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A Look Into the Future: Spontaneous Anticipatory Saccades Reflect Processes of Anticipatory Action Control

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According to ideomotor theory, human action control uses anticipations of one's own actions' future consequences, that is, action effect anticipations, as a means of triggering actions that will produce desired outcomes (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). Using the response-effect compatibility paradigm (Kunde, 2001), we demonstrate that the anticipation of one's own manual actions' future consequences not only triggers appropriate (i.e., instructed) actions, but simultaneously induces spontaneous (uninstructed) anticipatory saccades to the location of future action consequences. In contrast to behavioral response-effect compatibility effects that have been linked to processes of action selection and action planning, our results suggest that these anticipatory saccades serve the function of outcome evaluation, that is, the comparison of expected/intended and observed action outcomes. Overall, our results demonstrate the informational value of additionally analyzing uninstructed behavioral components complementary to instructed responses and allow us to specify essential mechanisms of the complex interplay between the manual and oculomotor control system in goal-directed action control.

Keywords: anticipation, action effect, action control, eye movement, saccade

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Research on human behavior usually focuses on instructed behavior. That is, participants are told how to respond to experimental stimuli and only the instructed responses are regarded as of interest. However, incidental, uninstructed movements that are performed simultaneously with instructed responses (e.g., speech-accompanying gestures or eye movements), might be an additional source of information regarding ongoing cognitive processes. One type of such uninstructed and often uninvestigated movements are spontaneous eye movements, typically taking place during cognitive tasks regardless of an experimental instruction to move one's eyes.

Here, we want to investigate both instructed manual responses and uninstructed, spontaneous eye movements occurring during goal-directed action. We propose that uninstructed, accompanying movements, such as spontaneous eye movements, may not only reflect cognitive processes that can also be inferred from instructed responses, but may possibly provide additional insights. We will address this question in the area of ideomotor action control, looking at mechanisms allowing humans to act voluntarily according to their behavioral goals.

In recent years, the anticipation of one's own actions' future consequences has been identified as a central mechanism for selecting voluntary actions and controlling actions to realize goals (e.g., Hommel, 2009; Hommel & Elsner, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1981/1890). According to ideomotor action control theory, goal-directed action relies on bidirectional action-effect associations (e.g., Elsner & Hommel, 2001, see Shin, Proctor, & Capaldi, 2010, for a review). These associations are incidentally formed when actions are observed to consistently evoke effects (Elsner & Hommel, 2001). Effects can be both proximal sensory changes as well as distal changes in the environment (e.g., Elsner & Hommel, 2001; Hommel, 2009). Once action-effect associations have been formed, the anticipation of a desired consequence triggers associated action, thus, realizing the goal (e.g., Hommel, 2009).

The response-effect (R-E) compatibility paradigm (Koch & Kunde, 2002; Kunde, 2001, 2003; Pfister, Kiesel, & Melcher, 2010) provides the opportunity of assessing the development of action effect anticipation via its behavioral consequences. In Kunde's (2001) study four spatially aligned responses were paired with four spatially presented action effect stimuli. Crucially, the spatial mapping of responses and effects was R-E compatible (left response ▸ action effect on the left side) in one half of the experiment and R-E incompatible (left response ▸ action effect on the right side) in the other half of the experiment. Kunde observed that reaction times (RTs) were shorter for R-E compatible in comparison with R-E incompatible mappings, suggesting that ac-

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tion effects had been anticipated before action, because stimuli that occurred after the action could only have influenced its execution by being anticipated beforehand.

Yet, current behavioral measures of action effect anticipation allow only a very indirect assessment of effect anticipation over a course of multiple trials via averaging. The same holds true for electroencephalogram (EEG; e.g., Band, van Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; Nikolaev, Ziessler, Dimova, & van Leeuwen, 2008; Waszak & Herwig, 2007), positron emission tomography (PET; Elsner et al., 2002), and functional magnetic resonance imaging (fMRI; e.g., Kühn, Seurinck, Fias, & Waszak, 2010; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008; Pfister, Melcher, Kiesel, Dechent, & Gruber, 2014) correlates of anticipation. Presently, there is no online measurement of action effect anticipation within a given trial. We propose that spontaneous eye movements triggered during the process of action effect anticipation might provide such an online measurement.

So far, action effect anticipation in eye movements has only been studied for saccades as a substitute of manual responses (Herwig & Horstmann, 2011; Huestegge & Kreutzfeldt, 2012; Verschoor, Spapé, Biro, & Hommel, 2013). In these settings, for instance, eye-movement latencies were used as an alternative means of assessing RT, but did not provide a direct assessment of anticipation on a single-trial basis. For instance, Herwig and Horstmann (2011), in a learning phase, had their participants perform saccades toward one of two neutral faces presented on the left and right side of the screen. A saccade toward the left contingently turned the neutral face into a smiling one and a saccade toward the right made the face frown. In a subsequent test phase, the smiling or frowning faces appeared in the middle of the screen and participants had to either perform saccades to the location previously associated with the respective face (R-E compatible) or toward the opposite location (R-E incompatible). Replicating R-E compatibility studies using manual responses, Herwig and Horstmann (2011) found the latency of saccades toward R-E incompatible locations to be prolonged in comparison with saccades toward R-E compatible locations.

We, however, suggest that eye movements might serve beyond being mere replacements of manual responses. When we act to reach a goal, that is, to produce an effect in the environment, we shift attention toward the location of the expected effect. For instance, when pointing or performing other spatially oriented movements, humans are known to shift their attention toward the spatial location of their movements' end points (goal locations); thus, facilitating the processing of stimuli appearing at these locations (e.g., Baldauf & Deubel, 2009; Baldauf, Wolf, & Deubel, 2006; see also Thomaschke, Hopkins, & Miall, 2012). This shift of visual attention is not restricted to a vague directional shift, but can also be exhibited toward specific goal locations. Here, we extend the notion of action-related shifts in visual attention to include distal effects of own actions, that is, visual stimuli produced by own manual actions. We propose that when we act to reach a goal, that is, to produce changes in the environment, not only is visual attention shifted toward the location of environmental effects we produce, but the shift in visual attention is also accompanied by saccades toward these self-produced effects. Crucially, we hypothesize that if an action predictably produces an effect in the environment, eye movements toward the location of the expected effect might occur before the actual onset of the effect. Such anticipatory saccades, that is, saccades to the location of an expected effect that occur before effect onset, would not only indicate that the actor anticipated the effect, supporting ideomotor theory, but also provide an online measure for action effect anticipation within a single trial.

Evidence in favor of this idea comes from studies on *stimulus-based* anticipatory processes and their reflection in eye movements. For instance, monkeys pressing buttons according to illuminated target positions in a grid that followed a predictable sequence started to exhibit anticipatory saccades in the direction of future target positions after some practice (Miyashita, Rand, Miyachi, & Hikosaka, 1996). Moreover, 3.5-month old infants have been shown to demonstrate anticipatory fixations when a series of stimuli are displayed in predictable sequence (Haith, Hazan, & Goodman, 1988) and adults viewing natural dynamic scenes exhibit anticipatory eye movements toward future changes in the scene (Vig, Dorr, Martinetz, & Barth, 2011). Furthermore, oculomotor studies on everyday activities such as driving (Land & Lee, 1994), walking (Patla & Vickers, 1997), and playing cricket (Land & McLeod, 2000) have demonstrated that we actively use anticipatory gazes toward expected stimulus positions to gather environmental information and to control upcoming actions. For instance, when performing everyday action sequences like preparing tea (Land, Mennie, & Rusted, 1999) or making a peanut butter and jelly sandwich (Hayhoe, 2000) our gaze anticipatorily moves toward the objects we will next interact with while we are still engaged with the preceding steps of the action sequence (Land & Hayhoe, 2001).

Such anticipatory eye movements, used for guiding upcoming actions, are thought to proactively serve the monitoring functions of locating objects for future use (*locating*), moving our gaze toward objects we are about to interact with to obtain position information (*directing*), guiding the movements of multiple objects (*guiding*), and checking whether necessary preconditions for future actions are met (*checking*; Land & Hayhoe, 2001; Land et al., 1999; for an overview see Land, 2006, 2009). As anticipatory eye movements in these situations are nearly always focused on task-relevant objects, they seem to be primarily guided by top-down processes in contrast to bottom-up processes like object salience (Land & Hayhoe, 2001). In all these studies, anticipatory eye movements in relation to subsequently occurring stimuli seemed to coincide with the planning and control of own actions.

Crucially, research of anticipatory eye movements so far has either exclusively focused on *stimulus-based* anticipations (i.e., when anticipations are not directly associated with one's actions) or the used paradigms did not allow for cleanly disentangling possible sources of anticipation. For instance, in studies on purely *stimulus-based* anticipatory processes (e.g., Haith et al., 1988), stimuli occurred in a predictable sequence or according to predictable patterns allowing participants to predict ensuing stimuli. In these studies, stimulus occurrence and/or position could not be inferred from own actions. On the other hand, for instance, in studies on anticipatory eye movements during everyday activities (e.g., Hayhoe, 2000; Land et al., 1999), various types of anticipatory processes may have caused the observed anticipatory eye movements. Participants could either have performed anticipatory eye movements because of *stimulus-based* anticipations or *action-based* anticipations. For instance, when making tea, because of

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their prior experience with this action sequence, participants could either have anticipated the sequence of stimuli they would interact with via stimulus-stimulus associations (*stimulus-based* anticipation), anticipatorily guiding their gaze toward the next relevant stimuli, or they could have anticipated the sequence of actions they would have to perform (*action-based* anticipation) via response-response associations, leading participants to direct their gaze toward the goal locations of their ensuing movements. More importantly, it is also possible that participants built up *goal-directed action-based* anticipations in these situations that were based on action-effect associations, that is, participants might have anticipated the predictable consequences of their actions and anticipatorily guided their gaze toward these action effects. The idea that action effect anticipation not only takes place during action sequences, but is also crucial for learning sequential actions, is supported by the finding that the learning of event sequences in a serial reaction task is primarily based on response-stimulus associations (i.e., action-effect associations) and not on stimulus-stimulus or response-response associations (Ziessler & Nattkemper, 2001). Here, we aim to develop a basic paradigm that will allow us to systematically study anticipatory eye movements based on action-effect associations in goal-directed action independent from other stimulus-based or action-based processes of anticipation. Specifically, we aim to focus on anticipatory eye movements toward the future location of self-produced environmental effects. Further, we intend to examine anticipatory eye movements in a setting that is devoid of prior knowledge about action-effect contingencies to investigate the development of such spontaneous anticipatory eye movements. Finally, we want to assess the functional relation of effect-generating manual actions and spontaneous anticipatory saccades.

The assumed checking function of anticipatory eye movements in everyday action sequences (e.g., Land, 2006, 2009) already points in the direction of action effect-related anticipatory saccades, as the necessary preconditions participants had to check for were, naturally, the consequences produced by their preceding actions. Further indication of goal-directed anticipatory action control comes from the previously mentioned study of Herwig and Horstmann (2011) in which participants' left and right saccades made formerly neutral faces in the periphery smile or frown. An interesting find was that effect-producing saccades in this experiment landed closer to the mouth/eye-brow region of the neutral face when their saccade would produce a smile/frown, respectively. Herwig and Horstmann (2011) interpreted this as evidence in favor of action effect anticipation, but did not conduct more detailed, systematic analyses.

