Anticipation of delayed action-effects: Learning when an effect occurs, without knowing what this effect will be

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Abstract

According to the ideomotor principle, behavior is controlled via a retrieval of the sensory consequences that will follow from the respective movement (“action-effects”). These consequences include not only what will happen, but also when something will happen. In fact, recollecting the temporal duration between response and effect takes time and prolongs initiation of the response. We investigated the associative structure of action-effect learning with delayed effects and asked whether participants acquire integrated action-time-effect episodes that comprise a compound of all three elements or whether they acquire separate traces that connect actions to the time until an effect occurs and actions to the effects that follow them. In three experiments, results showed that participants retrieve temporal intervals that follow from their actions even when the identity of the effect could not be learned. Furthermore, retrieval of temporal intervals in isolation was not inferior to retrieval of temporal intervals that were consistently followed by predictable action-effects. More specifically, when tested under extinction, retrieval of action-time and action-identity associations seem to compete against each other, similar to overshadowing effects reported for stimulus-response conditioning. Together, these results suggest that people anticipate when the consequences of their action will occur, independently from what the consequences will be. *(202 words)*

Keywords: ideomotor theory; action-effect learning; action control; temporal contiguity;

Introduction

Acting goal-directed requires that people learned the consequences of their bodily movements. By implication, this knowledge allows them to select appropriate movements to fulfill their intended goals. This is made more explicit in the ideomotor principle (Herbart, 1825; James, 1890) and its succeeding theoretical formulations (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). According to this notion, behavior is selected, initiated, and controlled by representations of the sensory consequences that will follow from the respective movement. Thus, the occurrence of response-contingent effects yields associative links between cognitive representations of actions and effects (A-E associations). Then, because of the bidirectional nature of such associations, retrieval of action-effects from memory is used to guide action control (for reviews, see Hommel, 2013; Shin, Proctor, & Capaldi, 2010).

Recently, there has been an increased effort to investigate the underlying mechanisms how learning and retrieval of A-E associations take place (e.g., Paulus, 2012; Pfister, Kiesel, & Hoffmann, 2011; Wolfensteller & Ruge, 2011; Hoffmann, Lenhard, Sebald, & Pfister, 2009). For instance, Elsner and Hommel (2001) showed that action-effects become automatically integrated with the responses that preceded them. In an initial acquisition phase, participants repeatedly performed two simple key presses that were consistently followed by distinct sensory effects (high- or low-pitch tones).

Learning of these arbitrary A-E associations was subsequently probed with either a forced-choice or a free-choice test phase. In the *forced-choice test phase*, the former action-effects (tones) were presented as imperative stimuli and participants responded to them according to fixed stimulus-response mappings. Instructed responses were either consistent or inconsistent with the A-E mapping of the preceding acquisition phase. Shorter reaction times (RTs) in the consistent relative to the inconsistent condition were taken as evidence for an automatic re-activation of A-E associations that may facilitate or conflict with the execution of the instructed response (see also Herwig, Prinz, & Waszak, 2007; Nattkemper, Ziessler, & Frensch, 2010). In the *free-choice test phase*, former action-effects are presented without stimulus-response instructions, and participants choose freely between the available responses. Response choices can be consistent or inconsistent with the A-E contingencies of the acquisition phase. A typical finding is that participants more frequently choose consistent than inconsistent responses (Elsner & Hommel, 2001; see also Pfister et al., 2011).

Going one step further, Kunde (2001, 2003; see also Hommel, 1993) provided evidence that mere retrieval of action-effects can function as a mental cue to activate corresponding movements. In the study of Kunde (2003), for example, participants pressed a response key for a short or a long duration and the response was followed contingently by either a short or a long tone. Facilitated responses with compatible (e.g., short key press > short tone) relative to incompatible response-effect relations (e.g., short key press > long tone) indicated that representations of intended action-effects were activated prior to response execution and presumably affected response selection (for more evidence, see Kunde, Pfister, & Janczyk, 2012; Paelecke & Kunde, 2007; Wirth, Pfister, Janczyk, & Kunde, 2015). Importantly, in this line of research action-effects never served as primes, thus action control must have involved an anticipatory retrieval of action-effects (see also Janczyk, Durst, & Ulrich, in press; Janczyk & Kunde, 2014).

Taken together, these studies provide support for an associative account of A-E learning (cf. Elsner & Hommel, 2001, 2004; see also Dickinson et al., 2001). An association is conceived as a mental link connecting two events (Pearce & Hall, 1980; Rescorla & Wagner, 1972). Traditionally, the strength of this link is construed as a function of the predictability (or contingency) and the temporal proximity (or contiguity) between representations of both events. In contrast to this view, modern theories of conditioning proposed that temporal information becomes the content of learning (Gallistel & Gibbon, 2000; Honig, 1981; Matzel, Held, & Miller, 1988; Miller & Barnet, 1993). For instance, the phenomena of inhibition of delay describes the tendency to withhold a conditioned response until the end of a long conditioned stimulus just before the unconditioned stimulus is presented (e.g., Drew, Zupan, Cooke, Couvillon, & Balsam, 2005; Pavlov, 1927; Rescorla, 1967). Furthermore, animals and humans form specific temporal expectancies that allow them to respond at specific points in time to maximize reward (Arantes & Machado, 2008; Church & Deluty, 1977; Los & van den Heuvel, 2001; Thomaschke, Wagener, Kiesel, & Hoffmann, 2011).

