. However, because it is assumed that the premotor shift of attention is linked to motor preparation and since one might expect that motor preparation is completed at the time of movement onset, one might also expect that after movement onset, attention is released again and might now be free to be allocated also to other positions. Given these assumptions, attentional effects that cannot be clearly assigned to the pre-motion-onset interval should be excluded from an analysis focused on the examination of premotor shifts of attention. For this reason, we conducted a second data analysis. Before this second data analysis, all trials were excluded for which the DT was not yet masked at the time of movement onset (Movement before probe offset). Furthermore and similar to our first analysis, we excluded all participants from the analyses for whom more than 45% of the test phase trials had to be rejected after applying all the relevant exclusion criteria (including the new one). On this basis, we had to exclude one further participant of the Training Same group, one further participant of the Training Opposite group, three further participants of the Control Same group, and ten further participants of the Control Opposite group. Given that the remaining sample of the Control Opposite group consisted of only three

participants, we dropped the Control Opposite group from the analysis and only analyzed the data of the Training Same group ($n = 13$), Training Opposite group ($n = 13$), and Control Same group ($n = 8$). A summary of the proportion of trials rejected according to our exclusion criteria prior to the second analysis is shown for each of the included groups in Supplementary Table S2.

The second analysis of the Training Same, Training Opposite and Control Same group revealed an overall pattern of results similar to that of our first analysis in terms of movement parameters (Supplementary Table S3), presentation times (Supplementary Figure S1A), and discrimination performance (Supplementary Figure S1B, Supplementary Figure S1C). A detailed description of statistical results of our second analysis is therefore reported in Supplementary Materials. Yet, the results of discrimination performance of the Training Opposite group revealed a clearer picture regarding attention allocation compared to our first analysis. As in the first analysis, there was a significant main effect of DT positions, $F(2, 24) = 5.39$, $p = 0.012$, $\eta_p^2 = 0.31$, a non-significant effect of SOA, $F(1, 12) = 0.04$, $p = 0.848$, $\eta_p^2 < 0.01$, and a nonsignificant interaction, $F(2, 24) = 0.79$, $p = 0.467$, $\eta_p^2 = 0.06$. However, in contrast to our first analysis, post hoc comparisons indicated that performance was not only enhanced at the opposite position ($M = 82.1\%$, $SD = 9.0\%$, $p = 0.036$) but also at the MT position ($M = 83.4\%$, $SD = 8.8\%$, $p = 0.024$) compared to neutral DT positions ($M = 77.9\%$, $SD = 10.2\%$), although there was no difference in discrimination performance between the MT and the opposite position ($p > 0.999$). These results suggest that, irrespective of the time available for motor preparation, participants of the Training Opposite group directed more attentional resources to the anticipated probe position and the movement goal location than to neutral positions.

Overall, the similarity of results of our two data analyses suggests that our findings in the Training Same, Training Opposite, and Control Same group were not caused by shifts of attention that occurred with or after movement initiation.

Discussion

The results of Experiment 1 indicate that attention allocation was biased towards the expected position of the attention probe in the Training Same group and, to a lesser degree, in the Training Opposite group. Surprisingly, we did not observe a premotor attention shift in the control groups (Control Same, Control Opposite), which is at odds with previous evidence suggesting a strict attention-action coupling in pointing movements (Deubel, Schneider, & Paprotta, 1998; Jonikaitis & Deubel, 2011). The results further suggest

that the training-induced effects on attention allocation did not require pre-programming of movements or (as confirmed by our second analysis) occur only with or after movement onset, but rather emerged during ongoing motor preparation.

Nonetheless, Experiment 1 revealed between-group differences in adjusted probe presentation times, rendering it difficult to compare results of discrimination performance between training groups. Moreover, relative differences in discrimination performance between probe positions were less pronounced with longer (Training Opposite, Control Same, Control Opposite) compared to shorter presentation times (Training Same). Thus we cannot rule out that the length of adjusted presentation times confounded performance in the discrimination task of Experiment 1. To examine this possibility and to allow better comparison of results of the discrimination task between training groups, we ran a second experiment (Experiment 2) similar to Experiment 1 but with a fixed probe presentation time that was identical in all training groups.

Experiment 2

Methods

Participants

Twenty-one naïve participants (16 female; 1 left-handed; mean age 23.8 years; age range 18–35 years) with normal or corrected-to-normal vision and normal motor behavior took part in Experiment 2. None of them had participated in the first experiment. Participants gave informed consent to participate in the study. The experiment was approved by the local ethics committee and conducted in accordance with the Declaration of Helsinki.