Based on these findings, here, we aim to develop a paradigm that allows for the study of processes of action effect anticipation while they are occurring. We intend to establish an online single-trial measure of anticipatory processes, that is, anticipatory saccades, because of *goal-directed action-based* anticipation. We assume that goal-directed movements are accompanied by spontaneous anticipatory saccades directed toward the location of anticipated future action consequences. These uninstructed anticipatory saccades will provide us with a more detailed insight into the underlying processes of ideomotor action control.

If we observed such spontaneous anticipatory saccades, directed toward the position of future action consequences, two possible functional relation between these anticipatory saccades and manual actions are conceivable. Either anticipatory saccades, like manual actions, reflect the influence of action effect anticipation on processes connected to action selection and action planning, or anticipatory saccades are linked to outcome evaluation (see Band et al., 2009; Verschoor et al., 2013). Whereas ideomotor theories of action control are mainly concerned with the mechanisms by which action-effect associations are formed and goal-directed action is generated (thus, investigating action production via outcome anticipation), cybernetic comparator models (e.g., Frith & Wolpert, 2000; Wolpert & Flanagan, 2001; Wolpert & Ghahramani, 2000) investigate the adjustment of motor actions via a comparison of intended and actual effects of own actions (Hommel, in press b). Ideomotor and comparator models are complementary in that action selection and action outcome evaluation might represent two distinct functional aspects of one common, underlying anticipatory process that emerges from learned action-effect associations (Chambon, & Haggard, 2013; Hommel, in press a). Thus, the same underlying mechanism (action effect anticipation) may be conveyed in two functionally distinct behavioral aspects. Hence, if anticipatory saccades are mainly linked to action selection, both manual and oculomotor measures of anticipation should be strongly correlated. However, if eye movements rather serve distinct outcome evaluation purposes, corresponding anticipation-based effects can be relatively independent from those in manual responses.

In this context, it has to be noted that the classic manual response-effect compatibility effect (Kunde, 2001) does not directly measure whether response effects are anticipated but rather reflects whether such mentally anticipated stimuli display characteristics akin to those observed for actually presented stimuli, such as spatial stimulus-response compatibility effects (e.g., Proctor & Vu, 2006). Thus, the absence of response-effect compatibility effects in manual RTs does not necessarily imply the absence of effect anticipation, which might be more directly reflected in anticipatory saccades toward future spatial effect locations. As such, effects observed in manual responses are principally dissociable from effects observed in saccade frequencies. Anticipatory processes reflected in saccade frequencies could, therefore, either be linked to a process of action selection (suggesting the functional equivalence of anticipatory processes reflected in manual responses and saccade frequencies) or to a process of outcome evaluation that functionally dissociates from the action selection process reflected in manual R-E compatibility effects.

To test our assumptions regarding anticipatory saccades in goal-directed action control, we conducted three experiments applying the R-E compatibility paradigm with manual key presses serving as instructed responses (see Figure 1A for the trial structure of Experiment 1). In all three experiments, we systematically varied the spatial R-E compatibility between actions (left vs. right key presses) and their subsequent visual effects (colored circles appearing on the left vs. right side) and measured the occurrence of anticipatory, that is, effect-congruent (SACC-E congruent; e.g., saccade to the right preceding an effect on the right), and counteranticipatory, that is, effect-incongruent (e.g., saccade to the right preceding an effect on the left), saccades (see Figure 1B for a graphical description). We hypothesized that action effect anticipation would be reflected in a substantial amount of anticipatory (i.e., effect-congruent) saccades. More specifically, we predicted that before the occurrence of an action effect, participants would

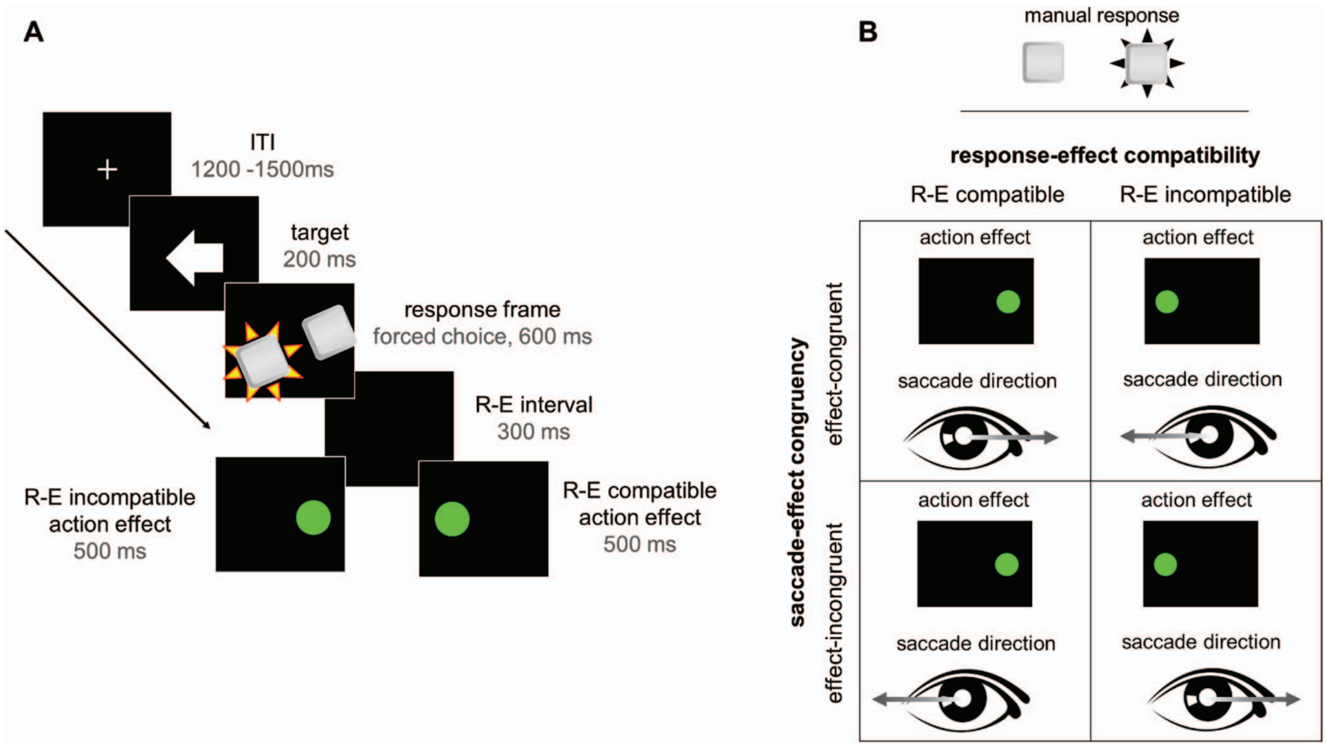

Figure 1. (A) Structure of Experiment 1: A forced-choice target is followed by a blank screen response frame. Participants' left/right responses reliably triggered a lateralized action effect on the left or right side that ensued after a fixed response-effect (R-E) interval. Actions and their effects were response-effect (R-E) compatible in one half of the experiment and R-E incompatible in the other half. Trials were separated by a variable intertrial interval (ITI). (B) Graphical description of the experimental conditions response-effect (R-E) compatibility (R-E compatible vs. R-E incompatible) and saccade-effect (SACC-E) congruency (effect-congruent vs. effect-incongruent). See the online article for the color version of this figure.

look significantly more often to the location of a subsequently appearing action effect than in the opposite direction, a pattern that we expected to observe in both R-E compatible and R-E incompatible conditions. Furthermore, in an exploratory analysis, we wanted to gain first insights into the temporal dynamics of anticipatory saccades in action control. Finally, two aspects of the study allow us to test whether anticipatory saccades are based on the same underlying mechanism (namely, action-based effect anticipation) as manual actions in the R-E compatibility paradigm. First, the inclusion of action-effect incompatible conditions (and nondirectional stimuli in Experiments 2 and 3) helps ruling out that anticipatory saccades are solely driven by stimulus features (e.g., leftward saccades triggered by arrows pointing to the left). Second, a free choice experiment (without action-defining stimuli) was included to exclude that oculomotor anticipations are based on stimulus-effect (instead of action-effect) associations (Experiment 2).

Experiment 1

Experiment 1 served as a first exploratory attempt to assess spontaneous anticipatory saccades in the context of action effect anticipation. In a forced-choice setting, participants performed left and right key presses that systematically triggered spatially corresponding (R-E compatible) action effects in one half of the experiment and spatially noncorresponding (R-E incompatible) action effects in the other half. To facilitate action selection as much as possible and to enhance the chance of observing early saccades even before action initiation, we used left and right arrows as targets signaling the to-be-performed response. Please note that all reported saccades occurred spontaneously in that participants did not receive any instructions or information regarding their eye movements before the experiment. Instead they were merely told to attend to the stimuli and to respond fast and accurately.

Method

Participants. Twenty-two participants (7 men, 1 left-handed, mean age = 21.8 years) were recruited and participated for course credit. All participants had normal or corrected to normal vision. The study was conducted in adherence to the standards set by the local ethics committee. Three participants had to be excluded because of problems with tracking their eye movements (tracking was repeatedly lost, for instance, because of reflections on participants' contact lenses or glasses, so that eye movements could not be reliably assessed or validation procedures revealed reoccurring deviations of more than 1.0° visual angle), resulting in a sample of 19 participants for analyses. Note that because of the reduced sample, counterbalancing of the sequence of R-E compatibility conditions (see below) was imperfect (the group starting with the R-E incompatible condition included one

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surplus participant). This however, did not endanger the interpretation of the results (see results section for details).

Apparatus. Participants sat approximately 60 cm from a 19" CRT screen (1,024 pixels × 768 pixels, 60 Hz) in a dimly lit, sound attenuated laboratory room. The index fingers of their left and right hands rested on a left and right key. The experiment was run via SR Research Experiment Builder (version 1.10.1025).

We used the Eye Link 1000 Desktop Mount (SR Research Ltd., Ontario, Canada) for eye movement tracking. Corneal reflection and pupil diameter were measured via an infrared camera and eye movements (right eye) were sampled at 1000 Hz with a spatial resolution of 0.01° visual angle. Calibration and validation were performed before the beginning of each block.