Regarding A-E learning, Haering and Kiesel (2012) showed that participants learn to exploit temporal regularities between actions and effects. In this study, participants were faster to detect the onset of an action-effect when it appeared after a learned delay as compared to an onset that occurred earlier or later than expected. However, recap that according to the ideomotor principle it is not only necessary to show that information about an action-effect is learned, but even more critical that anticipation of this action-effect is used for action control. Consequently, the bidirectional activation of the A-E association should not only activate events that were linked to each other, but also the temporal information of this link. According to this line of reasoning, temporal information between action and effect should influence response generation in the same way as the duration of an intended effect itself influences response generation (as suggested by Kiesel & Hoffmann, 2004, and Kunde, 2003). In a recent study we provided first evidence for this reasoning (Dignath, Pfister, Eder, Kiesel, & Kunde, 2014). In one experiment with a forced-choice procedure, participants responded to a cue, while in another experiment with a free-choice procedure, participants could freely choose their responses. Action-effects consistently followed the responses after a long or short temporal delay. In both experiments, RTs were prolonged for long relative to short delays suggesting that the temporal information *when* an action-effect occurs was not only learned, but also retrieved during response initiation. This makes sense, if assuming that action-effects are stored in percept-like codes as envisaged by early researchers (cf. James, 1980) and suggested by later results (Koch & Kunde, 2002; Kunde, 2003): recollection of a long time interval should take more time than the recollection of a short time interval (see also Wirth et al., 2015).

What is not clear from this research is the precise associative structure of temporal interval learning. Clearly, learning any temporal extension of an interval requires a stimulus that marks the beginning of the interval and some sort of stimulus that terminates the interval. Thus, in some sense the temporal information in an associative structure is part and parcel of the defining stimuli. Therefore, Dignath et al. (2014) speculated that the time between two events is stored as an “action-time-effect” (A-T-E) episode. Consequently, anticipating an effect reactivates the previously experienced episode in reversed order. One implication that can be derived from this *integrative episode* account is that the temporal information that specifies when an action-effect follows a response cannot be learned independently from the specific identity of the action-effect.

However, an alternative view would assume that temporal information is learned like any other perceptual action-effect. For instance, when producing an auditory action-effect, this would result in two separate A-E and action-time (A-T) associations. Consequently, anticipating either the auditory action-effect or the temporal interval can re-activate the previously associated response. Thus, learning and later retrieval of temporal information could proceed independently of action-effect identity. We will refer to this as the *separate trace* account.

The present research. The aim of the present research was to investigate whether the time interval between an action and its effect is learned and retrieved as a component of an A-T-E episode or whether it is learned independent from A-E associations as a separate A-T association. Three experiments tested these accounts by manipulating the contingency between actions and their auditory effects, while temporal delays between actions and auditory effects were 100% contingent. Experiment 1 tested the hypothesis that A-T association can be learned without A-T-E associations by examining retrieval of time intervals during response selection with two fixed time intervals between response and effect (A-T fixed) but unpredictable effects (A-E random). Thus, the time intervals were terminated by an action-effect, ensuring that temporal information could be learned. However, the identity of the action-effects was unpredictable, making it impossible for a specific effect to be associated with a particular response. Experiment 2 gave the opportunity to acquire A-T-E episodes and tested whether retrieval of A-T-E episodes have a stronger impact on action selection than mere retrieval of A-T associations. Therefore, two responses were consistently followed by action-effects with predictable identity (A-E fixed) after a short or a long delay (A-T fixed), and two further responses were followed by action-effects with unpredictable identity (A-E random) after a short or a long delay (A-T fixed).

Experiment 3 provided a further test of the integrative episodes and the separate trace account with a between-subjects design. While responses were followed by action-effects with predictable identity in an A-E fixed group, responses were consistently followed by action-effects with unpredictable identity in an A-E random group. In both groups, the effect tones were presented consistently after a short or a long delay (A-T fixed). In addition, a manipulation check was included to see whether participants in the A-E fixed group indeed acquired A-E associations. Therefore, in a subsequent free-choice test phase, the previously presented tones served as go-stimuli and participants had to randomly select one of the two response keys. For the A-E fixed group, frequency of response choice that were consistent with the previously learned A-E association served as an index of A-E learning. Furthermore, since A-T assignments were fixed for both groups, RTs in the free-choice test were analyzed to compare the delay-anticipation effect for both groups under extinction (because in the free-choice test phase, key presses no longer produced any tones or temporal intervals).

Experiment 1

We hypothesized that if time intervals are learned (and retrieved) only as part of A-T-E episodes, contingency of action-effect identity should be critical for the acquisition of such episodes. Therefore, if the identity of the action-effect is not contingent upon the time interval that follows a response, learning should be seriously impeded. However, according to the separate trace account, time intervals are learned independently of the action-effect identity, and thus learning of separate A-T associations should be independent of the particular action-effect identity, because any event that terminates the time interval should suffice for A-T learning to occur. Experiment 1 tested this hypothesis with a cued time interval learning task (see Dignath et al., 2014, Exp. 3). We expected that the time interval between action and effect is anticipated during response selection. Thus, short and long A-E intervals should affect the speed of response initiation differently, because anticipating long intervals should require more time and should prolong response initiation more than short intervals. One response key triggered a tone after a long delay (2000ms) while the other response triggered a tone after a relatively short delay (50ms). Most critically, however, the identity of the tone (high or low pitch) was randomly assigned on a trial-by-trial basis and was thus not predictable.

