Spatio-temporal dynamics of action-effect associations in oculomotor control[☆]

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A B S T R A C T

While there is ample evidence that actions are guided by anticipating their effects (ideomotor control) in the manual domain, much less is known about the underlying characteristics and dynamics of effect-based oculomotor control. Here, we address three open issues. 1) Is action-effect anticipation in oculomotor control reflected in corresponding spatial saccade characteristics in inanimate environments? 2) Does the previously reported dependency of action latency on the temporal effect delay (action-effect interval) also occur in the oculomotor domain? 3) Which temporal effect delay is optimally suited to develop strong action-effect associations over time in the oculomotor domain? Participants executed left or right free-choice saccades to peripheral traffic lights, causing an (immediate or delayed) action-contingent light switch in the upper vs. lower part of the traffic light. Results indicated that saccades were spatially shifted toward the location of the upcoming change, indicating anticipation of the effect (location). Saccade latency was affected by effect delay, suggesting that corresponding time information is integrated into event representations. Finally, delayed (vs. immediate) effects were more effective in strengthening action-effect associations over the course of the experiment, likely due to greater saliency of perceptual changes occurring during target fixation as opposed to changes during saccades (saccadic suppression). Overall, basic principles underlying ideomotor control appear to generalize to the oculomotor domain.

1. Introduction

Research and theory on action control mostly adopt a stimulus-driven view (i.e., that actions are mainly triggered by properties of preceding input stimuli). In contrast, the ideomotor view claims that actions are determined by the anticipation of their effects (Greenwald, 1970; Herbart, 1825; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890). Ideomotor theory implies that people acquire bidirectional action-effect (A–E) associations (i.e., knowledge about consequences of their behavior) and that the activated anticipatory idea of an action's effect (i.e., its goal) guides action selection, initiation and execution. Although the investigation of ideomotor learning has been of increasing interest in recent years (Elsner & Hommel, 2001; Herwig, Prinz, & Waszak, 2007; Herwig & Waszak, 2009, 2012) the underlying dynamics of A–E associations – especially for non-standard (i.e., non-manual) control systems – are still not sufficiently explored.

A–E associations have been studied mainly in the manual control domain (keypresses, grasping; e.g., Kunde, 2001), measuring anticipation effects via spatial A–E compatibility effects in manual reaction times (RTs). However, the extension and generalization of the ideomotor view to other action modalities have recently come into focus, for example to the oculomotor domain. Specifically, gaze-contingent paradigms have been applied for research on the development of action control in infants, addressing oculomotor reinforcement learning (Vernetti, Smith, & Senju, 2017) and mechanisms of controlling the environment via gaze (Verschoor, Paulus, Spapé, Biro, & Hommel, 2015; Wang et al., 2012; Wass, Porayska-Pomsta, & Johnson, 2011). A crucial advantage of this focus on gaze is that infants are able to control their eye movements in a goal-direction fashion at a very early age (Johnson, Posner, & Rothbart, 1991). These studies generally show that infants are already able to anticipate oculomotor action outcomes and to control their environment using their eyes.

Other studies focused more closely on effect-based oculomotor control in adults. For example, Caligiore et al. (2015) demonstrated that

the efficiency of learning action-effect associations in oculomotor control can be affected by specific characteristics of the effect. Herwig and Schneider (2014) studied basic underlying prediction mechanisms in saccade control, demonstrating that the visual system uses past experience to predict how peripheral objects will look like in the fovea. However, more relevant for the current topic, that is, the spatio-temporal dynamics of oculomotor A–E associations, are RT studies (Herwig & Horstmann, 2011; Huestegge & Kreutzfeldt, 2012; Verschoor, Spape, Biro, & Hommel, 2013; for a recent review see Herwig, 2015). These studies mainly focused on the measurement of anticipation effects through the oculomotor counterpart to manual RTs, namely saccade latencies.

Among them, the study of Herwig and Horstmann (2011) is especially relevant for the present research. It was based on the idea that the social (animate) environment is distinct from the inanimate environment with respect to the unique characteristic of gaze in social interactions: In addition to mere perceptual effect signals, eye movements can cause visible and gaze-contingent effects in the social environment, which is hardly ever the case in inanimate environments. In their study, they utilized visual effects in facial (emotional) expressions that were triggered by saccades toward left/right faces on the display screen. In an acquisition phase, participants were instructed to randomly saccade toward one of two emotionally neutral faces presented on the left and right part of the screen. With a delay of 100 ms, the saccades contingently triggered a change of the neutral face into either a happy (e.g., resulting from a leftward saccade) or an angry face (e.g., resulting from a rightward saccade). In a subsequent test phase, the happy or angry faces were presented as imperative stimuli with the instruction to either perform a saccade toward the position where the facial expression was previously triggered (i.e., action-effect (A–E) compatible) or to the other location (i.e., A–E incompatible). They found that latencies of saccades toward A–E compatible (vs. incompatible) locations were faster, thereby replicating the typical compatibility effect usually found in the manual domain. Additionally, an analysis of saccade landing positions in the acquisition phase revealed that participants anticipated the saccade-contingent change of facial expression over the course of the experiment by directing their initial gaze toward the location of this change (mouth region for happy expression, eyebrow region for angry expression). This difference in the vertical landing position between the two effect conditions (angry vs. happy face) increased over the course of the experimental blocks.