Design and procedure. The screen background was black throughout the experiment. Experimental trials began with a variable intertrial interval of 1,200 to 1,500 ms during which a white fixation cross (0.6° visual angle) was presented centrally (see Figure 1 for trial structure). The intertrial interval (ITI) was jittered to decrease the temporal predictability of target stimuli. By this, we aimed to discourage participants from preparing manual responses before target presentation. The fixation cross was then substituted by a target (response signal), a white arrow (1.9° visual angle, 200 ms) pointing either to the right or left side, and participants were instructed to press the key spatially corresponding to the direction of the target as fast as possible while avoiding errors. Please note that key presses were to be performed upon target offset to ensure that no visual stimulus was present during responding. This was done to enable us to assess anticipatory saccades already during action preparation. Both directions of arrow targets occurred equally often. The brief target stimulus duration was chosen, because we reasoned that the occurrence of uninstructed saccades would be less likely while a stimulus was still present at the screen center. The target was substituted by a blank screen response frame terminated upon response and presented for 600 ms at maximum. Correct responses (left vs. right key presses) were followed by another blank screen response-effect (R-E) interval of 300 ms before the action effect ensued and remained on screen for 500 ms. Action effects (2.8° visual angle) were red and green circles appearing left versus right of the center of the screen at about 9.3° visual angle. Action effect colors contingently followed responses (e.g., left key presses were always associated with a green action effect circle) whereas action effect position varied between the first and second half of the experiment. Although the color manipulation was not a necessary design feature, we reasoned that its inclusion might, to some extent, distract participants from selectively focusing on spatial effects of their actions only (given that in the real world action effects are usually multidimensional). Action effects appeared spatially compatible to responses (R-E compatible: e.g., left manual response ▸ action effect on the left side) in one half of the experiment and spatially incompatible (R-E incompatible: e.g., left manual response ▸ action effect on the right side) in the other half. R-E Compatibility order and action effect color assignment were counterbalanced across subjects. Participants were not informed about the switch in R-E compatibility. Premature and incorrect responses as well as response omissions triggered appropriate feedback (premature response: "zu früh"/"too early," incorrect response: "Fehler!"/"error!," response omission: "zu langsam!"/"too slow!," 1,000 ms) and the trial was aborted. The structure of practice trials was equivalent, but practice trials did not feature action effects.

The experiment consisted of one practice block of 16 trials and 10 experimental blocks of 50 trials each. Participants were neither informed about the initial R-E compatibility nor alerted to the change in R-E compatibility at the midpoint of the experiment. At the end of each block, participants had the opportunity to take a self-paced break.

Participants were instructed to respond as fast and accurately as possible. Furthermore, they were informed that colored circles, that is, the action effect stimuli, would appear following their key press. They were instructed to pay attention to these colored circles. Crucially, instructions did not contain any information regarding eye movements. We can therefore assume that all eye movements before the onset of the action effect occurred spontaneously.

Preprocessing of saccade data. For the saccade analyses of all three experiments, saccades were detected according to a combined velocity (30°/s), motion (0.1°), and acceleration (8,000°/s^2) threshold. Furthermore, for the analyses of possible anticipatory saccades, we only included saccades occurring during the interval between target offset (i.e., the signal to respond) and action effect onset. Saccades occurring during target presentation were excluded. Note that as the target was presented for 200 ms and participants could already select and prepare responses during target presentation, we may not have been able to detect very early anticipatory saccades in Experiment 1. Furthermore, to assess the temporal relation of manual (i.e., effect-generating) actions and saccades we divided the interval between target offset and action effect onset into a preresponse and postresponse segment.

For the analyses of possible anticipatory saccades, we aimed for a conservative strategy and counted only saccades that fulfilled several criteria to be regarded as systematic saccades in either effect-congruent or effect-incongruent direction. Saccades occurring in trials with premature or incorrect responses as well as saccades occurring in trials with response omissions were not counted as systematic saccades (equivalent to 32 saccades from a total of 7,663 saccades that occurred during the action effect anticipation interval across all participants). Only saccades that started during the action effect anticipation interval and at fixation (±30 pixels/1.1° visual angle) were counted as systematic (1,789 from a total of 7,630 saccades, 23.4%, were not considered because of this criterion). We only analyzed saccades that crossed at least one-third of the distance between saccade starting point and action effect center (additional 909 from a total of 7,630 saccades, 11.9%, were not considered) to ascertain that all detected and reported saccades were systematically initiated and not just small unsystematic saccades within the area of the central fixation cross. For instance, saccades starting exactly at fixation had to cross a distance of at least 3.1° visual angle (i.e., one-third of the distance between fixation and the action effect at 9.3° visual angle) to be regarded as sufficiently long. Moreover, we did not count saccades that occurred in a trial that contained both effect-congruent and effect-incongruent saccades (181 of 7,630 saccades, 2.4%), as we could not draw any clear inferences regarding the processes underlying these trials. Finally, we only counted saccades that occurred in a trial that either contained only preresponse saccades or only postresponse saccades to clearly distinguish the effects of these saccade types (68 of 7630 saccades, 0.9%, were not considered because of this criterion). Overall, after all preprocessing steps 61.4% of all saccades were counted as systematic saccades in our analyses. Please note that to estimate the relative frequency of trials with saccades (effect-congruent or effect-incongruent) we did not exclude trials that con-

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tained unclear, noncountable saccades, but we considered these trials as nonsaccade trials. Our rather conservative preprocessing criteria were applied to support unequivocal conclusions regarding our result patterns, but simultaneously may have led to an underestimation of the actual frequency of anticipatory saccades. Post hoc analyses, which also included saccades with short amplitudes as well as saccades that did not start at the central fixation cross, showed that, for all three experiments, the overall pattern of results remained the same as reported below.

Results

Manual RTs and error rates. Trials with premature responses (about 0.1%) and manual response omissions (about 0.7%) were excluded. For the error analysis, the percentage of error trials (PE) was computed separately for R-E compatible and R-E incompatible trials. For the RT analysis, trials with incorrect responses were excluded. Note that the inclusion of trials in the RT and PE analyses was independent of whether these trials contained saccades that did not fulfilled the saccade preprocessing criteria. RTs deviating by more than 3 *SD*s from their individual cell means were deemed as outliers and excluded from RT analysis. R-E compatibility effects in PEs and RTs were determined via paired *t* tests.

The mean manual RT, measured from target offset, was 165 ms and the mean error rate was 2.0%. Participants responded faster and made less errors in R-E compatible blocks (RT: 153 ms, PE: 1.6%) than in R-E incompatible blocks (RT: 178 ms, PE: 2.5%), RT: $t(18) = 3.70$, $p = .002$, $d = 0.85$; PE: $t(18) = 2.84$, $p = .011$, $d = 0.65$.[1] Additionally, the R-E compatibility effect was influenced by RT percentile, but remained significant for all RT percentiles (see Online Supplemental Material).

Moreover, separate 2 × 5 repeated measures analysis of variances (ANOVAs) with the within-subject factors R-E compatibility (R-E compatible vs. R-E incompatible) and trial block (1–5) were conducted for RTs and PEs. For RTs, this analysis revealed a significant main effect of R-E compatibility, $F(1, 18) = 13.77$, $p = .002$, $\eta_p^2 = .43$, with longer RTs in R-E incompatible compared with R-E compatible trials. The main effect of trial block failed to reach significance, $F < 1$. The interaction between R-E compatibility and trial block was significant, $F(4, 72) = 3.04$, $p = .023$, $\eta_p^2 = .14$. Subsequent paired *t* tests showed that the R-E compatibility effect was significant for all but the first block, block 1: $t(18) = 1.82$, $p = .086$, $d = 0.42$, block 2: $t(18) = 2.80$, $p = .012$, $d = 0.64$, block 3: $t(18) = 3.19$, $p = .005$, $d = 0.73$, block 4: $t(18) = 4.03$, $p = .001$, $d = 0.92$, block 5: $t(18) = 3.78$, $p = .001$, $d = 0.87$. Thus, these results are in line with the assumption that participants first have to learn the R-E mapping contingencies before the anticipation of the effect location can induce compatibility effects.

An equivalent analysis for PEs revealed a significant main effect of R-E compatibility, $F(1, 18) = 8.05$, $p = .011$, $\eta_p^2 = .31$, with larger error rates for R-E incompatible than for R-E compatible trials. The main effect of trial block, $F < 1$, and the interaction of R-E compatibility and trial block, $F(4, 72) = 1.50$, $p = .212$, $\eta_p^2 = .08$, failed to reach significance.

Anticipatory saccades. The mean saccade latency, measured from target offset, was 248 ms. The average saccade amplitude was 6.57° visual angle. The average saccade velocity amounted to 123.8° visual angle per second.

We assessed the emergence of anticipatory (i.e., effect-congruent) saccades by computing the percentage of trials in which saccades took place and by comparing the relative frequency of trials with effect-congruent and effect-incongruent saccades. Note that an equal amount of effect-congruent and effect-incongruent saccades would indicate a lack of spatial action effect anticipation, whereas significantly more effect-congruent than effect-incongruent saccades indicate successful anticipation. To further examine the time course of effect-related (effect-congruent/effect-incongruent) anticipatory saccades over the entire experiment we assessed the relative frequency of saccade trials separately for each block. Finally, we differentiated between saccades in R-E compatible and R-E incompatible R-E conditions. This resulted in the factors SACC-E congruency (trials involving effect-congruent vs. effect-incongruent saccades), R-E compatibility (R-E compatible vs. R-E incompatible), and trial block (trial numbers 1–50 vs. 51–100 vs. 101–150 vs. 51–200 vs. 201–250). A corresponding 2 × 2 × 5 Repeated Measures ANOVA was used to assess the emergence of anticipatory saccades. Significant factor interactions were further analyzed using appropriate Repeated Measures ANOVAs or paired *t* tests. Greenhouse-Geisser correction was applied where appropriate.

The analysis of the relative frequency of saccades revealed a significant main effect of SACC-E congruency, $F(1, 18) = 63.03$, $p < .001$, $\eta_p^2 = .78$. Effect-congruent saccades (44.0% of trials) occurred significantly more often than effect-incongruent saccades (2.2% of trials; see Figure 2A for relative saccade frequencies). Furthermore, we found a significant main effect of R-E compatibility, $F(1, 18) = 13.70$, $p = .002$, $\eta_p^2 = .43$, with saccades occurring more frequently in R-E compatible trials than in R-E incompatible trials. Additionally, SACC-E congruency and R-E compatibility significantly interacted, $F(1, 18) = 17.76$, $p = .001$, $\eta_p^2 = .50$. The frequency difference between effect-congruent and effect-incongruent saccades was more pronounced in the R-E compatible condition, $t(18) = 9.36$, $p < .001$, $d = 2.15$, compared to the R-E incompatible condition, $t(18) = 5.58$, $p < .001$, $d = 1.28$. Moreover, we found a significant main effect of trial block, $F(4, 72) = 4.65$, $p = .008$, $\eta_p^2 = .21$, with relative saccade frequencies rising with increasing trial block. SACC-E congruency and trial block significantly interacted, $F(4, 72) = 6.19$, $p = .002$, $\eta_p^2 = .26$. Saccade frequency significantly increased over time for effect-congruent saccades, $F(4, 72) = 5.53$, $p = .004$, $\eta_p^2 = .24$, but did not change for effect-incongruent saccades, $F(4, 72) < 1$. All other interactions failed to reach significance, $Fs < 1$.[2]

[1] To ensure that these effects were not driven by the imperfect counterbalancing in Experiment 1, we computed separate *t* tests for all permutations of equal participant distributions ($N = 18$, 9 R-E compatible first, 9 R-E incompatible first). For both RT and PE analyses, this resulted in significant effects of R-E compatibility for all permutations, RT: $ts(17) \geq 3.38$, $ps \leq .004$, $ds \geq 0.80$, PE: $ts(17) \geq 2.64$, $ps \leq .017$, $ds \geq 0.62$.