Faster responses for keys associated with a short action-effect delay compared to prolonged responses for keys associated with a long action-effect delay are taken as an index of *delay-anticipation*. Observing a delay-anticipation effect with randomly varying action-effect identities can be taken as evidence for the possibility of A-T associations independently of A-T-E episodes.

Method

Participants

20 participants were tested in Experiment 1 (3 left-hander, 16 women, *M* = 22.9 years, range: 19–31 years). Data of one participant was excluded due to an exceptionally high error rate (*M* > 25%, > 2.5 SDs).

Stimuli and procedure

Participants were to press an instructed response key as quickly as possible at the onset of a colored asterisk. They were told to press the left key ("D" on a QWERTZ keyboard) when a green (red) asterisk appeared and to press the right key ("L" on a QWERTZ keyboard) when a red (green) asterisk appeared on the screen (color-key assignment was counterbalanced across participants).[1] A key press triggered a 400 Hz or 800 Hz tone (presented via headphones for 500 ms) after a short (50 ms) or a long (2000 ms) time interval (with counterbalanced assignment of delays to the response keys). Responses during the delay were logged to check whether participants performed additional key presses. The next trial started after an inter-trial interval of 1000 ms.

In cases of incorrect responses or responses that were too fast (RT < 100 ms) or too slow (RT > 1000ms) a warning message appeared on the screen for 1000 ms. These trials were repeated in random order at the end of the experiment. Participants worked through 24 practice trials which were not further analyzed and six blocks with 28 trials each presented in random order. After each block, a summary informed about the mean RT and error rate in the last block.

[1] Due to a programming error, instructions stated that in some trials a white asterisk would appear and participants would have to freely decide which key they wanted to press. However, these trials were never presented during the experiment.

Results

Responses during the action-effect interval were rare (<0.1%). Trials that followed an error (3.5%) were removed from all analyses. In addition, trials with erroneous responses (3.3%) and RTs that deviated more than 2.5 *SD*s from the corresponding condition mean (1.8%) were discarded for the RT analyses.

Forced-choice test phase (A-T learning and test)

Key presses were slower when the action-effect delay was long (*M* = 414 ms) relative to short (*M* = 397ms), *t*(18) = 2.24, *p* = .038, *d* = 0.51. A similar analysis on error rates was conducted to rule out any speed-accuracy trade-off. This analysis revealed more errors for long-delay responses (*M* = 4.3%) than for short-delay responses (*M* = 2.5%), *t*(18) = 2.11, *p* = .049, *d* = 0.49.

Discussion

Action initiation was prolonged for responses that were followed by tones after a long compared to a short delay. Importantly, predictability of specific action-effects was not a necessary condition for this effect to occur. Even when action-effects merely served as an unspecific event that terminated the duration of the temporal interval, the duration of the interval became associated with a particular response.

Experiment 2

Although results from Experiment 1 provide first evidence that the temporal duration between action and effect is learned and retrieved independently from the identity of the action-effect, it remains unclear whether the temporal duration can potentially be integrated into an A-T-E episode, if action-effects are contingent upon the response (and the temporal interval) preceding them. Thus, it is possible that although temporal duration can be learned independently, integrative A-T-E episodes are beneficial for learning and retrieval and result in stronger delay-anticipation effects. The purpose of

Experiment 2 was to test this version of the integrative episode account. Therefore, four response keys and four different, clearly distinguishable action-effects were used while we manipulated the contingency between responses and action-effect identity. Half of the responses were followed by action-effects of predictable identity (fixed A-E mapping) and half of the responses were followed randomly by action-effects of unpredictable identity (random A-E mapping). For both mapping conditions, the temporal interval between actions and effects was either short or long (overall fixed A-T mapping).

Statistically, the integrative episode account would predict an interaction. The predictability of the A-E mapping should modulate the size of the delay-anticipation effect, with the possible result that fixed A-E mappings facilitate a retrieval of the complete episode in reversed order (effect > temporal interval > action) compared to random A-E mappings, that should impair retrieval of the episode. Consequently the delay-anticipation effect should be increased for fixed A-E mappings compared to random A-E mapping.

Alternatively, the separate trace account would assume that A-T associations are acquired independently of the identity of action-effects. Regarding the usage of A-E associations, one could derive two different prediction from this view. On the one hand, one could assume that only the most salient feature that has been associated with a response is retrieved in order to evoke this response. Since temporal duration is a feature that applies to all responses in Exp. 2 – whereas action-effect identity applies only to half of the responses – one would only predict a main effect of the temporal interval, but no main effect of the A-E mapping and no interaction.

On the other hand, one could assume that all features that have been associated with a response are retrieved for action selection. Thus, this version of the separate trace account would also predict an interaction. However, the direction of this interaction is quite different from the predicted interaction of the integration account. This is because retrieval of A-T and A-E associations affect RTs in opposite directions (cf. Dignath et al., 2014). Whereas retrieval of the temporal interval prolongs RTs, retrieval of the action-effect identity shortens RTs. Thus, under fixed A-E mappings (in contrast to random A-E mappings) the delay-anticipation effect should be reduced.