Apparatus

The experimental setup was identical to the one used in Experiment 1.

Design and procedure

Experiment 2 was similar to Experiment 1, except for the following modifications. First, we used a fixed presentation time for the DT of 83.33 ms in each part of the experiment that included the discrimination task. The fixed DT presentation time was identical for all training groups.

Second, Experiment 2 included only two training conditions. As in Experiment 1, we had a Training Opposite group in which the DT was presented in all

trials of the training phase at the location opposite the MT position. In a Control group, the DT was presented with equal probability at one of the four placeholder positions. However, since average adjusted presentation times (first analysis: 90 ms; second data analysis: 76 ms) of the Training Same group in Experiment 1 were similar to the fixed DT presentation time of Experiment 2, we did not include this training condition in Experiment 2.

Third, in Experiment 2, we focused on training-induced effects on attention allocation within the critical movement preparation phase. To this end, we only included a movement delay (i.e., SOA between movement cue and go-signal onset) of 100 ms in the discrimination task.

Fourth, it is possible that implicit learning of the spatial relationship between the DT and MT in the training phase of Experiment 1 was limited due to the enhanced difficulty of the discrimination task compared to the study of Dignath et al. (2019). To rule out this possibility, we thus explicitly informed participants in Experiment 2 about the spatial relationship of the MT and DT prior to the training phase. Yet, as in Experiment 1, participants were not informed about the position of the DT before the test phase.

Fifth, we conducted a screening phase before Experiment 2 to ensure that each participant was able to reliably discriminate the DT at a presentation time of 83.33 ms at a covertly attended position in the subsequent experiment. The screening phase consisted of eight blocks of 30 trials of the discrimination task without concurrent pointing movement. The DT was presented in 80% of the trials at a placeholder position (likely probe position) that was known to the participants and which was held constant over a trial block. In the remaining 20% of trials, the probe appeared with equal probability at one of the three remaining placeholder positions. Participants continued with the experiment only if their discrimination performance for DTs at the likely probe position exceeded a value of 75% in the last two trial blocks of the screening phase.

Finally, to ensure that participants were sufficiently familiar with the dual-task, they had to complete four blocks of the dual-task training (instead of only two blocks as in Experiment 1) prior to the training phase and the test phase of Experiment 2.

Data analysis

Six participants were excluded from the experiment because they did not reach the threshold of discrimination performance in the screening phase. Before the data analyses of Experiment 2, we discarded trials of the remaining sample ($N = 15$ out of a total of 21) if one of the following exclusion criteria was met: Fixation violation, Blink violation, No movement,

Movement too early, Movement inaccurate, Movement latency outlier, Movement before probe offset (cf., Experiment 1). None of the participants had to be excluded due to exceeding the maximum percentage of excluded test phase trials ($>45\%$; cf., Experiment 1). However, we excluded one further participant of the Training Opposite group because discrimination performance in the test phase was below chance level at each probe position, presumably because of confusing the mapping between DT identity and response button. The final sample consisted of seven participants in the Training Opposite group and seven participants in the Control group. A summary of the proportion of trials rejected according to the applied exclusion criteria is shown for each group in Supplementary Table S4.

To examine the movement parameters, we employed independent samples t tests with movement latency and movement duration as the dependent variables. For analyses of discrimination performance, we conducted repeated measures ANOVAs with factors DT position (DT at MT vs. DT at neutral positions vs. DT at opposite position) for each training group (Training Opposite, Control). Greenhouse-Geisser corrections were applied when sphericity was violated. Post hoc pairwise comparisons were Bonferroni corrected.

Results

Movement parameters

Movement parameters of each training group are shown in Table 3. Results showed that neither movement latency, $t(12) = -0.23$, $p = 0.826$, $d = 0.54$, nor movement durations, $t(12) = -0.62$, $p = 0.549$, $d = 0.54$, differed between the Training Opposite and the Control group.

Interestingly, descriptive results indicate that movement latencies for trials with an SOA of 100 ms were shorter in Experiment 2 than in Experiment 1. This presumably reflects an effect of the applied movement delays. Experiment 2 contained only a short movement delay of 100 ms, likely allowing participants to consistently execute movements rapidly after the movement cue appeared. In contrast, movement delays were varied between 100 ms and 800 ms across trials of Experiment 1, which possibly increased uncertainty and thereby generally slowed down movement initiation.

	Training opposite M $\pm$ SD	Control M $\pm$ SD
Latency	231 $\pm$ 48	237 $\pm$ 49
Duration	344 $\pm$ 109	374 $\pm$ 63

Table 3. Movement latencies and movement durations for each training group in Experiment 2. *Note:* Values in ms.