[2] The pattern of results did not change when controlling for the imbalance in the number of participants across R-E compatibility order conditions. The main effect of SACC-E congruency was significant for all counterbalanced permutations of participants ($N = 18$), $Fs \geq 55.50$, $ps \leq .001$, $\eta_p^2 \geq .77$. Similarly, the main effect of R-E compatibility, $Fs \geq 11.37$, $ps \leq .004$, $\eta_p^2 \geq .40$, and the interaction of SACC-E Congruency and R-E compatibility, $Fs \geq 15.16$, $ps \leq .001$, $\eta_p^2 \geq .47$, were significant for all permutations. Furthermore, the main effect of trial block, $Fs \geq 3.73$, $ps \leq .008$, $\eta_p^2 \geq .18$, and the interaction of SACC-E congruency and trial block, $Fs \geq 5.03$, $ps \leq .006$, $\eta_p^2 \geq .23$, were significant for all permutations. All other effects failed to reach significance, $Fs \leq 1.61$, $ps \geq .181$, $\eta_p^2 \leq .09$.

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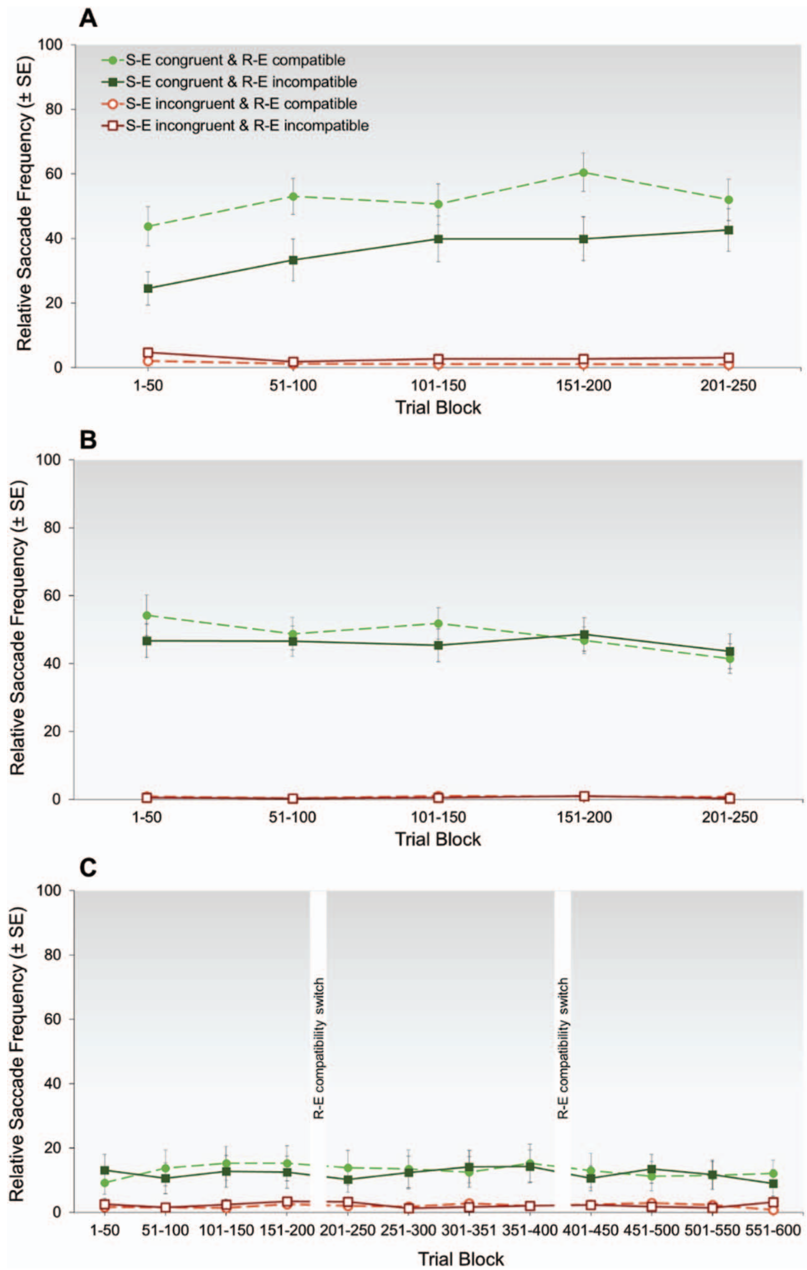

Figure 2. Relative saccade frequency in (A) Experiment 1, (B) Experiment 2, and (C) Experiment 3 as a function of saccade-effect (SACC-E) congruency (effect-congruent vs. effect-incongruent), response-effect (R-E) compatibility (R-E compatible vs. R-E incompatible), and trial block. Error bars indicate *SE*s. Frequencies are displayed relative to the total number of trials. R-E compatible and R-E incompatible saccade trials can each reach 100%. See the online article for the color version of this figure.

To further assess whether anticipatory saccades were already present very early at the beginning of the experiment or after a switch in R-E compatibility (thus, after a few trials of experiencing the R-E mappings), we conducted a 2 × 2 Repeated Measures ANOVA with the factors SACC-E congruency and R-E compatibility for the first R-E compatible and R-E incompatible block, respectively. Like the overall analysis, this analysis revealed main effects of both SACC-E congruency, $F(1, 18) = 40.35$, $p < .001$, $\eta_p^2 = .69$, and R-E compatibility, $F(1, 18) = 6.09$, $p = .024$, $\eta_p^2 = .25$. Effect-congruent saccades were significantly more frequent than effect-incongruent saccades and saccades overall were significantly more frequent in R-E compatible blocks. Furthermore, we found a significant interaction between SACC-E congruency and R-E compatibility, $F(1, 18) = 12.55$, $p = .002$, $\eta_p^2 = .41$. Effect-congruent saccades were significantly more frequent than effect-incongruent saccades for both R-E compatible blocks, $t(18) =$

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6.46, $p < .001$, $d = 1.48$, and R-E incompatible blocks, $t(18) = 4.02$, $p = .001$, $d = 0.92$, with the frequency difference between effect-congruent and effect-incongruent saccades being significantly more pronounced in R-E compatible blocks.

Finally, to explore the temporal dynamics of the observed anticipatory saccades, we conducted a 2 × 2 Repeated Measures ANOVA with the factors SACC-E congruency and R-E compatibility on saccade latencies. Please note that the overall frequency of effect-incongruent trials was very low and only 16 participants who provided trials in every cell were included in this analysis. Thus, these findings should be interpreted cautiously.

The analysis of saccade latencies revealed a nonsignificant trend regarding the main effect of SACC-E congruency, $F(1, 15) = 4.033$, $p = .063$, $\eta_p^2 = .21$, with effect-incongruent saccades ($M = 239$ ms) tending to occur earlier than effect-congruent saccades ($M = 274$ ms). Furthermore, the main effect of R-E compatibility, $F(1, 15) = 5.90$, $p = .028$, $\eta_p^2 = .28$, and the interaction of SACC-E congruency and R-E compatibility, $F(1, 15) = 7.76$, $p = .014$, $\eta_p^2 = .34$, reached significance. Overall, saccades on R-E compatible trials were initiated faster (mean R-E compatible = 239 ms vs. mean R-E incompatible = 275 ms), yet only effect-congruent, $t(15) = 6.26$, $p < .001$, $d = 1.44$ (mean R-E compatible = 246 ms vs. mean R-E incompatible = 303 ms), but not effect-incongruent, $t(15) = 0.18$, $p = .857$, $d = 0.05$ (mean R-E compatible = 233 ms vs. mean R-E incompatible = 246 ms), saccades showed faster latencies for R-E compatible trials in comparison with R-E incompatible trials. Figure 3 illustrates saccade latencies by displaying saccade frequencies as a function of latency with trial time divided into 50 ms bins (ranging from 600 ms preresponse, 600 ms being the maximum RT limit, to 300 ms postresponse, the occurrence of the action effect). 88.3% of the observed saccades occurred after participants' manual actions, whereas 11.7% of the observed saccades occurred before manual actions.

Correlations. Furthermore, we correlated participants' mean manual RT and mean saccade latency for trials with effect-congruent (i.e., anticipatory) saccades. Participants' manual RTs and saccade latencies did not significantly correlate, $r = .182$, $p = .456$. To further investigate the relation between manual RTs and saccade latencies in trials with effect-congruent saccades we correlated these measures on a trial basis *within* participants, separately for R-E compatible and R-E incompatible trials. A subsequent one sample t test showed that participants' mean correlations (R-E compatible condition: mean $r = .204$, R-E incompatible condition: mean $r = .162$; means based on Fisher's z transformation procedure) significantly differed from zero, R-E compatible: $t(18) = 4.43$, $p < .001$, $d = 1.02$; R-E incompatible: $t(18) = 2.56$, $p = .020$, $d = 0.59$.

Moreover, to assess whether anticipatory processes reflected in manual R-E compatibility effects and SACC-E congruency effects were interrelated, we correlated participants' individual R-E compatibility effects on manual RTs ($RT_{\text{R-E incompatible}} - RT_{\text{R-E compatible}}$) and their SACC-E congruency effects on saccade frequencies ($F_{\text{effect-congruent}} - F_{\text{effect-incongruent}}$). We found no significant correlation between participants' manual R-E compatibility effects and their SACC-E congruency effects, $r = .264$, $p = .276$. Finally, we correlated R-E compatibility effects in manual RTs and R-E compatibility effects in saccade frequencies ($F_{\text{R-E compatible}} - F_{\text{R-E incompatible}}$). Manual and saccadic R-E compatibility effects did not significantly correlate, $r = -0.064$, $p = .793$.

Discussion

Experiment 1 investigated whether a predictable action-effect setting induces spontaneous anticipatory saccades in the direction of an actor's own actions' future consequences. To this end, we used a spatial R-E compatibility paradigm with left and right manual actions triggering left and right action effects that were spatially compatible to the actions (R-E compatible) in one half of the experiment and spatially incompatible (R-E incompatible) in the other half.

Results revealed slower RTs and higher error rates in R-E incompatible blocks compared with R-E compatible blocks, indicating that participants indeed anticipated their own actions' future consequences and that the spatial characteristics of these anticipations affected action control (in terms of a spatial R-E compatibility effect). This finding replicates previous studies on action effect anticipation using the R-E compatibility paradigm (e.g., Koch & Kunde, 2002; Kunde, 2001, 2003).

More importantly, this action effect anticipation is directly mirrored in participants' eye movements. In line with our predictions, we demonstrated that effect-congruent saccades were significantly more frequent than effect-incongruent saccades during the temporal interval between target presentation and effect onset, showing that participants successfully predicted the occurrence of their actions' effects and, therefore, directed their gaze in the direction of future self-caused environmental changes. Furthermore, anticipatory saccades already occurred during the very first block of trials and quickly reemerged after a change in R-E compatibility. These results are in line with findings showing that even a very small number of prior action-effect pairings is sufficient for action effect anticipation to emerge (Dutzi & Hommel, 2009).