Method

Participants

Sixty-one participants were tested in Experiment 2 (five left-hander, 39 women, *M* = 29.5 years, range: 19-58 years). Data of two participants were excluded due to an exceptionally high error rate (*M* > 34%, > 2.5 SDs).

Stimuli and procedure

Experiment 2 was identical to Experiment 1, except for the following changes. Participants now had to press one of four response keys (“D”, “G”, J”, and “L” on a QWERTZ keyboard) with the index and middle finger of their left and right hand as a response to the onset of a colored (red, green, blue, yellow) asterisk at the beginning of the trial (four different key-color combinations were randomly chosen and counterbalanced across participants).

Each key press produced one of four different tones (guitar, flute, bells, and trombone) presented for 1000ms. Furthermore, participants were instructed with an emphasis on producing action-effects (e.g. „a yellow asterisk indicates that you have to produce a sound with the inner left key“). Such instructions are known to boost the impact of action-effects (Ansorge, 2002; Janczyk, Yamaguchi, Proctor, & Pfister, 2015). For the left (right) keys the tone followed a key press after a delay of 50ms, for the right (left) keys the tone followed after a delay of 2000 ms (counterbalanced across participants). Furthermore, the outer (inner) keys produced always the same ton (e.g., outer left key press → guitar in 100% of the cases), whereas the inner (outer) keys produced one of two tones randomly (e.g., inner left key press → flute or bells in 50% of the cases) (counterbalanced across participants). Participants worked through 24 practice trials which were not further analyzed and seven blocks with 40 trials each. Incorrect trials were repeated in random order at the end of the experiment.

Results

As in the previous experiments, responses during the action-effect interval were rare (0.2%). Trials that followed an error (11.4%) were removed from all analyses. In addition, trials with erroneous responses (9.1%) and RTs that deviated more than 2.5 SDs from the corresponding condition mean (1.1%) were discarded for the RT analyses.

Forced-choice test phase (A-T learning and test)

Data was analyzed with a repeated measures ANOVA with the factors *action-effect delay* (long delay vs. short delay) and *action-effect mapping* (fixed vs. random). Key presses were slower when the action-effect delay was long (M = 587 ms) relative to short (M = 554ms), as indicated by the significant main effect of *action-effect delay*, $F(1,58) = 30.81$, $p < .001$, $\eta_p^2 = .35$. Neither the main effect of *action-effect mapping*, $F < 1$, nor the interaction, $F(1,58) = 1.19$, $p = .278$, $\eta_p^2 = .02$, reached significance (see Table 1 for means of all conditions). To further draw inferences about this null-effect, we employed Bayesian statistics as an alternative to null-hypothesis significance testing. The advantage of Bayesian statistics is that it offers a way of evaluating evidence in favor of a (null-)hypothesis. The Bayesian approach is a model selection procedure that indicates how much more likely given data is under one model than under the other model. For the present case, the models are the null-hypothesis (i.e., that the delay-anticipation effect is not enhanced for fixed action-effect mapping manipulations) and the alternative-hypothesis (i.e., that the delay-anticipation effect is enhanced for fixed compared to random action-effect mapping). The Bayes-factor (BF) gives an index how strong the data is in favor of the null-hypothesis. We calculated BFs with JASP, a freely available and easy to use program for Bayesian statistics (Love et al., 2015; Rouder, Speckman, Sun, Morey, & Iverson, 2009). The resulting BF = 2.32 indicates that the null-hypothesis is more than two times as likely as the alternative hypothesis. According to traditional conventions regarding the interpretation of the BF, such a BF is considered as weak evidence in favor for the null hypothesis that *fixed action-effect mappings* did not increased the delay-anticipation effect compared to *random action-effect mappings* (see Jarosz & Wiley, 2014, for an overview of different terminology).

Error rates mirrored the RT data. Participants made fewer errors for short-delay responses (M = 9.0%) than for long-delay responses (M = 11.2%), $F(1,58) = 9.99$, p = .002, $\eta_p^2 = .15$, all other Fs < 1.

Discussion

Experiment 2 tested an alternative formulation of the integrative episodes account. According to this reasoning, A-T-E episodes are not necessary for learning of action-effect intervals. Nevertheless, if action-effects follow predictably from specific responses, A-T-E episodes can be formed and used to guide behavior more efficiently than only A-T associations. Therefore, in Experiment 2, for half of the responses the action-effect mapping was constant, while for the other half the action-effect mapping varied. For both conditions, A-T mappings were always fully predictable. Results did not support superior A-T-E learning with predictable action-effects, because delay-anticipation did not differ between the predictable and the unpredictable condition. The results also speak against a version of the separate trace account that would assume that participants in the predictable condition use both A-T and A-E association at the same time. This account predicted that with fixed A-E mappings, retrieval of the A-T association should prolong RTs, whereas retrieval of the A-E association should shorten RTs, resulting in a reduced delay-anticipation effect compared to random A-E mappings. Again, this was not supported by the results. Instead, similar delay-anticipation effects irrespective of the predictability of the action-effect identity suggest that participants retrieved merely A-T associations.

However, results of Experiment 2 cannot conclusively rule out the integrative episode account for two reasons. First, it remains unclear whether participants actually learned any A-E associations in the fixed A-E condition. And second, while A-T associations were hand-specific (e.g., left hand > short delay), the mapping of A-E associations was more complex (e.g., outer responses > fixed tones). These limitations will be addressed in Experiment 3.