Another pioneering study investigating the role of action effects in oculomotor control (Huestegge & Kreutzfeldt, 2012) – conducted independently and in parallel to the Herwig and Horstmann (2011) study – used inanimate, geometric stimuli (square/diamond) instead of social face stimuli as left/right saccade targets. It was shown that a task-irrelevant visual stimulus which was either congruent, incongruent or unrelated to the subsequent action effect and which was presented prior to an imperative auditory stimulus influenced saccade performance: Saccade RTs were faster and less error-prone in congruent (vs. incongruent) conditions. The results indicated that learned oculomotor A–E associations affect saccade control generally, even in an inanimate (non-social) environment. This idea is further supported by recent findings indicating that acquired non-social effects of oculomotor actions affect visual search performance (Herwig & Schneider, 2014; Weiß, Schneider, & Herwig, 2014). However, these studies' designs did not allow for an analysis of spatial saccade characteristics as an index of anticipation. Thus, the question of whether saccade landing positions can reflect anticipation in an *inanimate* environment remained an open issue.

Another line of research in the context of manual ideomotor control has focused on dynamic aspects underlying A–E association learning, that is, regarding the temporal contiguity between actions and effects. Specifically, it was shown that the length of the temporal A–E interval affected the latency of the (manual) action (Dignath, Pfister, Eder, Kiesel, & Kunde, 2014). They explained this effect by assuming that

temporal information about the A–E interval is integrated into a cognitive action script (or event file) in a bidirectional manner, which is then automatically retrieved during action preparation and thereby affects the timing of response selection. If this general interpretation is correct, one would expect a corresponding phenomenon in the oculomotor domain, a prediction that has not been tested yet. Furthermore, it is not known whether and how different temporal A–E intervals affect the dynamic buildup of A–E associations in oculomotor control. Since eye movements differ from other action modalities (e.g., manual actions) in that they consist of fast sequences of jerky saccades and stationary fixations (Liversedge, Gilchrist, & Everling, 2011), it appears especially interesting to investigate this phenomenon in the oculomotor domain.

The central aspect of the present study was to narrow down basic mechanisms underlying the acquisition of action-effect learning in the oculomotor domain with respect to both spatial (by focusing on effects on spatial oculomotor control) and temporal aspects (by studying effects of temporal A–E intervals and by examining learning dynamics). To do so, we analyzed saccadic eye movements that contingently resulted in specific (immediate or delayed) changes in inanimate objects (traffic lights). The experimental paradigm was a free-choice design that did not include a congruency manipulation, but rather focused on evidence of spatial effect location anticipation in eye movements. We presented two neutral identical traffic lights (i.e., lights without any lamp turned on) on the screen, one on the left and one on the right side of central fixation. Contingent upon the participant's freely selected gaze direction (toward the left versus right traffic light), one lamp of the light turned on (e.g., upper lamp when the left traffic light was targeted vs. lower lamp when the right traffic light was targeted). The temporal onset of the action effect was either immediate (0 ms A–E interval) or delayed (100 ms or 300 ms).

We addressed three novel research questions. First, we tested whether action-effect anticipation in oculomotor control is reflected in corresponding spatial saccade characteristics in inanimate environments (similar to corresponding effects demonstrated in a social context, see Herwig & Horstmann, 2011). If A–E learning occurs and thus saccade preparation toward the peripheral target involves the mental representation of the action effect, participants should anticipate the specific change in the neutral target objects and direct the landing position of their initial saccade toward the anticipated effect location (upper/lower lamp of traffic light). Second, we tested whether the previously reported dependency of action latency on the temporal effect delay (A–E interval, see Dignath et al., 2014) also occurs in the oculomotor domain. Third, we asked which temporal effect delay is optimally suited to develop strong associations between oculomotor actions and their visual effects over the course of the experiment. While effects of our actions in the inanimate environment usually occur instantaneously (e.g., in the case of light switches), thus supporting the prediction that immediate effects should be optimal for learning, it is also possible that immediate visual changes in the oculomotor domain (i.e., changes occurring during the saccade toward the target) are less salient than delayed changes due to saccadic suppression phenomena, which would rather support the prediction of enhanced learning with delayed effects.