An interesting find was that neither SACC-E congruency effects nor R-E compatibility effects in saccade frequencies significantly correlated with R-E compatibility effects in manual RTs. These findings suggest that the observed anticipatory saccades, in contrast to the effects underlying manual action control, might not be functionally linked to action selection, but to outcome evaluation and effect-monitoring purposes, even though both processes are to some (minor) extent temporally coordinated, as evidenced by the significant *within*-participant correlations between manual and saccade latencies.

At first sight, one might argue that the observed saccades to the left and right might as well have been triggered in a bottom-up fashion by the target stimuli that were arrows pointing to the left or right. However, this potential mechanism clearly cannot account for the larger number of effect-congruent saccades in comparison with effect-incongruent saccades in R-E incompatible blocks in which the directions of the target/response and effect were opposite.

Furthermore, we found that effect-congruent saccades were significantly more frequent in R-E compatible blocks in comparison to R-E incompatible blocks. This finding mirrors the manual RT and error rate results and suggests that the anticipation of R-E incompatible action consequences might be more demanding than the anticipation of R-E compatible action consequences. Yet, there is also an alternative explanation. As mentioned before, the target

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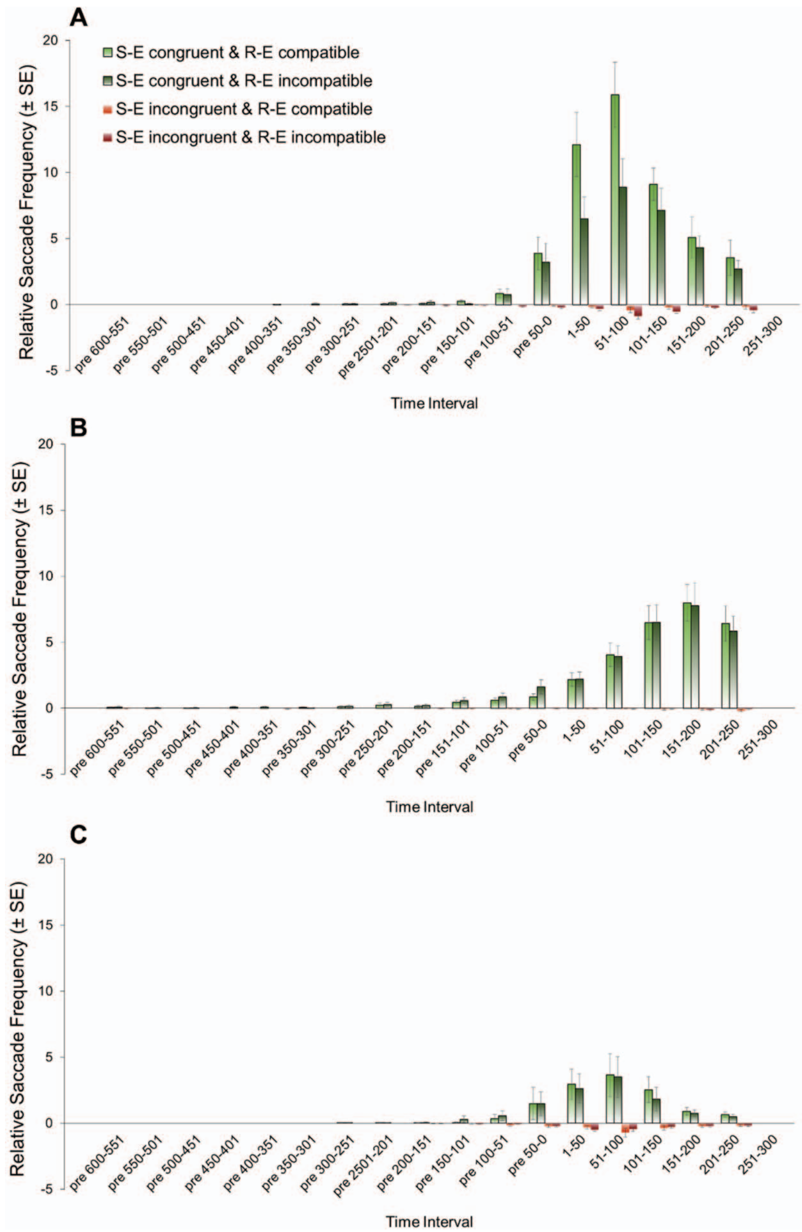

Figure 3. Relative saccade frequency as a function of saccade time interval in (A) Experiment 1, (B) Experiment 2, and (C) Experiment 3 depicted as a function of SACC-E congruency and R-E compatibility. Results are displayed locked to the manual response occurring at 0 ms. Error bars indicate *SE*s. The relative frequencies of effect-congruent saccades are plotted upward and the relative frequencies of effect-incongruent saccades are plotted downward to indicate saccade direction. See the online article for the color version of this figure.

stimuli might have triggered (or at least primed) corresponding left and right saccades. If so, target stimuli would have facilitated effect-congruent saccades in R-E compatible blocks, when target arrow direction and effect position corresponded, and hindered effect-congruent saccades in R-E incompatible trials, when target arrow direction and effect position were opposite, leading to the observed result pattern. This interpretation is also compatible with our finding of shorter saccade latencies (for anticipatory, i.e., effect-congruent saccades) in R-E compatible blocks in comparison to R-E incompatible blocks. This issue will be addressed in the following experiments by either resorting to a free-choice setting without effect-specific target stimuli (Experiment 2) or by conducting another forced choice study with arbitrary target stimuli which could not trigger or prime saccades in a bottom-up manner (Experiment 3).

More important, based on Experiment 1 alone, we cannot ascertain that anticipatory saccades in the direction of future action consequences in fact emerged because of a process of goal-

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directed *action-based* anticipation. As we used distinct stimuli (arrows pointing to the left vs. right) as targets signaling the correct response, *stimulus-based* anticipation and goal-directed *action-based* anticipation cannot be dissociated since both target stimuli and responses reliably predicted future action effects. Thus, the observed saccades might have been triggered by a *stimulus-based* anticipation of the subsequently ensuing action effects (i.e., based on stimulus-effect associations). Even though the anticipatory saccades occurred around the time of the manual action, suggesting a link between anticipatory saccades and manual actions, we cannot completely rule out this alternative explanation with Experiment 1.

In Experiment 2, we conducted a free-choice version of Experiment 1 to address this issue. We used the same free-choice target stimulus for both left and right responses; thus, ruling out *stimulus-based* anticipations. Should we still observe higher frequencies of effect-congruent saccades than of effect-incongruent saccades under these conditions, these saccades must have been triggered by a process of goal-directed *action-based* anticipation, as only the chosen response allows for a prediction of the position of the ensuing effects.

Experiment 2

As outlined before, target stimuli as well as responses reliably predicted future action effects in Experiment 1. Thus, Experiment 1 did not allow us to disentangle *stimulus-based* anticipations (e.g., right arrow ▸ right effect) from goal-directed *action-based* anticipations (right response ▸ right effect). Thus, we conducted Experiment 2, a free-choice version of Experiment 1, to ascertain that the observed anticipatory (i.e., effect-congruent) saccades were in fact caused by an *action-based* anticipation process. Experiment 2 only used one free-choice target stimulus (a go signal) indicating that participants should freely choose a left or right response. Therefore, the same target stimulus is associated with both left and right action effects and only the respective response is predictive of the ensuing action effect. Thus, if anticipatory saccades should emerge in this free-choice setting, these anticipatory saccades cannot be the product of *stimulus-based* anticipation processes, but must have been caused by processes of goal-directed *action-based* anticipation of action effects.

Method

Participants. Twenty-two participants (5 men, 2 left-handed, mean age = 25.5 years) were recruited and participated for course credit. All participants had normal or corrected to normal vision. The study was conducted in adherence to the standards set by the local ethics committee. Two participants had to be excluded because of eye tracking problems (see Experiment 1 for details), resulting in a sample of 20 participants for analyses. Note that the sequence of R-E compatibility conditions was still fully counterbalanced in the reduced sample.

Apparatus. All settings were equivalent to those in Experiment 1.

Design and procedure. The trial structure of Experiment 2 was the same as in Experiment 1—including the intertrial interval (1,200–1,500 ms), target, response frame, interstimulus interval (300 ms), and action effect (500 ms)—with only minor changes. First, Experiment 2 was a free-choice experiment and participants did not have a response time limit. Second, a white asterisk (0.4° visual angle), the free-choice target that served as a choice signal, substituted the arrow targets of Experiment 1. Participants were instructed to spontaneously choose their next response (left vs. right key press) while the asterisk (500 ms) was present and perform the chosen response as fast as possible once the asterisk had disappeared.

Participants were instructed to freely choose their response (left vs. right key press) while trying to achieve equal numbers of left and right key presses. They were asked to make their choices spontaneously within a given trial, just like flipping a coin, instead of following a prechosen pattern. Furthermore, they were instructed to respond as fast as possible and to pay attention to the colored circles, that is, to the action effects that followed their responses. Instructions did not contain any information regarding eye movements.

Like Experiment 1, Experiment 2 consisted of one practice block of 16 trials and 10 experimental blocks of 50 trials each (5 blocks R-E compatible, 5 blocks R-E incompatible). Again, participants were not informed about the change in R-E compatibility. At the end of each block participants had the chance to take a self-paced break. After each block, they were informed about the number of left and right key presses they had performed.

Preprocessing of saccade data. Data preprocessing was equivalent to Experiment 1. Saccades occurring in trials with premature responses were not counted as systematic saccades (equivalent to 0 saccades from a total of 10,700 saccades that occurred during the action effect anticipation interval across all participants); 34.9% of saccades (3,734 from a total of 10,700) were not counted as systematic saccades, because their recorded start point did not coincide with the fixation cross region. Another 19.7% of saccades (2,105 of 10,700) were not counted as systematic saccades as these saccades did not cover at least one-third of the distance between start point and effect location. Additionally, 3.3% of saccades (353 of 10,700) occurred in trials with multiple saccades of opposing directions and 1.1% of saccades (121 of 10,700) occurred in trials that contained both preresponse and postresponse saccades. These saccades were also not considered. Overall, 41.0% of saccades were counted as systematic saccades in the final analyses.

Results

Manual RTs. Overall participants chose right responses on 50.3% or the trials and left responses on 49.7% of the trials, $t(19) = 0.97$, $p = .345$, $d = 0.22$. Premature responses (i.e., responses before the disappearance of the asterisk) occurred on 2.9% of the trials. The mean RT of valid responses amounted to 279 ms.

Participants' RTs did not significantly differ between R-E compatible blocks (271 ms) and R-E incompatible blocks (286 ms), $t(19) = 1.44$, $p = .165$, $d = 0.32$. An analysis of R-E compatibility by RT percentile showed that although significant R-E compatibility effects did not emerge for any percentile, RT differences between R-E compatible and R-E incompatible trials significantly increased with increasing percentile (see Online Supplemental Material).

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Anticipatory saccades. The average saccade amplitude amounted to 6.0° visual angle. The average saccade velocity was 117.9° visual angle per second.