Experiment 3

Experiment 3 compared A-T learning (in terms of a delay-anticipation effect) for a fixed A-E mapping and a random A-E mapping and additionally assessed A-E learning in a subsequent free-choice test phase. We decided to manipulate the A-E mapping between subjects to render A-E learning as simple as possible (cf. Watson, van Steenbergen, de Wit, Wiers, & Hommel, 2014). For one group of participants, responses were consistently and predictably followed by the same action-effects (fixed A-E mapping), while for the other group of participants, responses were followed randomly by unpredictable action-effects (random A-E mapping). For both mapping groups, the temporal interval between actions and effects was predictably either short or long (overall fixed A-T mapping). This test of A-T learning was followed by a manipulation check that probed whether participants in the fixed A-E group had learned A-E associations. In a free-choice test phase, stimuli that were presented as action-effects in the previous phase were presented as go-signals: upon the onset of a tone, participants should freely choose between the two responses. Responses during the free-choice test no longer produced any action-effects.

Response choices in the free-choice test can be consistent or inconsistent with the (learned) A-E contingencies of the previous phase. A typical finding is that participants choose consistent responses more frequently than inconsistent responses. This bias in response choices is taken as evidence for A-E learning. While participants in the random A-E group could logically not learn any specific associations, participants in the fixed A-E mapping possibly have learned specific A-E associations. Thus, for the fixed A-E mapping group presentation of an acoustic action-effect should affect the selection of the corresponding response and participants should show a bias towards more consistent response choices.

While A-E learning was only possible in one group, A-T learning was possible in in both groups. However, assessing the strength of A-T associations with the delay-anticipation effect in the free-choice phase differs from the assessment during the forced-choice phase in two important aspects. First, in the free-choice test phase, tones were no longer presented and consequently there was no temporal interval between keypress and tone. Thus, the free-choice test phase assessed the delay-anticipation effect *under extinction*. Second, in a forced-choice phase it remained unclear whether participants learned to associate their actions or the imperative stimuli with a specific temporal interval. This confound is removed in the free-choice test phase, because no imperative stimuli were presented. For the delay-anticipation effect during the free-choice test, the two accounts make opposing predictions. According to the integrative episodes account, the time interval between an action and its effect is learned and retrieved as part of an A-T-E episode. Therefore, the delay-anticipation effect should be stronger in the A-E fixed group. However, according to the separate trace account, time is learned independently from A-E associations. Thus, the delay-anticipation effect should not differ between groups. Indeed, if both associations are learned separately, it is also possible that learning and retrieval of different associations competes with each other (cf. Kamin, 1969). In this case, the delay-anticipation effect should be stronger for the A-E random group, because in this group only A-T associations could be learned.

Method

Participants

Sixty-three participants were tested in Experiment 3 (5 left-hander, 51 women, *M* = 24.9 years, range: 19-50 years). Participants were randomly assigned to the groups. Data of one participant were excluded due an exceptionally high error rate (*M* > 16%, > 2.5 SDs).

Stimuli and procedure

Experiment 3 was identical to Experiment 1, except for the following changes. In the fixed A-E mapping the two response keys produced always the same ton (e.g., a left key press → high tone in 100% of the cases), whereas in the random A-E mapping, the response keys produced one of the two tones randomly (e.g., left key press → high tone in 50% of the cases).

Participants worked through 24 practice trials which were not further analyzed and seven blocks with 40 trials each. Subsequently, participants performed the free-choice test. Here, a Go/No-go-task was used to minimize strategic response choices (for a similar procedure, see Elsner & Hommel, 2001, Exp. 3). Each trial started with the presentation of one of three tones for 500ms. The high and low tones that were presented as action-effects during the previous phase served as Go-signals (the high tone appeared in 25% of the trials, and the low tone appeared in another 25%). A neutral tone (a metallic sound) was presented as a No-Go signal in the remaining trials. For the Go trials, participants were instructed to choose freely one of the two response keys, according to the following instructions:

> *Now it´s time for the second part of the experiment. At the beginning of each trial a tone will be played. This tone will be either one of the two tones you heard previously (high or low tone) or a new, metallic tone. If you hear one of the familiar tones, try to react as fast as possible and press either the left or the right key. Decide*

spontaneously which key you want to press. If you hear the metallic tone, you must not press a key. Just wait until the beginning of the next trial. Try to be as fast as possible, but avoid any errors.

Following the response, the next trial started after 1500 ms. An error message appeared for 1000 ms on the screen after a premature response (RT < 100 ms), a response omission (RT > 1000 ms), or after a response in a No-Go trial. Incorrect trials were repeated at the end of the experiment. In the free-choice A-E test phase key presses no longer produced tones. Participants worked through 5 blocks with 20 Go-trials and 20 No-Go trials. After each block, a summary informed participants about their mean RT and error rate (i.e., produced responses in No-Go trials).

Results

As in the previous experiments, responses during the action-effect interval were rare (<0.1%). Trials that followed an error (3.3%) were removed from all analyses. In addition, trials with erroneous responses (3.6%) and RTs that deviated more than 2.5 *SD*s from the corresponding condition mean (2.7%) were discarded for the RT analyses.