2. Method

2.1. Participants

Forty-eight students took part in the experiment (35 women and 13 men; age range: 18–41 years, $M = 24.21$, $SE = 0.63$) and received course credits. All participants reported normal or corrected-to-normal vision and were naïve with respect to the purpose of the experiment. They gave their informed consent before the experiment was started.
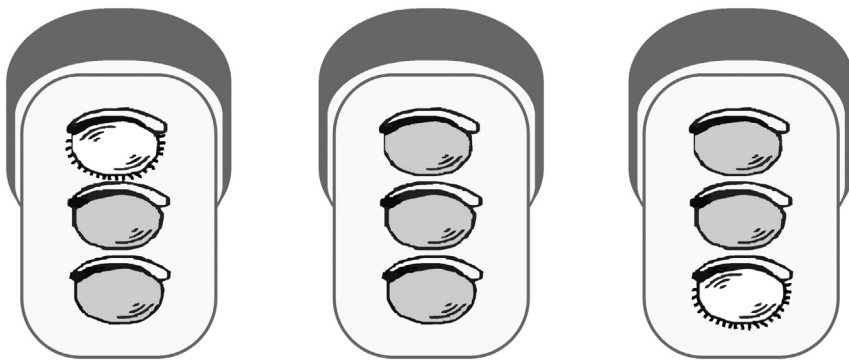
2.2. Stimuli

The stimulus type used in the present study (i.e., traffic lights) is depicted in Fig. 1. There were three different versions of the traffic light stimulus (no lamp vs. upper lamp vs. lower lamp turned on) that differed only in the upper or the lower lamp region (i.e., the upper or lower light was switched on or off). The (greyscale) stimuli were presented on a white background. The size of each stimulus was 5.09° × 7.36° (width × height) of visual angle. Stimuli were located to the left and right of a black fixation cross at a horizontal distance of 8° visual angle. The size of the fixation cross amounted to 0.4° × 0.4° of visual angle (14 × 14 pixels).

2.3. Apparatus, task and procedure

The experiment was performed in a dimly lit room with a viewing distance of 71 cm (Bielefeld) or 62 cm (Aachen) to the display monitor (refresh rate: 100 Hz). Screen resolution was set to 1024 × 768 pixels on a 36 cm × 27 cm (width × height) screen (Bielefeld) or 41 cm × 30 cm (Aachen). Eye movements of the right eye were recorded with a video-based eye tracker (Eye Link, SR Research, Ontario, Canada). Half of the participants were recorded using an EyeLink 1000 (1000 Hz sampling rate), while the other half were recorded using an Eye Link II system (at 500 Hz). Head and chin were stabilized by a forehead and chin rest, respectively. The experiment was programmed using Experiment Builder (SR Research, Ontario, Canada).

Participants received a visual instruction prior to the onset of the four experimental blocks involving 56 trials each (224 trials in total). Each trial started with a central fixation cross (see Fig. 2). The length of the fixation interval varied randomly between 1000 and 1500 ms. Then, two neutral traffic light stimuli appeared simultaneously to the left and right of the fixation cross. Participants were instructed to look at the fixation cross and then to freely decide for one of the two (left/right) objects as a saccade target as soon as these objects appeared. Participants were told to avoid possible preferences in gaze or regularities in saccade sequences. Every 56 trials, feedback was provided regarding the number of location choices (left vs. right) to ensure that the experience of each saccade-effect combination was equally balanced. Each saccade triggered a particular change (turning-on of the upper/lower lamp) within the fixated neutral light. The time of the onset of the stimulus change after the arrival of the initial saccade at the effect location, that is, the action-effect interval (AEI), was manipulated between participants in three stages (0 ms vs. 100 ms vs. 300 ms). Note that for the 0 ms AEI condition, stimulus change after target presentation was initiated by the first saccade leaving the interest area around the fixation cross to ensure a change during saccade execution. The change lasted for 500 ms (for the 0 ms group after saccade landing), after which participants were instructed to reorient their gaze toward the screen center.

Crucially, the stimulus' change depended on the saccade's direction: For half of the participants, a leftward saccade triggered a change from

a neutral light to a light with the upper lamp turned on, and a rightward saccade triggered a change from a neutral light to a light with the lower lamp turned on. For the other half of participants, this saccade-effect mapping was reversed. No explicit information about the mapping was provided for the participants.