The analysis of saccade frequencies (see Figure 2B) showed a significant main effect of SACC-E congruency, $F(1, 17) = 133.81$, $p < .001$, $\eta_p^2 = .89$. Effect-congruent saccades were significantly more frequent than effect-incongruent saccades. Furthermore, we found a main effect of trial block, $F(4, 68) = 3.44$, $p = .013$, $\eta_p^2 = .17$, indicating that the number of saccades slightly decreased over time. The interaction between SACC-E congruency and trial block was also significant, $F(4, 68) = 3.08$, $p = .022$, $\eta_p^2 = .15$. Subsequent Repeated Measures ANOVAs conducted separately for trials with effect-congruent and effect-incongruent saccades revealed that for both effect-congruent trials, $F(4, 76) = 1.94$, $p = .113$, $\eta_p^2 = .09$, as well as effect-incongruent trials, $F(4, 76) = 1.89$, $p = .173$, $\eta_p^2 = .09$, the main effect of trial block did not reach significance. The interaction between SACC-E congruency and trial block originated from a diverging pattern of relative frequencies over time. Whereas the frequency of effect-congruent saccades showed a downward trend over time, the frequency of effect-incongruent saccades did not show any systematic trend. All other effects failed to reach significance, *F*s < 1.

An additional analysis of saccade frequencies during the first R-E compatible and R-E incompatible block only revealed a significant main effect of SACC-E congruency, $F(1, 18) = 121.67$, $p < .001$, $\eta_p^2 = .87$, with effect-congruent saccades occurring more often than effect-incongruent saccades. The main effect of R-E compatibility, $F(1, 18) = 2.88$, $p = .107$, $\eta_p^2 = .14$, and the interaction between SACC-E congruency and R-E compatibility, $F(1, 18) = 2.29$, $p = .147$, $\eta_p^2 = .11$, again failed to reach significance.

The analysis of saccade latencies (see Figure 3B) revealed a main effect of SACC-E congruency, $F(1, 14) = 14.49$, $p = .002$, $\eta_p^2 = .51$, with effect-incongruent saccades (501 ms) occurring earlier than effect-congruent saccades (585 ms). All other effects failed to reach significance, *F*s < 1. Saccades occurred less often before manual actions (8.2%) than following manual actions (91.8%).

Correlations. Again, participants' mean manual RTs and mean anticipatory (i.e., effect-congruent) saccade latencies did not significantly correlate, $r = .293$, $p = .210$. However, a one sample *t* test showed that mean *within*-participant correlations (see Experiment 1 for computation details) between manual RTs and saccade latencies (R-E compatible condition: mean $r = .361$, R-E incompatible condition: mean $r = .390$) significantly differed from zero, R-E compatible: $t(19) = 5.66$, $p < .001$, $d = 1.27$; R-E incompatible: $t(19) = 7.81$, $p < .001$, $d = 1.75$. Participants' R-E compatibility effects (see Experiment 1 for details) and SACC-E congruency effects did not significantly correlate, $r = .136$, $p = .568$. Finally, participants' R-E compatibility effects in manual RTs and saccade frequencies did not significantly correlate, $r = -0.226$, $p = .338$.

Discussion

In Experiment 2, participants freely chose their actions when a free-choice target appeared and they initiated these actions after it had disappeared. As the free-choice target was the same across all experimental conditions, *stimulus-based* anticipations, which might have occurred in Experiment 1, can be ruled out. Yet, effect-congruent saccades were still significantly more frequent than effect-incongruent saccades, suggesting that action effects had been anticipated. These results imply that the execution of spontaneous anticipatory saccades is part of the process of anticipating one's own actions future sensory consequences (i.e., evidence of learned action-effect associations). Again anticipatory saccades emerged very fast and were already present in the first block of trials.

Interestingly, we replicated the finding of Experiment 1 that SACC-E congruency effects and R-E compatibility effects in saccade frequencies did not significantly correlate with manual R-E compatibility effects. Moreover, whereas in Experiment 2 manual actions failed to show significant R-E compatibility effects that would have indicated an influence of future action effects on action selection and action planning, SACC-E congruency effects were clearly present. These results point toward a functional dissociation of manual actions and anticipatory saccadic eye-movements: Whereas manual actions are part of an anticipatory process serving action selection, anticipatory saccades rather seem to serve effect-monitoring and outcome evaluation purposes. Nevertheless, the substantial within-participant correlation between manual and saccade latencies suggests a certain amount of temporal coordination between both processes, which appears plausible since a delayed action should also result in a correspondingly postponed effect evaluation.

Importantly, the absence of a significant R-E compatibility effect in manual RTs does not imply that participants did not anticipate their actions' effects. In fact, the SACC-E congruency effect clearly shows that participants anticipated the spatial location of the sensory consequences their actions would produce. The nonsignificant R-E compatibility effect in manual RTs only suggests that the anticipated effect did not affect manual action selection akin to a presented stimulus. In this context, it should be noted that spatial R-E compatibility effects (e.g., Kiesel & Hoffmann, 2004; Kunde, 2001, Experiment 1) are less frequently reported than, for instance, intensity-based or duration-based R-E compatibility effects (e.g., Kunde, 2001, Experiments 2 and 3; Kunde, 2003; Pfister, Pfeuffer, & Kunde, 2014), probably suggesting that spatial R-E compatibility effects are rather weak and thus, less reliably found.

Furthermore, in contrast to Experiment 1, we found no differences in the frequency of effect-congruent saccades for R-E compatible and R-E incompatible blocks. This suggests that the respective frequency differences observed in Experiment 1 were probably caused by the specific spatial target stimuli (arrows). Remarkably, R-E compatibility effects such as manual RT and PE differences observed in Experiment 1 and in previous studies on action effect anticipation (e.g., Koch & Kunde, 2002; Kunde, 2001, 2003) have been interpreted by suggesting that anticipating R-E incompatible (vs. R-E compatible) action consequences could be more demanding. However, regarding the anticipatory saccades, we observed no difference in the processing of R-E compatible and R-E incompatible action effects. Likewise, our finding in Experiment 1 that saccade latencies differed between R-E compatible and R-E incompatible mappings was not replicated in Experiment 2. Here, we only found that saccade latencies were shorter for effect-incongruent (nonanticipatory) saccades in comparison with effect-congruent (anticipatory) saccades. This suggests that the significant difference in saccade latency between R-E compatible and R-E incompatible saccades and the nonsignificance of the trend toward faster effect-incongruent saccades observed in Experiment 1 may also have been caused by the specific target stimuli which inherently carried spatial information. As the forced-choice setting of Experiment 1 cannot be ruled out as an alternative explanation for both differences in saccade effects across experiments, we conducted Experiment 3, a version of Experiment 1 with arbitrary target stimuli (i.e., stimuli that did not inherently carry spatial information).

Experiment 3

The results of Experiment 1 revealed that effect-congruent saccades were both more frequent and initiated faster in R-E compatible blocks in comparison with R-E incompatible blocks. However, frequency and latency differences between R-E compatible and R-E incompatible blocks were not present in Experiment 2. Apart from the forced-choice/free-choice setting, the only difference between Experiment 1 and Experiment 2 was the use of two inherently spatial (arrows) versus nonspatial (asterisk) target stimuli. We hypothesize that the spatial target stimuli used in Experiment 1 may have triggered or primed (some) saccades to the right or left and thus, led to a larger number of effect-congruent saccades on R-E compatible (vs. R-E incompatible) trials, as target direction and effect position matched on R-E compatible trials and mismatched on R-E incompatible trials.

In Experiment 3 we wanted to replicate the findings of Experiment 2 (i.e., the lack of a substantial difference in saccade frequency and latency between R-E conditions) in a forced-choice set-up with arbitrary target stimuli that should not trigger saccades based on their inherent features (i.e., in a rather bottom-up manner). Please note that the contingency between stimulus, action, and action effect was the same as in Experiment 1. One distinct target stimulus was paired with one response that caused one predictable action effect. However, in Experiment 1, spatial (left/right) manual action were triggered by spatial stimuli (left/right arrows), yielding spatial (left/right) visual effects. Thus, Experiment 1 involved dimensional (specifically, spatial) overlap between (action-triggering) stimuli and responses (set-level compatibility, see Kornblum, Hasbroucq, & Osman, 1990). In contrast, in Experiment 3 only response and action effect overlapped on a spatial dimension, but not target and action effect. As target stimuli in Experiment 3 did not inherently carry relevant spatial information, these centrally presented target stimuli could not trigger or prime saccades based on their inherent spatial features. Furthermore, we extended the paradigm and had participants work through more trials in an attempt to achieve a more reliable estimate of the frequency of preresponse saccades. Finally, to increase the probability of preresponse saccades, we reduced the target presentation duration from 200 to 50 ms.

Method

Participants. Twenty-nine participants (8 men, 3 left-handed, mean age = 24.0 years) were recruited and participated for course credit. All participants had normal or corrected to normal vision. The study was conducted in adherence to the standards set by the local ethics committee. Two participants had to be excluded as they accidentally pressed a key that aborted the experiment. Six additional participants were excluded because of eye tracking problem (see Experiment 1 for details) resulting in a sample of 21 participants for the analyses. Because of the reduced sample, the counterbalancing of R-E compatibility sequences was imperfect (the group starting with the R-E compatible action-effect condition consisted of one additional participant). Note that this did not affect the interpretation of results (see results section for details).

Apparatus. All settings were equivalent to those in Experiment 1.

Design and procedure. The trial structure of Experiment 3 was equivalent to that in Experiment 1 except for the target. In Experiment 3, we used a white triangle and a white square (1.1° visual angle) as targets that were only presented for 50 ms. This setting ruled out target-induced saccadic movements and allowed us to more effectively assess the occurrence of very early anticipatory saccades. Target-response mappings were counterbalanced across participants. The time course of a trial was as follows: intertrial interval (1,200–1,500 ms), target (50 ms), response frame (600 ms), interstimulus interval (300 ms), and action effect (500 ms; see Figure 1).

Experiment 3 consisted of one practice block and 24 blocks of 50 trials each. The R-E compatibility mapping switched after every four blocks resulting in three sequences of four compatible and four incompatible blocks. R-E compatibility order was counterbalanced across participants. Instructions were equivalent to Experiment 1 and did not contain any information regarding eye movements. As in Experiment 1 and 2, participants were not informed about the switches in R-E compatibility.

Preprocessing of saccade data. Data preprocessing was equivalent to Experiment 1. Saccades occurring in trials with premature responses, incorrect responses, or response omissions were not counted as saccades (equivalent to 155 saccades from a total of 12,615 saccades that occurred during the action effect anticipation interval across all participants); 25.7% of saccades (3206 from a total of 12,460) were not considered as systematic saccades, because they did not start in the predefined fixation region. Another 39.6% of saccades (4928 of 12460) were not counted as saccades as they did not cover at least one-third of the distance between center and effect. Additionally, 2.6% of saccades (322 of 12,460) were not considered as systematic saccades as they occurred in trials with multiple saccades with opposing directions and 0.1% of saccades (16 of 12,460) were not counted, because trials contained both preresponse and postresponse saccades. Overall, 32.0% of saccades were counted as systematic saccades in the final analyses.