Forced-choice test phase (A-T learning and test)

Data was analyzed with a mixed ANOVA with the *action-effect delay* (long delay vs. short delay) as a repeated measure and the between-subjects factor *action-effect mapping* group (fixed vs. random). Key presses were faster when the action-effect delay was short (M = 390 ms) relative to long (M = 413 ms), $F(1,60) = 62.09$, $p < .001$, $\eta_p^2 = .51$. Neither the main effect of *action-effect mapping group*, $F < 1$, nor the interaction, $F(1,60) = 2.16$, $p = .147$, $\eta_p^2 = .03$, reached significance. Analysis of JZS-Bayes-factors with default prior scales (Love et al., 2015; Rouder et al., 2009) revealed positive evidence in favor for the null hypothesis, with BF = 8.62. The null hypothesis that fixed *action-effect mappings* do *not* increase the delay-anticipation effect was more than eight times as likely as the alternative hypothesis.

Error rates mirrored the RT data. Participants made fewer errors for short-delay responses (M = 2.5%) than for long-delay responses (M = 4.3%), $F(1,60) = 21.68$, $p < .001$, $\eta_p^2 = .26$, all other ps > .14.

Free-choice test phase (A-E learning manipulation check)

Trials with premature response (< 0.1%) or response omissions (0.8%) and trials with erroneous responses in No-Go trials (2.6%) were excluded from the analysis, as were trials that followed such errors (2.8%). Two participants were excluded from these analyses, because they pressed one single key throughout the test phase.

Choice Frequencies. To assess whether the fixed A-E group had acquired any action-effect associations, the frequency of response choices during the test phase was evaluated with a one-sample t-test against an equal distribution of choices (i.e. 50%). For the fixed action-effect mapping group, effect-consistent responses were selected more often (M = 58.8%) than expected when assuming an equal distribution of responses, $t(30) = 1.75$, $p = .045$ (see Figure 1, top panel, left side). For completeness, we also report choice frequencies for the random effect-mapping group and the comparison between groups. Here, effect-consistent responses (M = 51.2%) were not selected more often than expected when assuming an equal distribution of responses, $t<1$. (see Figure 1, top panel, right side). Comparing effect-consistent responses between groups with an one-sided, independent sample t-test revealed no significant difference, $t(58) = 1.27$, $p = .104$. Please note that for the random effect-mapping group, it is logically impossible that participants could acquire any specific A-E associations. Therefore, any deviation from randomness in this group has to be attributed to error variance. Arguably, this error variance makes the between group comparison less sensitive to detect a choice bias.

Reaction times. Because participants in both groups had learned specific A-T associations in the previous phase, analysis of RTs during the free-choice test phase allows us to probe whether an anticipation-delay effect is present under extinction (because in this phase of experiment, responses did not produced any tones). Therefore, we analyzed the RT data with a mixed ANOVA with *learned action-effect delay* (long delay vs. short delay) as a repeated measure and the between-subjects factor *action-effect mapping* group (fixed vs. random). Neither the main-effect *learned action-effect delay,* $F(1,58) = 2.53$, $p = .117$, $\eta_p^2 = .04$, nor the main effect *action-effect mapping* group was significant, $F<1$. However, there was a significant interaction, $F(1,58) = 6.24$, $p = .015$, $\eta_p^2 = .097$. Participants who had experienced fixed A-E mappings in the previous phase showed no delay-anticipation effect, $|t|<1$[2]. However, participants who had experienced random A-E mappings in the previous phase showed a significant delay-anticipation effect with slower responses for keys that were associated with a long delay (M = 431 ms) and faster responses for keys that were associated with a short delay (M = 411 ms), $t(28) = 3.02$, $p = .005$, $d = 0.56$ (see Figure 1, lower panel).

Discussion

Experiment 3 provided a further test of the integrative episodes account (A-T-E learning) by assessing whether A-T learning is facilitated by additional learning of A-E associations. Two groups of participants learned a constant A-T mapping. Critically, for one group of participants the A-E mapping was constant and effects thus predictable,

[2] Possibly, if participants in the fixed-effect mapping group had formed integrative A-T-E episodes, temporal information would only be retrieved for consistent responses (e.g. E>T>A), but not for inconsistent responses. However, an additional analysis for consistent response choices only showed no evidence for a delay-anticipation effect, $|t|<1$.

while for the other group of participants the A-E mapping varied and effects therefore unpredictable. Replicating Experiment 2, results did not support integrative A-T-E learning with predictable action-effects, because delay-anticipation did not differ between the predictable and the unpredictable group.

Results of the subsequent free-choice test phase confirmed that participants in the A-E fixed mapping group indeed acquired A-E associations. Interestingly, retrieval of these A-E associations seemed to have impaired retrieval of A-T associations. While the A-E fixed mapping group showed no evidence for a delay-anticipation effect during the free-choice test phase, the A-E random mapping group showed a robust delay-anticipation effect. Possibly, presentation of the tones as go-signals made the identity of the action-effect more salient and as a consequence participants retrieved only the tone-response association during the free-choice phase. In contrast, participants in the random A-E mapping group who could not learn to associate the identity of an action-effect with a specific response, retrieved the temporal information during the free-choice test.