2.4. Design

We utilized a mixed design with block (4 separated blocks of equal length) as a within-subjects independent variable and AEI (0 ms vs. 100 ms vs. 300 ms) as a between-subjects independent variable. We measured spatial and temporal saccade parameters. For spatial analyses, we computed relative vertical landing positions (rVLP), that is, the difference (measured in degrees of visual angle) between the mean upper (in upper lamp condition) and the mean lower (in lower lamp condition) vertical saccade landing position, indicating a spatial deviation of the saccade landing position toward the effect location. Thus, positive rVLP values were indicators for spatial effect anticipation (irrespective of actual lamp position). We additionally analyzed whether already the initial saccade toward the peripheral target reflected maximal anticipation of the effect location, or whether the saccade after the initial saccade is directed even closer to the effect location. The latter would indicate that anticipation is reflected in a sequence of saccades rather than being restricted to the initial saccade. To address this issue, we calculated the distance (measured in degrees of visual angle) between the mean vertical landing position of the saccade (both the initial saccade and the subsequent saccade) and the vertical position of the enlightened effect location (analyzed separately for the upper and lower lamp condition). If a smaller deviation for the second saccade (compared to the initial saccade) is found, this would indicate that anticipation is reflected in a sequence of saccades.

For temporal analyses, we analyzed saccade latency, which was defined as the interval between the onset of the light stimuli and the initiation of the saccade to one of the two targets. Mixed analyses of variance (ANOVA, α = 0.05, throughout) were conducted for data analysis. In case of sphericity violations, Greenhouse-Geisser corrections were applied.

2.5. Additional remark

Note that the actual study included four additional blocks of 56 trials each involving schematic face stimuli (as an alternative to the inanimate traffic lights) that changed emotional expression similar to the photographic face stimuli used in Herwig and Horstmann (2011). The sequence of blocks involving face stimuli was presented either before or after the sequence of blocks involving traffic light stimuli (counterbalanced across participants). However, no empirical evidence of effect anticipation was found for these newly designed schematic stimuli, most likely due to the fact that the changes were less salient than in the photographs used in Herwig and Horstmann (2011), where anticipation effects were shown in natural, photographic face stimuli.
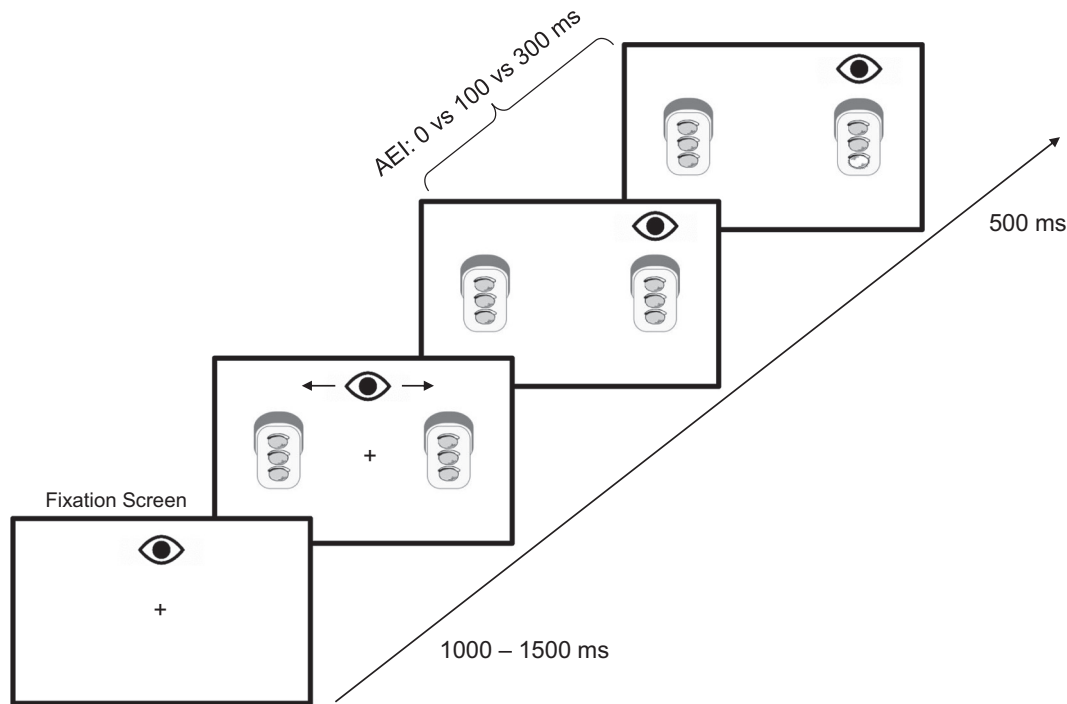
Fig. 2. Schematic representation of a trial: After the presentation of a white screen with a black fixation cross (randomized duration of 1000–1500 ms), two identical light stimuli appeared simultaneously to the left and right of the fixation cross. The participant's freely chosen saccade to one of the stimuli (left/right) triggered a change within the fixated light stimulus which lasted for 500 ms. Per each action-effect interval (AEI) condition, a total of 224 trials were presented.