Results

Reaction times and error rates. Trials with premature responses (about 0.1% of the trials) and response omissions (about 1.1% of the trials) were excluded. The mean RT was 316 ms and the mean error rate was 3.1%. RT analysis did not show a significant difference between R-E compatible (314 ms) and R-E incompatible (318 ms) trials, $t(20) = 1.51$, $p = .147$, $d =$

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0.33. Equivalent results were obtained for error rates, $t(20) = 1.42$, $p = .170$, $d = 0.31$ (R-E compatible: 2.9%, R-E incompatible: 3.3%).[3] Again the R-E compatibility effect was not significant for any RT percentile, but RT differences between R-E compatible and R-E incompatible trials increased with percentile (see Online Supplemental Material).

Anticipatory saccades. The mean saccade latency was 374 ms. Saccade latencies were not significantly affected by SACC-E congruency or R-E compatibility, Fs ≤ 2.12, ps $\geq .165$, $\eta_p^2 \leq .12$. The average saccade amplitude was 3.5° visual angle and the average saccade velocity was 61.3° visual angle per second.

The analysis of relative saccade frequencies across the factors SACC-E congruency, R-E compatibility, and trial block revealed a significant main effect of SACC-E congruency, $F(1, 20) = 5.24$, $p = .033$, $\eta_p^2 = .21$ (see Figure 2C). Effect-congruent saccades occurred significantly more often than effect-incongruent saccades. All other effects failed to reach significance, Fs ≤ 1.69, ps $\geq .209$, $\eta_p^2 \leq .08$.[4]

Furthermore, we conducted three separate 2 × 2 Repeated Measures ANOVAs with the factors SACC-E congruency and R-E compatibility for the first R-E compatible and R-E incompatible blocks that participants performed either at the beginning of the experiment or after a switch in R-E compatibility (R-E compatibility switch 1–3). These analyses revealed a significant main effect for SACC-E congruency for the *first* blocks (first R-E compatible and R-E incompatible block in the first section, i.e., block 1 and 5, of the experiment), $F(1, 20) = 5.91$, $p = .025$, $\eta_p^2 = .23$, as well as for the *second* blocks (i.e., block 9 and 13), $F(1, 20) = 4.97$, $p = .037$, $\eta_p^2 = .20$, with effect-congruent saccades being significantly more frequent than effect-incongruent saccades. For the *third* blocks (i.e., block 17 and 21), the main effect of SACC-E congruency showed a nonsignificant trend toward more effect-congruent than effect-incongruent saccades, $F(1, 20) = 4.22$, $p = .053$, $\eta_p^2 = .17$. For the first, second, and third blocks, the main effect of R-E compatibility, Fs ≤ 1.48, ps $\geq .238$, $\eta_p^2 \leq .07$ and the interaction of SACC-E congruency and R-E compatibility, Fs ≤ 1.41, ps $\geq .249$, $\eta_p^2 \leq .07$ failed to reach significance.

The analysis of saccade latencies failed to show any significant effects. Both the main effects of SACC-E congruency, $F(1, 16) = 2.12$, $p = .165$, $\eta_p^2 = .12$, and R-E compatibility, $F < 1$, as well as their interaction, $F < 1$, were nonsignificant (see Figure 3C). 82.2% of the observed saccades occurred after participants′ manual actions, whereas 17.8% of the observed saccades occurred before manual actions.

Correlations. As in Experiments 1 and 2, participants' manual RTs and saccade latencies did not significantly correlate, $r = -0.097$, $p = .675$. However, mean *within*-participant correlations between manual RTs and saccade latencies (R-E compatible condition: mean $r = .111$, R-E incompatible condition: mean $r = .176$; see Experiment 1 for computation details) again significantly differed from zero for R-E incompatible conditions, $t(20) = 2.65$, $p = .015$, $d = 0.58$, but not for R-E compatible conditions, $t(20) = 1.42$, $p = .172$, $d = 0.31$. The correlation between R-E compatibility effects and SACC-E congruency effects (see Experiment 1 for details) also failed to reach significance, $r = .271$, $p = .235$. Moreover, participants' R-E compatibility effects in manual RTs and saccade frequencies did not significantly correlate, $r = .068$, $p = .769$.

Discussion

Replicating our previous findings, effect-congruent saccades occurred much more frequently than effect-incongruent saccades during the effect anticipation interval, suggesting that these saccades had been triggered by processes of action effect anticipation. Similar to the previous experiments, anticipatory saccades were already evident in the first block after a switch in R-E compatibility. Furthermore, we replicated the finding of Experiment 2 that the frequency of effect-congruent saccades did not differ between R-E compatibility conditions, which is in line with our hypothesis that the differences between R-E compatible and R-E incompatible blocks observed in Experiment 1 were caused by the particular target stimuli. That is, the arrows used as targets in Experiment 1 likely tended to trigger (or prime) corresponding saccades; thus, facilitating effect-congruent saccades in R-E compatible blocks and interfering with effect-congruent saccades in R-E incompatible blocks. Furthermore, the latency of effect-congruent and effect-incongruent saccades did not differ in Experiment 3.

Moreover, even though we again found anticipatory saccades toward the direction of future action consequences, effects of action effect anticipation on manual RTs and error rates did not reach significance in Experiment 3. That is, manual actions did not show the typical RT and PE increases associated with R-E incompatible trials in comparison with R-E compatible trials. Future studies could try using, for instance, audio-visual, spatially lateralized action effects, to probably achieve more stable R-E compatibility effects in manual RTs and PEs.

Nevertheless, the finding that anticipatory saccades were again present even though manual RTs and PEs did not reflect processes of action effect anticipation further supports the notion that anticipatory saccades (unlike manual actions) are not closely coupled anticipatory processes serving action selection, but are rather connected to a functionally different purpose, namely outcome evaluation. This idea of a functional dissociation (despite the same underlying mechanism of action-effect association learning) is further supported by the nonsignificant correlation of R-E compatibility effects and SACC-E congruency effects.

Additionally, as saccades seem to reflect anticipatory processes even when the typical behavioral measures of RT and PE do not, these results suggest that anticipatory saccades (despite serving a different functional purpose) might be considered a much more sensitive measure of action effect anticipation than previously used behavioral measures (e.g., manual key press latencies). In Experiment 1, where we did observe manual R-E compatibility effects, the presence of inherently spatial target stimuli may have enhanced

[3] Separate t tests for RTs and PEs accounting for all possible counterbalanced permutations of equally distributed participants per group showed nonsignificant effects for PEs for all permutations, ts(19) ≤ 1.70, ps $\geq .105$, ds ≤ 0.38, and nonsignificant RT effects for all but one permutation, significant RT effect: $t(19) = 2.16$, $p = .044$, $d = 0.48$, other RT effects: ts(19) ≤ 1.74, ps ≥ 0.099., ds ≤ 0.39.

[4] The pattern of results did not change when controlling for the imbalance in the number of participants across R-E compatibility order conditions. The main effect of SACC-E congruency was significant for all but two of the counterbalanced permutations of participants ($N = 20$), Fs ≥ 5.06, ps $\leq .037$, $\eta_p^2 \geq .21$. For the remaining two permutations, the main effect of SACC-E congruency approached significance, Fs ≥ 3.87, ps $\leq .064$, $\eta_p^2 \geq .17$. All other effects failed to reach significance, Fs ≤ 2.70, ps $\geq .117$, $\eta_p^2 \leq .12$.

attention toward spatial aspects of the experimental setup (including the position of action effects), eventually yielding clear effects of spatial effect anticipation on both manual (RT, PE) and oculomotor (anticipation frequency) action control, a pattern that was not present in Experiment 3.

General Discussion

The present experiments explored whether processes of action effect anticipation, as an underlying mechanism of goal-directed action, do not only trigger actions, but simultaneously trigger spontaneous (uninstructed) anticipatory saccades toward the position of a later on occurring action effect. Participants performed left and right key presses that predictably triggered action effects (colored circles) on the left and right side of the screen. R-E mappings were R-E compatible in one half of the trials and R-E incompatible in the other half. In two forced-choice experiments (Experiments 1 and 3) and one free-choice experiment (Experiment 2), we examined whether participants executed spontaneous saccades in the direction of their own actions' predictable consequences before these consequences occurred. Crucially, participants were never instructed to perform eye movements toward these action effects, but their task was either to press a left or right key in response to a forced-choice target (Experiment 1 and 3) or to freely choose their actions (left vs. right key press) in response to a free-choice target (Experiment 2). Participants were instructed to respond fast and accurately and the action effects were irrelevant to their actual task.

We demonstrate that the anticipation of their own action's future consequences led participants to perform anticipatory saccades, that is, effect-congruent saccades in the direction of the later on occurring action effects. Effect-congruent saccades were substantially more frequent than effect-incongruent saccades in both forced-choice and free-choice experiments. Furthermore, anticipatory (i.e., effect-congruent) saccades emerged already during the first block of the experiment and were also present during the first block following a switch in R-E compatibility. These findings are in line with previous studies suggesting that only few learning instances are necessary to form action-effect associations (Dutzi & Hommel, 2009). Furthermore, they suggest that apart from rather indirect markers of action effect anticipation like RT and PE, anticipatory saccades can serve as excellent online measures of spatial action effect anticipation that emerges after only a few trials of having experienced action-effect pairings.

Because we also observed evidence for anticipatory saccades in R-E incongruent conditions of Experiment 1, we can effectively rule out that the saccades in this experiment were only triggered by the stimuli in a purely bottom-up fashion based on inherent spatial characteristics of the target stimuli. Interestingly, however, the target stimuli in Experiment 1 clearly had an influence on the frequency of effect-congruent saccades. When target arrow direction and action effect direction matched, the frequency of effect-congruent saccades was significantly higher in comparison with trials in which target arrow direction and action effect direction did not match. Experiments 2 and 3 instead involved either a single free-choice target stimulus (Experiment 2) or arbitrary forced-choice target stimuli without any (spatial) dimensional overlap (Kornblum et al., 1990) with the action effects (Experiment 3). Under these conditions, effect-congruent saccades were not only equally frequent on R-E compatible and R-E incompatible blocks, but also the latency of effect-congruent saccades on R-E compatible and R-E incompatible trials did not differ, suggesting that the effect of R-E compatibility on saccades in Experiment 1 was solely because of the inherently spatial target characteristics. This finding is interesting as it suggests that in contrast to previous conclusions based on instructed behavioral measures (manual RTs and PEs; see, e.g., Koch & Kunde, 2002; Kunde, 2001, 2003), which typically showed a performance decrease in R-E incompatible blocks, the present results based on anticipatory saccades suggest that oculomotor processes of anticipation are not substantially affected by the spatial compatibility between action and effect. Probably, R-E incompatibility does not hamper anticipation per se, but might rather only affect the process of translating action effect anticipations into corresponding (manual) action.

Furthermore, in Experiment 2 the two forced-choice target stimuli were replaced by a single free-choice target stimulus that was the same on all trials. We introduced the free-choice target to ensure that only the performed response and not the preceding target stimulus was predictive of the ensuing action effect. Thus, in Experiment 2, possible *stimulus-based* anticipations because of the predictable relation between target and action effect (Experiments 1 and 3) could be ruled out by demonstrating that effect-congruent saccades were significantly more frequent than effect-incongruent saccades in a free-choice setting, too. Thus, anticipatory, effect-congruent saccades could not have been driven by predictable target-effect mappings, but were indeed caused by processes of action effect anticipation.