General Discussion

Retrieval of action-effects functions as a mental cue to reactivate corresponding movements. In the present article, we sought to clarify the associative structure of effect-based action control and therefore focused on the temporal delay between a response and its corresponding effect. Two competing accounts were tested: (i) According to the integrative account, the time interval between an action and its effect is learned and retrieved as part of an A-T-E episode, whereas according to the (ii) separate trace account, time is learned independently from any A-E associations as a separate A-T association. The integrative episodes account would require that the duration of a temporal interval between action and effect, as well as the identity of the action-effect is to some extent contingent upon a specific action, in order to facilitate the acquisition of

A-T-E episodes. In contrast, the separate trace account requires only that the duration of the interval is contingent upon a specific action, but is mute regarding the identity of an action-effect. In Experiment 1, A-E mappings were unpredictable to render A-E learning impossible while A-T mappings were fully predictable. A delay-anticipation effect was observed, showing that temporal information was retrieved during action control independently of the identity of action-effects that terminate the interval. These results are in line with the separate traces account, but cannot be explained with the integrative episodes account. In a next step, we tested whether A-T-E episodes are formed if possible and whether they have a stronger impact on action control than retrieval of mere A-T associations. In Experiment 2, half of the responses were consistently followed by the same action-effects and half of the responses were followed randomly by different action-effects, while the temporal interval between actions and effects was predictably either short or long. Results revealed substantial delay-anticipation effects that did not differ between both conditions. Finally, Experiment 3 replicated this finding, but additionally verified in a subsequent test phase that participants with predictable A-E mappings had also learned the identity of effects.

Taken together, these findings indicate that information about temporal regularities is learned and retrieved in the course of action control in a similar way like previous studies suggested for information about the identity of to-be-produced action-effects. Furthermore, the observation that retrieval of temporal information does not hinge on a simultaneous retrieval of the action-effects' identify is in line with a recent study by Haering and Kiesel (2012). Here participants learned about the occurrence of action-effects that followed a specific action after different delays. Whereas the predictability of temporal intervals between action and effect facilitated the detection of rare deviant action-effects, predictability of the action-effect identity had no influence on detection rates. Thus, this study showed that people form expectancies about *when* an event should occur, independently of what this event is expected to be. However, it should be noted that studies using simple target classification tasks found evidence in favor of the idea that participants can acquire covariations between temporal information and target identity as well (Thomaschke et al., 2011).

Similarly, research on the *intentional binding* effect (Haggard, Clark, & Kalogeras, 2002; for a review, see Hughes, Desantis, & Waszak, 2012) – that is the subjective comprehension of time intervals that is observed when participants voluntarily produce a specific but delayed action-effect compared to passive movement conditions – attributed this phenomena (at least partly) to a prediction of a specific action-effect (cf. Haggard & Cole, 2007). Indeed, some studies reported evidence that the identity of the action-effects modulates the intentional binding effect (e.g., Yoshie & Haggard, 2013; Takahata et al., 2012), while others failed to find evidence for the role of action-effect identity (e.g., Desantis, Hughes, Waszak, 2012; Haering & Kiesel, 2014). To summarize, people form expectancies *when* an action-effect will occur and they also form expectancies *what* action-effect will occur, but different lines of research are inconclusive whether they do both at the same time.

One possible explanation for this discrepancy comes from research on stimulus interactions in associative learning (e.g., Kamin, 1969; Mackinosh, 1976). In a classical experiment, Pavlov (1927) observed that cues which became conditioned in compound with another stimulus elicited less conditioned responses compared to cues that were conditioned in isolation. Such a reduction in learning due to the presence of an alternative stimulus has been termed overshadowing. Flach, Osman, Dickinson, and Heyes (2006) showed that overshadowing can also be observed in action-effect learning. Pretraining and compound presentation of action-effects that followed a specific movement led to reduced subsequent learning of new action-effect associations for the same movement (Flach et al., Exp. 2). Thus, overshadowing might also occur in situations with two or more action-effects and reduce learning of the less salient effect.[3] Indeed, in the present experiments, temporal information was retrieved under extinction when no A-E association had been learned, while temporal information could not be retrieved when participants also retrieved previously learned A-E associations (Exp. 3). Future research should test overshadowing for action-effect identity and action-effect intervals in a systematic manner, for instance, by manipulating salience due to pretraining (cf. Flach et al., 2006).

A different explanation comes from studies on temporal orientation of attention (for a review, see Nobre & Coull, 2010). This line of research provided rich evidence that people can learn to voluntarily direct their attention to the duration of time intervals and use this information to guide selection of stimuli (e.g., Coull & Nobre, 1998; Miniussi, Wilding, Coull, & Nobre, 1999; but see Los & van den Heuvel, 2001). Interestingly, a study by Correa and colleagues showed that people can not only learn to use time for simple detection tasks, but also for more complex discrimination tasks (Correa, Lupianez, Milliken, & Tudela, 2004). However, this ability critically depended on the task demands: with rapidly varying temporal information from trial-to-trial and arbitrary mapping between color cues and temporal information, participants were not able to benefit from temporal expectation. Thus, according to their interference hypothesis, temporal orienting effects are strictly capacity limited (see also Capizzi, Sanabria, & Correa, 2012). Possibly, during the free-choice test phase under extinction, retrieval of A-E associations interfered with A-T associations in the A-E fixed mapping group, while no interference was present in the A-E random mapping group. Further studies should

[3] A similar effect may have taken place in some studies where multiple action-effects provided contradictory information, for example, with the proprioceptive feedback occurring on the left side, whereas a visual action-effect occurred on the right side (e.g., Hommel, 1993; Janczyk, Pfister, Hommel, & Kunde, 2014). In such studies, one effect feature emerged as the main determinant of behavior and reduced/eliminated the impact of the other feature(s).

test this explanation, possibly by comparing the delay-anticipation effect under different cognitive load conditions.