The failure to find effect anticipation in these schematic face stimuli might also have its root in their unnatural character. To ensure comparability, the face stimuli were designed comparable to the traffic light stimuli with respect to the limited location of the change (i.e., the effect): The change of emotional expression in the face was restricted to either the eyebrow (c.f. the upper lamp change) or the mouth (c.f. the lower lamp change) region. Since it is well known that emotional expressions are not limited to a specific face region, our design decision may have induced a somewhat strange, unnatural appearance for these stimuli. Since the observation of spatial effect anticipation in oculomotor control is a prerequisite for addressing the specific present research questions, we here only focus on reporting the results for the traffic light stimuli. However, the role of stimulus type presentation order is addressed in the results section and a depiction of the face stimulus material as well as a detailed analysis of the face stimulus data is provided in the Supplementary material.

3. Results

3.1. Distribution of choice frequencies

The distribution of choice frequencies of leftward and rightward saccades was close to the instructed balanced distribution. The average proportion of left versus right saccades of all valid trials ($N = 10,181$) amounted to 49.93% versus 50.07%, respectively. No consistent preference in gaze or regularities in saccade sequences were apparent.

3.2. Spatial oculomotor performance

We excluded trials in which the action effect was not triggered by a saccade within 1000 ms after onset of the light stimuli (3.18%, equivalent to 342 of 10,752 trials). Further, trials with more than one saccade within the critical time interval prior to effect presentation were excluded, as it was not possible to unambiguously determine the saccade which triggered the effect in these trials (0.13%, equivalent to 14 of 10,752 trials). Furthermore, we only included saccades with

latencies longer than 99 ms to control for anticipatory saccades (2.07% anticipatory saccades, equivalent to 215 of 10,396 trials), resulting in 10,181 valid trials in total.

The rVLPs were submitted to a two-way mixed ANOVA with block as a within-subjects factor and AEI as group factor (see Fig. 3). There was a significant main effect of block on rVLP, $F(2.12, 95.54) = 8.12$, $p < 0.001$, $\eta_p^2 = 0.15$. The rVLP was smallest in the first block ($M = 0.64$, $SE = 0.12$), increased in the second and third block ($M = 0.98$, $SE = 0.14$; $M = 1.07$, $SE = 0.14$, respectively) and remained nearly constant in the last block ($M = 1.05$, $SE = 0.14$). Simple contrasts revealed that this significant main effect of block mainly resulted from the significant contrasts of the first block when compared to the second, $p = 0.001$, the third, $p < 0.001$, and the fourth block, $p = 0.002$. The second compared to the third and fourth block, as well as the third and fourth block did not significantly differ (all $ps > 0.10$).

Block significantly interacted with AEI, $F(4.25, 95.54) = 3.11$, $p = 0.017$, $\eta_p^2 = 0.12$. To further qualify this interaction, we
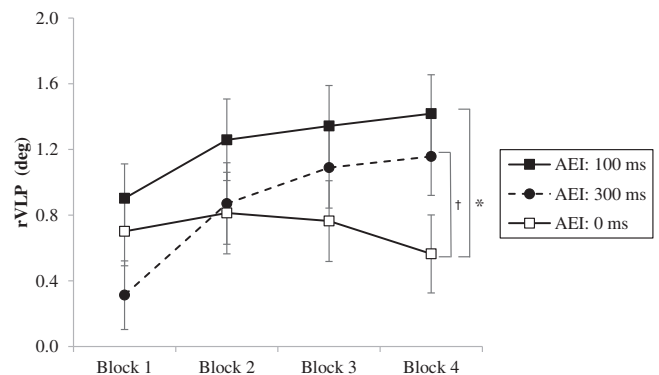

Fig. 3. Mean relative vertical landing position (rVLP) as a function of action-effect interval (AEI: 0 ms, 100 ms, 300 ms) and the 56 trial experimental blocks (1–4). Error bars depict standard errors of the mean. Asterisks and daggers indicate significance levels of two-tailed paired t-tests. *$p < 0.05$, † = marginally significant with $p = 0.084$.

conducted separate one-way ANOVAs for each block condition. While there was no significant effect of AEI in Blocks 1–3, all $ps > 0.10$, the AEI significantly affected the rVLP in Block 4, $F(2, 45) = 3.40$, $p = 0.042$, $\eta^2_\rho = 0.13$. In this block, the AEI = 0 ms condition showed a significantly smaller effect on rVLP compared to the AEI = 100 ms condition, $p = 0.014$, and a marginally significant difference (in terms of a smaller effect) from the AEI = 300 ms condition, $p = 0.084$, while the AEI = 100 ms and the AEI = 300 ms condition did not significantly differ, $p > 0.10$. For every experimental block, the mean value of the rVLP (averaged across AEI conditions) was significantly different from zero (all $ps < 0.001$). The main effect of AEI was not significant, $F(2, 45) = 1.62$, $p = 0.210$, $\eta^2_\rho = 0.07$.