Of course, processes of *stimulus-based* anticipation may have taken place in addition to goal-directed *action-based* anticipation in our forced-choice experiments. Surprisingly though, the relative frequency of anticipatory saccades during free-choice was not lower than during forced-choice even when comparing Experiment 2 to Experiment 1, in which arrows, that might have directly triggered (some) saccades irrespective of anticipatory processes, were used as targets. These results match behavioral findings showing that effects of action effect anticipation are more reliably found when participants adopt an intention-based action mode like, for instance, during free-choice (Herwig, Prinz, & Waszak, 2007; Herwig & Waszak, 2012; Pfister et al., 2010).

Although we demonstrate that action effect anticipation is reflected in anticipatory eye movements, it clearly has to be noted that these saccades do not occur on every trial. Specifically, across the three experiments effect-congruent saccades occurred on about 10–50% of all trials, depending on the specific experiment and condition. Although we used rather restrictive saccade selection criteria for our analyses and thus, might have underestimated the actual frequency of anticipatory saccades, there is definitely a substantial proportion of trials in which no saccade occurred. This poses a limitation to using effect-anticipatory saccades as an all-or-nothing measure of effect anticipation in each trial, as we cannot account for trials without saccades. While the nonexistence of anticipatory saccades might implicate failures of anticipation, it is also possible that in these trials spatial attention-related processing was simply just below a certain threshold, ultimately preventing overt execution of a saccade program (see, e.g., the premotor theory of attention; Rizzolatti, Riggio, Dascola, & Umiltá, 1987). Future studies will have to determine whether corresponding covert shifts of spatial attention toward the position of future action

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effects do occur in trials without overt shifts of attention via saccades.

Our results also speak to the issue of the interplay between the control systems (or modules) for manual responses and covert or overt shifts of visual attention, the latter being associated with the oculomotor control system. For example, a strong account of cross-modal interference as an underlying mechanism of manual R-E compatibility effects would assume that longer manual RTs in R-E incompatible conditions might be solely because of interference from spatially incompatible overt or covert shifts of attention. An interesting find was that Experiments 2 and 3 that did not use inherently spatial (and eye movement-inducing) target stimuli, neither the frequency of anticipatory saccades nor overall manual RTs differed between R-E compatible and R-E incompatible blocks. This is remarkable as it suggests that performing opposing manual actions and saccades neither impaired the performance of anticipatory eye movements, nor the performance of manual actions. This finding is in line with research indicating that in coordinated eye and hand movements to separate locations, attention can be allocated in parallel (Jonikaitis & Deubel, 2011, see also Huestegge & Adam, 2011; Huestegge & Koch, 2010), suggesting largely independent attentional systems or modules (Huestegge, Pieczykolan, & Koch, 2014) for eye and hand movements under these circumstances.

Despite this overall evidence for strong modularity of the manual and oculomotor systems (in terms of resistance to mutual crosstalk), it is interesting that R-E compatibility effects selectively emerged in conjunction for both manual and oculomotor responses in Experiment 1 only, in which the inherently spatial target stimuli obviously increased the difficulty to execute effect-congruent saccades (i.e., saccades toward the effect location) in R-E incompatible conditions. This oculomotor processing obstacle might have enhanced oculomotor processing effort in terms of a stronger activation of the correct spatial code for the anticipatory saccade. This in turn may have led to a stronger potential for spatial code interference between effector systems (i.e., an increased conflict between the diverging spatial codes for manual and oculomotor responses), eventually giving rise to (or at least enhancing) the manual R-E compatibility effect in terms of slowed manual response execution in R-E incompatible trials. Although this mechanism is rather speculative and should be tested more explicitly in subsequent research, it can provide a satisfying explanation for the selective emergence of R-E compatibility effects across both effector systems in Experiment 1.

Our finding that saccade-effect congruency effects were not modulated by R-E compatibility as well as the finding that neither R-E compatibility effects and SACC-E congruency effects nor R-E compatibility effects in manual RTs and saccade frequencies correlated might be considered as a hint that manual actions and anticipatory saccadic eye movements (although based on a common action-effect association learning mechanism) serve different functions. Whereas manual actions were affected by their spatial overlap with their future sensory consequences, implying that R-E compatibility effects assess anticipatory action selection and action planning, the anticipatory saccades we observed seem to be linked to an (functionally independent) anticipatory process of outcome evaluation rather than action selection. Even though, further testing is required to support this hypothesis, especially as we did not observe significant R-E compatibility effects in Experiments 2 and 3, the notion of a functional dissociation is further supported by the dissociation of manual and saccadic anticipatory effects in Experiments 2 and 3. Although we could not find reliable R-E compatibility effects in manual RTs and PEs in these experiments, sizable saccade-effect congruency effects were present nonetheless. Moreover, saccade latencies were also unaffected by manipulations of R-E compatibility, providing further support for the idea that whereas anticipatory measures in manual actions reflect an impact of action effect anticipation on action selection, anticipatory saccades rather serve a different function of efficient effect-monitoring and outcome evaluation. Specifically, the efficiency of effect-monitoring should be greater for trials with anticipatory saccades compared with trials in which saccades only occur after action effect onset, since the later saccades would necessarily imply additional time-consuming shifts of attention after peripheral effect processing.

Moreover, additional support for the idea that anticipatory saccades serve the function of outcome evaluation comes from our finding that anticipatory saccades mainly occurred after manual actions and only in some cases preceded manual action execution. While saccade programming is also a time-consuming process (Becker & Jürgens, 1979) and might have occurred before manual response execution in some trials, it is still unlikely that a substantial number of saccades were prepared before manual response selection. Instead, anticipatory saccades were apparently initiated around action execution when responses had either already been performed or when action execution was about to be conducted and action effects were imminent. The idea that the observed anticipatory saccades serve a monitoring function is supported by the finding that R-E compatible action effects are more easily discriminated in a time frame starting 220 ms before action execution (Desantis, Roussel, & Waszak, 2014), suggesting that the perceptual representation of future action effects occurs during the later stages of motor preparation when prepared motor patterns are internally tested (Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). As the anticipatory saccades we observed fall into this time frame, we assume that these saccades were executed during later stages of motor preparation when a perceptual representation of the action effects had already been generated. In line with Ziessler and Nattkemper (2011) who investigated at which stages of manual action preparation ideomotor anticipations occur, we thus, assume that the observed anticipatory saccades, emerging after responding or during a later stage of action preparation associated with internal response testing, serve a monitoring function and are used to compare intended and observed outcomes.

This mechanism is more explicitly addressed in cybernetic comparator models (Frith & Wolpert, 2000; Wolpert & Flanagan, 2001; Wolpert & Ghahramani, 2000), suggesting that ideomotor and comparator models are complementary in that action selection and action outcome evaluation might represent two distinct functional aspects (as observed in manual responses and eye movements, respectively) of one common underlying anticipatory process based on learned action-effect associations (Chambon, & Haggard, 2013; Hommel, in press a).

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However, despite the dissociated functional roles of the two effector systems, the fact that anticipatory saccades occurred almost exclusively after manual actions might suggest that the anticipatory processes of action selection and outcome evaluation are not entirely independent from one another. Possibly, outcome evaluation is only initiated once a certain response threshold has been exceeded and the production of an action is imminent. We speculate that a (largely independent) process of action outcome evaluation might be triggered during one of the later stages of anticipatory action preparation (note that evidence for a certain amount of temporal coordination between the two functionally dissociated responses, manual and oculomotor responses, is evident in the significant within-participant correlations between the respective response latencies, especially in the free-choice setting). If that were the case, humans should be able to veto and stop the process of outcome evaluation if motor preparation was aborted during an early stage of motor preparation, but not when it was aborted during later stages of motor preparation. The question of whether the anticipatory processes underlying effect-generating manual actions and effect-monitoring saccadic eye movements are interdependent in such a manner (veto account) is a tantalizing question for future research to address, which could, for instance, be assessed by introducing no-go trials and having participants stop their manual actions at various stages of motor preparation in a proportion of trials.

Another explanation for our finding that anticipatory saccades occurred mainly after manual actions might be that, as the response-effect interval had a fixed duration, participants developed temporal predictions regarding the point in time when their actions' effects would occur (e.g., Haering & Kiesel, 2012) and only directed their gaze toward the future location of these action effects when their occurrence was imminent. Therefore, future studies on anticipatory saccades, varying the response-effect interval, should address the question of whether saccade latencies are influenced by temporal predictions.

Additionally, action outcome evaluation has been linked to the experience of agency (Hommel, in press a, in press b). That is, the closer actual effects match expected effects, the stronger are participants' feelings of being the causal agent who produced these effects (Chambon & Haggard, 2013). Thus, as the here reported anticipatory saccades reflect exactly this process of outcome evaluation, they might also be usable in assessing agency-related processes. Future studies should investigate whether spontaneous anticipatory saccades can also provide additional information regarding the processes underlying agency.

Finally, it has recently been suggested that ideomotor control mechanisms might not be restricted to motor control, but might extend to language, numeric processing, and tool use, thus, connecting actions and abstract concepts (Badets, Koch, & Philipp, 2016). In the context of our present findings, these assumptions suggest that anticipatory saccades might also emerge in contexts other than goal-directed motor control. Thus, the investigation of anticipatory eye movements in these contexts might provide further insights into processes of outcome evaluation underlying, for instance, language and numeric processing.

Conclusion

In conclusion, our findings demonstrate that uninstructed eye movements toward the direction of future action consequences, that is, anticipatory saccades, emerge when actions produce predictable effects in the environment. These saccades appear to serve the function of evaluating whether observed and expected action outcomes match or mismatch and, thus, support the adaptation of action-effect associations and action effect anticipation to changing environmental requirements. In this way, our results demonstrate the informational value of additionally analyzing uninstructed behavioral components and reveal important mechanisms of the complex and spontaneous interplay between the manual and oculomotor effector system in goal-directed action. Whereas effect-generating manual actions reflect processes of anticipatory action selection, spontaneously occurring anticipatory saccades reflect anticipatory action outcome evaluation. We thus, extend ideomotor theories of action control by providing a framework for simultaneously studying complementary processes of anticipation-based behavioral control that have so far been addressed rather within cybernetic models than within the context of ideomotor theorizing.

We establish spontaneous anticipatory saccades as a viable tool for assessing processes of anticipatory outcome evaluation complementary to behavioral and electrophysiological measures of anticipatory action selection. These spontaneous anticipatory saccades were shown to be particularly sensitive, online indicators of outcome anticipation and might represent an interesting tool for assessing anticipatory processes in populations that cannot be reliably tested with common RT-based paradigms, like for instance, young children or clinical patients. Thus, the use of this new measure could also provide new insights into processes of action effect anticipation as well as its functionality, for instance, in psychopathology. Tantalizing questions for future research include the degree of automaticity of the observed anticipatory saccades as well as their adaptation to different environmental and goal-attainment demands.

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