Whatever the reasons may be why action-effect interval and action-effect identity are not easily integrated, the present results demonstrate that temporal duration of the action-effect interval can be acquired and used independently of the action-effect identity. This observation encouraged the claim that temporal information is not just a catalyst that fosters or hinders action-effect learning, but becomes the content of representations that guide action control.

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Table 1

Mean correct reaction times (in ms) and error rates (in %) in each experiment for short and long action-effect time intervals and for Experiment 2 and 3 also for random and fixed action-effect mappings.

	action-effect time interval	action-effect mapping	RT (ms)		Errors (%)	
			M	*SE*	*M*	*SE*
Exp. 1	short	random	397	10	2.5	0.6
	long	random	414	12	4.3	0.6
Exp. 2	short	random	558	9	8.8	0.9
	long	random	585	9	11.6	0.9
	short	fixed	549	8	9.0	1.2
	long	fixed	589	8	10.8	1.2
Exp. 3	short	random	390	7	2.6	0.5
	long	random	417	7	4.9	0.5
	short	fixed	390	7	2.5	0.5
	long	fixed	409	7	3.7	0.5

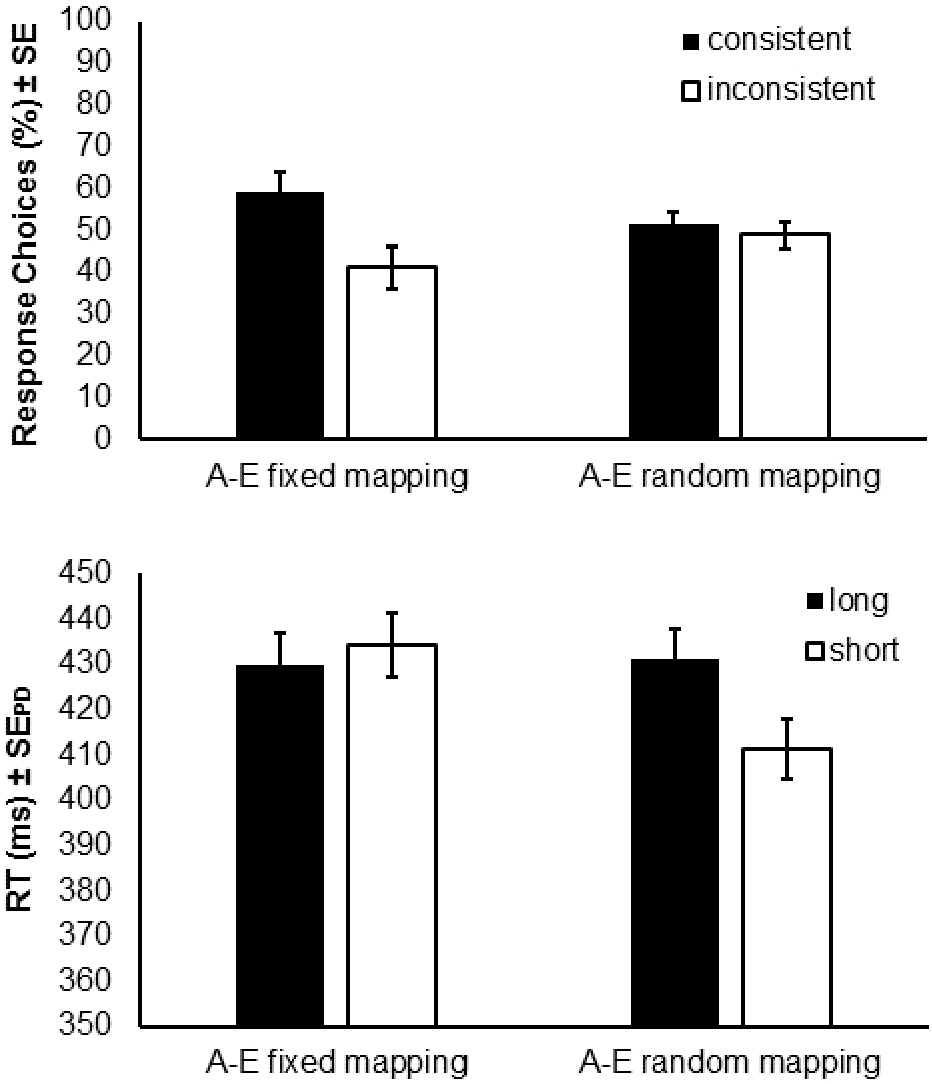

Figure 1. Data for the free-choice test phase of Experiment 3 for the random and fixed action-effect mapping group. Action-time mapping was always fixed for both groups. The upper panel depicts mean response choices (in %) for response choices that were consistent with previously learned response-tone mapping (black bars) or inconsistent (white bars). Error bars indicate standard errors. The lower panel depicts mean correct reaction times (in ms) for responses that had been *previously* associated

with long (black bars) and short (white bars) delays. Error bars indicate standard errors computed for paired differences (Pfister & Janczyk, 2013).