Discrimination performance

Figure 4 shows the results of the discrimination task for each training condition in the test phase of Experiment 2. For the Control group, discrimination performance significantly differed between probe positions, $F(1.13, 6.76) = 17.39$, $p < 0.001$, $\eta_p^2 = 0.74$. Post-hoc pairwise comparisons showed that discrimination performance was significantly enhanced at the MT position compared to both the opposite position ($p = 0.019$) and neutral positions ($p = 0.013$), although there was no significant difference in discrimination performance between the opposite position and neutral positions ($p > 0.999$). This indicates that attention was strictly linked to the movement goal location in the Control group.

For the Training Opposite group, ANOVA results showed a significant effect of DT position on discrimination performance, $F(1.09, 6.55) = 49.28$, $p < 0.001$, $\eta_p^2 = 0.89$. Post-hoc pairwise comparisons revealed that discrimination performance was significantly enhanced at the opposite position compared to both the MT position ($p = 0.004$) and neutral positions ($p < 0.001$), indicating that participants of the Training Opposite group directed most attentional resources towards the expected DT position. However, for the difference in discrimination performance between the MT position and neutral positions we only found a marginally significant effect ($p = 0.060$). To explore whether this nonsignificant benefit in discrimination performance at the MT position was less pronounced compared to the one found in the Control group, we conducted an additional independent samples t test with the discrimination performance at the MT position as the dependent variable. Results showed that discrimination performance was indeed higher at the MT position in the Control group than in the Training Opposite group, $t(12) = -7.19$, $p < 0.001$, $d = -3.84$, suggesting that shifting attentional resources
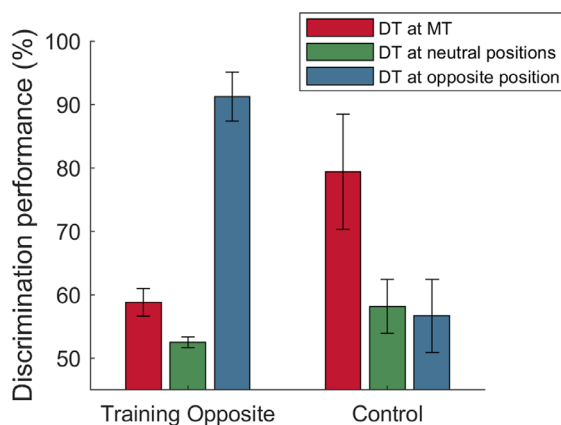
to the anticipated DT position (opposite position) came at the expense of attentional performance at the MT position in the Training Opposite group.

Discussion

In line with previous evidence for a strict attention-action coupling in pointing movements (Deubel, Schneider, & Paprotta, 1998; Jonikaitis & Deubel, 2011), we now observed a clear premotor shift of attention towards the movement goal location in a control condition (Control) with unpredictable DT position. Importantly, the findings of the Training Opposite group in Experiment 2 demonstrate that participants were capable of guiding most attentional resources towards a non-movement target at which they had learned to anticipate the attention probe, indicating a crucial role of habitual top-down processes in premotor attention allocation. Moreover, since we only used a short SOA of 100 ms between the movement cue and movement go-signal in Experiment 2, the results suggest that the observed attentional effects emerged during ongoing movement preparation.

General discussion

The current study investigated whether the commonly observed coupling between visual attention and motor preparation is associated with a habitual expectation of spatial congruence between objects of interest and targets of motor actions. In particular, we addressed the question of whether attentional resources can be decoupled from ongoing motor preparation based on a learned expectation of spatial incongruence between visual and motor targets. To this end, we conducted two experiments in which we combined a visual discrimination task with a pointing task. To examine attention allocation at different stages of the motor preparation phase, pointing movements had to be executed upon a variable movement delay of either 100 ms or 800 ms in Experiment 1. In Experiment 2, only a fixed movement delay of 100 ms was applied. Both experiments comprised a training phase and a subsequent test phase. The training phase served to establish distinct top-down expectations regarding the spatial relationship between the discrimination target (DT) and the motor target (MT). This was realized via systematically varying the likelihood of the DT to appear at a specific position. For different groups in Experiment 1, the DT either always appeared at the position of the current MT (Training Same), at the position opposite to the current MT (Training Opposite), or at a randomly selected position (Control Same and Control Opposite) throughout the training phase. In Experiment 2, we focused on eliciting an

Figure 4. Discrimination performance of each DT and training condition in Experiment 2. Error bars indicate within-participants *SEM*.

expectation of spatial incongruence between DT and MT positions and included only a Training Opposite group in addition to a Control group with unpredictable DT position. After the training phase, participants of all groups completed a test phase in which the DT position was randomized, allowing us to assess training-induced, expectancy-driven biases in premotor attention allocation on the basis of discrimination performance data. The test phase differed between the experiments only regarding the DT presentation time. While DT presentation times were determined individually for each participant in Experiment 1 (based on a thresholding procedure in the training phase), a fixed DT presentation time was used in Experiment 2.