To address the question of whether anticipation is reflected in the initial saccade or, alternatively, in a sequence of (two) consecutive saccades, two three-factorial repeated measurement ANOVAs (for upper/lower lamp condition) were conducted with block and saccade index (initial vs. subsequent saccade) as within-subjects factors and AEI as group factor. For the upper lamp condition, the main effect of saccade index was not significant, $F < 1$. Also, there were no significant interactions with saccade index: There was neither a significant three-way interaction, $F(6, 135) = 1.10$, $p = 0.365$, $\eta^2_\rho = 0.05$, nor a significant two-way interaction of saccade index and block, $F(3, 135) = 1.33$, $p = 0.266$, $\eta^2_\rho = 0.03$, or of saccade index and AEI, $F < 1$. In the lower lamp condition, saccade index significantly affected rVLPs, $F(1, 45) = 4.69$, $p = 0.036$, $\eta^2_\rho = 0.09$. However, there was a greater deviation for the subsequent saccade ($M = 1.39°$, $SD = 0.12$) compared to the initial saccade ($M = 1.14°$, $SD = 0.11$). Further, the interaction of saccade index and block was significant, $F(3, 135) = 11.74$, $p < 0.001$, $\eta^2_\rho = 0.21$. Paired t-tests revealed that rVLPs were comparable for the first and second saccade in Block 1, $p > 0.20$. From Block 2, $p = 0.060$, to Block 3, $p = 0.010$, and to Block 4, $p = 0.002$, the difference between the initial and subsequent saccade increased, indicating smaller deviations from the effect location for the initial, but greater deviations from the effect location for the subsequent saccade. Thus, with their subsequent saccade participants directed their gaze rather away from the effect location (in the lower lamp condition) or kept the same distance to the effect location (in the upper lamp condition).

To explore effects of stimulus type presentation order (faces first vs. traffic lights first), rVLP was submitted to a three-factorial repeated measurement ANOVA with block as within-subjects factor and stimulus type presentation order as well as AEI as group factors. The significant interaction of stimulus type presentation order and block, $F(2.22, 93.39) = 4.39$, $p = 0.012$, $\eta^2_\rho = 0.10$, indicated an influence of presentation order, with greater anticipation effects for light stimuli when they were presented first compared to presenting face stimuli first. Crucially, paired t-tests for each block revealed that stimulus presentation order was irrelevant for rVLP in Block 1, $p > 0.10$. Differences were marginally significant in Block 2, $p = 0.090$, and Block 3, $p = 0.053$, and significantly differed in Block 4 only, $p = 0.039$. Importantly, the three-way interaction was not significant, $F(4.45, 89.39) = 2.06$, $p = 0.086$, $\eta^2_\rho = 0.09$, indicating that the order of stimulus type presentation did not differentially influence the rVLP depending on AEI and block.

Taken together, these results indicate fast learning of spatial action-effect contingency in all AEI conditions (i.e., already in the first block). However, this contingency affected saccade control in terms of stronger spatial biases predominantly in the two delayed effect conditions. While there was no significant change of rVLP across blocks in the AEI = 0 ms condition, $F < 1$, we observed significant linear trends in the 100 ms condition and the 300 ms condition, $F(1, 15) = 5.06$, $p = 0.040$, $\eta^2_\rho = 0.25$ and $F(1, 15) = 9.36$, $p = 0.008$, $\eta^2_\rho = 0.39$, respectively. The sequential saccade analysis revealed that after their initial saccade, participants did not direct their gaze more closely to the effect location, suggesting that anticipation is reflected in the initial saccade, not in a sequence of successive saccades. Stimulus presentation order was
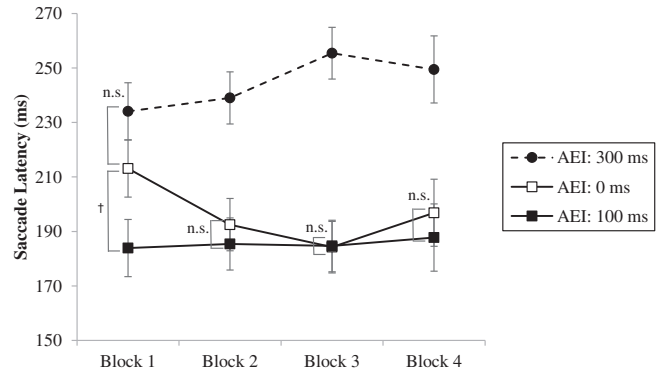