The data obtained in Experiment 2 provide strong evidence that habitual top-down processes play a crucial role in the emergence of the attention-action coupling. Consistent with previous findings (Deubel, Schneider, & Paprotta, 1998; Jonikaitis & Deubel, 2011; Hanning et al., 2022), we observed a premotor shift of attention in the Control group in which participants had not learned to expect the DT at a particular position. In contrast, the results of the Training Opposite group revealed that attentional resources were selectively allocated to a movement-irrelevant, yet task-relevant, visual target when participants anticipated spatial incongruence between the DT and MT positions. This evidence for a decoupling of attentional resources from the movement goal is difficult to reconcile with the assumption of functional equivalence of motor preparation and visual attention as proposed by the Premotor Theory of Attention (Rizzolatti et al., 1987; Rizzolatti, Riggio, & Sheliga, 1994). In fact, we observed that the attentional enhancement at the expected DT position was substantially larger than at the MT position in the Training Opposite group. This implies that, contrary to earlier findings on saccadic eye movements (Kowler et al., 1995; Montagnini & Castet, 2007), participants were able to divert *most* attentional resources from the target of upcoming movements. Importantly, this effect was observed in movements that were delayed by only 100 ms, contradicting previous evidence that attention can only be decoupled from a reach target when there is sufficient time available to complete movement preparation (Deubel & Schneider, 2003). In other words, the results of Experiment 2 suggest that the observed top-down modulations of attention occurred during ongoing movement preparation. A similar effect has been previously reported only in pointing movements that were substantially delayed and therefore presumably allowed for motor pre-programming (Dignath et al., 2019). Our findings thus complement previous studies on saccades, which have demonstrated that endogenous attentional control can operate independently of movement planning processes (Gabay et al., 2010; Smith et al., 2004; Smith et al., 2012). However, it

is conceivable that the decoupling of attentional resources from motor preparation processes was achieved only through tradeoffs in other aspects of task performance. However, our results do not support this assumption. Training groups did not differ in terms of movement latency or movement duration, suggesting that participants did not adopt a strategy to decouple attention from the movement goal at the expense of movement performance. Despite the absence of significant between-group differences at the motor level, we cannot rule out that motor behavior was generally affected, at least to some extent, by dual-task costs in the current study. Thus the attentional effects observed here may be specific to dual-task conditions.

Experiment 2 suggested that expectancy-driven allocation of attentional resources toward a movement-irrelevant position interfered with shifting attention toward the upcoming movement goal. We observed that discrimination performance at the MT position was significantly reduced in the Training Opposite group (in which participants expected the DT to appear at the position opposite to the MT) relative to the Control group (in which participants had no particular expectation about the DT position). Interestingly, in a recent dual-task study, Hanning et al. (2022) reported a different pattern of results. In this study, the preparation of both eye and pointing movements was found to deteriorate voluntary attention allocation toward a movement-irrelevant position likely to contain a discrimination target. However, contrary to the current study, participants had to perform several different experimental conditions, and there was no designated initial training phase. Thus it is possible that the precedence of motor-based attention shifting over top-down expectancy-driven attention allocation (as observed by Hanning et al., 2022) reflects a default mode, which (as implied by the present results) can only be reversed through sufficient training. Accordingly, an interesting endeavor for future studies will be to more systematically examine tradeoffs between action-driven and expectancy-driven attentional selection as a function of training duration.

In line with the idea that the attention-action coupling is influenced by habitual top-down processes, we also observed a small benefit in discrimination performance at the anticipated DT position compared to neutral control positions in the Training Opposite group in Experiment 1. However, although our results suggest that this effect did not require preprogramming of movements or emerged only with or after movement onset, the differences between training groups in adjusted DT presentation times combined with the lack of evidence for a premotor attention shift in the Control Same group limited the explanatory power of the discrimination task results in this experiment. Nonetheless, the between-group differences in presentation times provided insights

into the varying difficulties in guiding attention to the anticipated DT position during the training phase, thereby complementing our findings in Experiment 2. In particular, the finding of prolonged DT presentation times in the Training Opposite group compared to the Training Same group demonstrates an increased difficulty in directing attentional resources to a position that deviates from the target of an upcoming movement. This suggests a stubborn, yet not necessarily obligatory, nature of the attention-action coupling. Furthermore, it shows that training may play an essential role in overcoming this default mode of shifting attention to the target of imminent goal-directed movements. However, in contrast to Experiment 2, we did not explicitly inform participants about the spatial relationship between the DT and MT prior to the training phase in Experiment 1, which might have rendered predictability of the DT position more difficult. Nonetheless, previous studies in which participants were explicitly informed about the position of the attention probe did not observe a substantial disengagement of attention from movement targets (Deubel, 2008; Deubel & Schneider, 1996; Deubel et al., 1998; Hanning et al., 2022; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Schiegg et al., 2003). This suggests that training is indeed critical for effective top-down modulations of premotor attention allocation.

The results of Experiment 1 also revealed that DT presentation times were longer in the Control Same group than in the Training Same group. Since presentation times in these two groups were adjusted only on the basis of trials in which the DT was presented at the MT position and incorrect responses resulted in an increase in presentation time, this finding implies that participants of the latter group directed attention more consistently towards the MT position over the course of the training phase. Considering that the training of the two groups differed only in the position at which the DT was presented (Training Same: MT position; Control Same: random DT position), the shorter presentation times in Training Same might therefore suggest that the expectation of spatial congruence between DT and MT facilitated attention shifts to the MT position. Indeed, if visual attention shifts were a mere by-product of motor preparation processes, no group differences in presentation times should be found. However, it is possible that participants in the Control Same group became aware of the fact that the DT did not always appear at the MT position and therefore attempted to divert attention away from the MT position to detect DTs at other positions as well. Because of the unpredictability of the DT position in this control condition, this would have led to a prolongation of the adjusted presentation times, which would explain the difference in DT presentation times between the Training Same group and the Control Same group.

Surprisingly, in Experiment 2, the results of the Training Opposite group revealed no significant difference in discrimination performance between the MT position and neutral control positions, which suggests that the commonly observed premotor shift of attention towards the upcoming movement goal reflects the expectation that a relevant visual target appears at the MT position and is not just a simple by-product of motor preparation. Otherwise it would be hard to explain why the Training Opposite condition should abolish the typical MT-superiority. Yet, as can be seen in Figure 4, discrimination performance was slightly enhanced at the MT position compared to neutral positions. Although this benefit was only marginally significant, it is possible that such an effect would become apparent with a larger sample size. However, it is important to note that even if we had observed significant attentional facilitation at the MT position, it would have remained unclear whether this effect could be attributed to processes of motor preparation or to the fact that the expected DT position was defined relative to the MT position (i.e., opposite to it) in the Training Opposite group. In other words, the MT position was needed as a spatial reference or landmark to determine the DT position in this training group. Accordingly, a plausible alternative explanation for an observation of attentional facilitation at the MT position would be that participants first focused their attention on the MT before they could allocate attention to the (opposite) location where the DT was expected to appear. Future research is therefore needed to determine the precise extent to which attentional processes are truly required for planning goal-directed movements (e.g., by using a stationary position, unrelated to the MT, to induce an expectation of spatial incongruence between the DT and MT positions).

Nevertheless, the present study demonstrates that attention and action can be decoupled to a considerable extent by training. In contrast to previous research (Dignath et al, 2019), this effect was demonstrated in a dual-task paradigm in which the task did not provide an opportunity to complete motor preparation before attention was probed, but in which attention allocation was assessed during ongoing movement planning. Overall, our results thus suggest that the premotor attention shift phenomenon is not solely attributable to processes of motor preparation, but involves a hitherto largely neglected habitual top-down component that is linked to an anticipation of spatial congruence between behaviorally relevant visual and motor targets.

Conclusions

The present study provided evidence for the notion that the close link between visual attention and the

preparation of goal-directed actions is related to a habitual expectation of spatial congruence between objects of interest and targets of upcoming movements. We demonstrated that a training-induced anticipation of spatial incongruence between positions of a motor target and a task-relevant visual target allowed for a marked decoupling of attentional resources from targets of upcoming pointing movements. Importantly, this effect emerged while motor programming was still in progress and without impairment of movement performance. This suggests that the link between attentional deployment and motor preparation is less strict than typically assumed. In light of these findings, we suggest that the commonly observed premotor shift of attention is not a sole consequence of motor preparation per se, but that habitual top-down processes play a relevant role in its formation.

Keywords: visual attention, reaching movements, motor planning, learning, dual-task

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