Fig. 4. Mean saccade latencies (in ms) as a function of action-effect interval (AEI: 0 ms, 100 ms, 300 ms) and block (1–4). Error bars represent standard errors of the mean, n.s. = nonsignificant, † = marginally significant with $p = 0.056$.

shown to be irrelevant in the first block of each sequence with traffic light stimuli.

3.3. Temporal oculomotor performance

Saccade latencies were submitted to a mixed ANOVA with block as within-subjects factor and AEI as group factor. Overall, the mean saccade latency amounted to 209 ms ($SE = 5.32$). There was a significant main effect of AEI, $F(2, 45) = 11.59$, $p < 0.001$, $\eta^2_\rho = 0.34$ (see Fig. 4). On average, saccade latency was longest for an AEI of 300 ms ($M = 245$ ms, $SE = 9.22$), but much shorter in both the 100 ms condition ($M = 185$ ms, $SE = 9.22$) and the 0 ms condition ($M = 197$ ms, $SE = 9.22$).

There was a significant interaction of AEI and block, $F(4.84, 108.85) = 3.23$, $p = 0.010$, $\eta^2_\rho = 0.13$. When analyzing the four experimental blocks separately with one-way ANOVAs, there were selective differences between AEI conditions in every block (all $ps < 0.006$). In Block 1, the AEI = 300 ms condition did not significantly differ from the AEI = 0 ms condition ($p = 0.165$). Regarding the AEI = 100 ms condition, there was a marginally significant difference to the AEI = 0 ms condition ($p = 0.056$), and a significant difference to the AEI = 300 ms condition ($p = 0.002$). In Blocks 2, 3, and 4, there was no significant difference between the AEI = 0 ms and AEI = 100 ms conditions (all $ps > 0.10$), while both the AEI = 0 ms and the AEI = 100 ms conditions were significantly different from the AEI = 300 ms condition (all $ps < 0.005$). The main effect of block was not significant ($F < 1$).

In sum, the most important result regarding the analysis of temporal oculomotor control is that throughout all blocks the long effect delay (AEI = 300 ms) resulted in significantly longer saccade latencies than the short delay (AEI = 100 ms), and at least in three of the four blocks the long effect delay also resulted in significantly longer saccade latencies than the non-delayed (AEI = 0 ms) condition.

4. Discussion

The aim of the present study was to gain insight into the mechanisms underlying A–E learning in the oculomotor domain. Accordingly, we analyzed spatial and temporal parameters of left/right eye movements that contingently triggered location-specific changes in non-social, *inanimate* objects (traffic lights). Spatial aspects were addressed by examining spatial shifts of saccade target locations toward the anticipated location of the visual change, while temporal aspects were addressed by manipulating the temporal effect delay (AEI) and by studying the dynamics of A–E learning over the course of the experiment.

Our results clearly support the hypothesis that action-effect anticipation in oculomotor control is reflected in corresponding spatial

saccade characteristics in inanimate environments, similar to corresponding effects demonstrated in a social context (Herwig & Horstmann, 2011). Participants anticipated the specific change in the target objects and directed their initial saccade landing position toward the location of the anticipated effect (upper/lower lamp of traffic light). A shift in the saccade landing position was already present in the first block of trials (indicating fast buildup of A–E associations) and across all AEI conditions. Thus, the upcoming effect clearly influences saccade planning. This is consistent with the assumption that spatial saccade preparation involves a mental representation of the upcoming effect, even in inanimate environments. These results – together with previous findings in a social context by Herwig and Horstmann (2011) – thus indicate that formation of oculomotor A–E associations can occur in both types of environment (inanimate-nonsocial and animate-social).

Due to our failure to find anticipation effects in schematic face stimuli (see Section 2.5 for details), we were not able to directly compare the spatio-temporal dynamics of A–E learning across the two types of situation (social vs. inanimate). To explicitly address this particular issue, a future study should utilize sets of stimuli that are both natural and highly comparable, for example, with respect to saliency, contrast etc. of the effect.

Furthermore, the present findings extend previous, related observations. For example, Huestegge and Kreutzfeldt (2012) also reported evidence for A–E anticipation in oculomotor control in an inanimate environment, but only with respect to congruency effects evident in saccade RTs, not in terms of spatial oculomotor control (i.e., saccade landing point). Conversely, another recent study already demonstrated effect anticipation evidenced by spatial oculomotor control (Pfeuffer, Kiesel, & Huestegge, 2016). Crucially, in that study the spatial effects were contingent upon manual (not oculomotor) actions, which triggered spatially defined visual effects. Anticipation processes were evidenced by the occurrence of uninstructed anticipatory saccades in direction of the subsequently occurring manual action effects. Despite this important difference to the present study, both studies together confirm that spatial saccade parameters are a very sensitive (and probably more direct) measure of effect anticipation with many advantages over traditional, more indirect measures, like, for example, congruency effects reflected in RTs or percentage of error (PE) measures. These advantages include, inter alia, that anticipatory saccades can serve as a measure of anticipatory processes even in the absence of congruency effects in RTs or PEs. Further, measuring anticipatory saccades might be applied for the assessment of effect anticipation in populations where common RT-based paradigms reach their limits (e.g., clinical patients or young children, cf. discussion in Pfeuffer et al., 2016).

A second important result of the present study is the dependency of action latency on the temporal effect delay (A–E interval) in the oculomotor domain. Especially in the AEI = 300 ms condition participants took more time to initiate their saccade toward one of the lateralized target objects than in the AEI = 0 ms and 100 ms conditions. A similar observation was already reported for manual action control (Dignath et al., 2014), and was interpreted as evidence for the assumption that during the acquisition of action-effect associations actions become not only associated with the subsequent effect but also with the temporal AEI within an event file representation (Hommel et al., 2001). This temporal information is then assumed to be automatically retrieved during action selection, thus affecting latencies (see also Dignath & Janczyk, 2016). Note that in both previous studies on temporal AEI effects the distance in length between short and long AEI (50 ms vs. 2000 ms) was considerably more salient for the participant than in our study, where the difference was rather subtle. Based on the fact that saccade latencies are usually shorter than corresponding manual RTs, it could be that temporal AEI effects scale accordingly. Of course, this proposal has to be empirically addressed by using a broader spectrum of temporal intervals, before further conclusions can be made.

A further observation regarding the temporal AEI effect is that we could not find a clearly significant difference between the 0 ms and 100 ms AEI conditions. We suspect that the 100 ms spacing between these two conditions is too small to eventually affect saccade latencies. Again, this calls for future studies with a broader range of AEI intervals. Despite these limitations of the current data, our results are still in line with the claim of a general mechanism underlying A–E learning by showing that effects of different temporal effect delays can also be observed in other than manual action domains, and that timing information regarding action effects plays a seminal role in the guidance of oculomotor actions.

Finally, a third important set of results is related to the dynamics of action-effect learning. Overall, our results indicate that saccade-effect associations can be easily acquired, since anticipation effects were already present from Block 1 (i.e., the rVLP averaged over the AEI conditions significantly differed from zero in all experimental blocks). This observation is in accordance with previous findings suggesting that only few learning trials are needed to acquire action-effect associations (Dutzi & Hommel, 2009; Pfeuffer et al., 2016). More interestingly, our results also showed that anticipation effects increased over the course of the experiment in the two delayed effect (AEI) conditions (see Herwig & Horstmann, 2011, for a corresponding finding in a setup using a constant delay of 100 ms). A plausible explanation for the result that A–E learning only increased for the delayed effect conditions (but not in the immediate effect condition) might be that the visual change in the target object was less salient in the immediate condition, because the latter involves a display change during the saccade, which is less well perceived due to the well-known phenomenon of saccadic suppression. Thus, in the non-delayed condition, perception of the change must rely on comparing the fixated object with a memory representation of the object prior to its fixation. This mechanism appears to be sufficient to explain a significant anticipation effect in the non-delayed condition already in Block 1. This memory-based source of information is principally also available in the delayed conditions, but here the change additionally provides a salient onset signal during fixation, which should attract even more attention (Enns, Austen, Di Lollo, Rauschenberger, & Yantis, 2001; von Mühlenen, Rempel, & Enns, 2005; Yantis & Jonides, 1984). Probably, this additional source of change information in the delayed conditions takes some time (over several blocks) to fully build up. On a general level, our study further highlights the universality of the ideomotor view of action (Greenwald, 1970; Herbart, 1825; James, 1890) including its underlying principles and mechanisms by demonstrating its applicability not only in the manual domain (Elsner & Hommel, 2001; Kunde, 2001), but also in the oculomotor control domain (Herwig & Horstmann, 2011; Huestegge & Kreutzfeldt, 2012).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.actpsy.2017.09.003.

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