Representing the Hyphen in Action–Effect Associations: Automatic Acquisition and Bidirectional Retrieval of Action–Effect Intervals

David Dignath, Roland Pfister, Andreas B. Eder, Andrea Kiesel, and Wilfried Kunde
University of Würzburg

We examined whether a temporal interval between an action and its sensory effect is integrated in the cognitive action structure in a bidirectional fashion. In 3 experiments, participants first experienced that actions produced specific acoustic effects (high and low tones) that occurred temporally delayed after their actions. In a following test phase, the tones that were presented as action effects in the previous phase were now presented as primes for the responses that had caused them previously and, critically, also as primes for the interval that previously separated action and effects. The tones were presented as go-signals in a free-choice test and as response-imperative stimuli in a forced-choice test. In the free choice test, participants were more likely to choose responses consistent with the previous pairing, but these responses were initiated slower than responses that were inconsistent with previous action–effect learning (Experiment 1). Effect-consistent responses were also initiated slower in the speeded forced-choice test (Experiment 2). These observations suggest that retrieval of a long action–effect interval slows down response initiation. In Experiment 3, response-contingent effects were presented with a long or short delay after a response. Reaction times in both, a forced-choice and free-choice setup, were faster in the short- than in the long-interval condition. We conclude that temporal information about the interval between actions and effects is integrated into a cognitive action structure and is automatically retrieved during response selection.

Keywords: ideomotor theory, action–effect learning, action control, temporal contiguity

People must learn the consequences of their behavior for goal-directed action. Ideomotor theory proposes that action effects become associated with the preceding movements in memory and that, in turn, the action effect is used to select, initiate, and control an action (Herbart, 1825; James, 1890/2011; for a modern version, see Hommel, Müsseler, Aschersleben, & Prinz, 2001). According to this theory, observations of response-contingent effects create bidirectional links between cognitive representations of responses and effects; retrieving the action effect from memory can then be used to initiate the associated action (for reviews, see Hommel, 2013; Nattkemper, Ziessler, & Frensch, 2010; Shin, Proctor, & Capaldi, 2010).

Despite recent interest in ideomotor learning (Elsner & Hommel, 2001; Paulus, 2012; Pfister, Kiesel, & Hoffmann, 2011; Wolfensteller & Ruge, 2011), the nature of action–effect (A–E) associations is not yet fully understood (cf. Hoffmann, Lenhard, Sebald, & Pfister, 2009). This holds especially true for situations in which effects do not follow instantaneously after an action but occur after a given delay. Here, longer intervals between actions and effects were suggested to

hinder the acquisition of A–E associations (Elsner & Hommel, 2004). This interpretation rests on the assumption that an association between two events (here, a response and a sensory effect) is only formed during a brief critical integration window. With longer intervals, the associative link is weakened, resulting in decreased or no learning. Thus, close temporal proximity is considered a necessary condition for learning (Dickinson, 2001).

However, in everyday life, people are often confronted with situations in which effects follow an action after considerable delays. For instance, when opening a hyperlink in a Web browser, the intended effect is sometimes delayed by up to 2 s or even more. How can people acquire these simple yet delayed A–E associations, and what do these associations consist of? We aim to answer these questions in the present article by suggesting that temporal intervals themselves are actually represented in addition to action and effect features. Building on previous work on associative learning of temporal information (Gallistel & Gibbon, 2000; Miller & Barnet, 1993), we propose that the interval between an action and an effect is not only a moderating factor for the formation of an association but that the interval itself is part of the association. More precisely, we assume that intervals are actually represented in addition to action and effect features. To anticipate the present results, we show that intervals indeed become part of the A–E association. These results built on previous approaches to A–E learning and related findings on the structure of A–E associations that we describe in the following.

Action–Effect Learning and Action Control

Most studies on A–E learning have used *induction paradigms* to investigate the acquisition of bidirectional A–E associations (El-

sner & Hommel, 2001; Greenwald, 1970). These paradigms typically consist of an acquisition phase that is followed by a test phase. The acquisition phase is used to establish arbitrary A–E associations: Participants repeatedly perform two or more actions such as pressing left or right response keys. Each response produces a distinct sensory effect, for example, a high or low tone. In a subsequent test phase, the former action effects (i.e., tones) are presented as stimuli, and participants respond to them. In line with ideomotor theory, it is assumed that the presentation of a stimulus resembling an action effect automatically activates the associated motor pattern via bidirectional A–E associations (see also Herwig, Prinz, & Waszak, 2007; Hoffmann et al., 2009; Hommel, 2013; Nattkemper et al., 2010; Pfister et al., 2011; Wolfensteller & Ruge, 2011; for a review, see Shin et al., 2010).

Two measures were used for probing whether bidirectional A–E associations were formed in the test phases of such induction paradigms: response time (RT) and choice frequencies. These measures are typically obtained in different test phases. In a *forced-choice test* phase, participants execute an instructed response to the stimuli as quickly as possible according to fixed stimulus–response rules. The instructed response is either consistent with the A–E mapping of the preceding acquisition phase, or it is inconsistent with previous learning episodes. Shorter RTs in the consistent condition relative to the inconsistent condition indicate automatic activation of A–E associations that may concur or conflict with the instructed response. In *free-choice test* phases, by contrast, stimuli that were presented as action effects in the acquisition phase are presented without stimulus–response instructions; rather 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.

Another paradigm that was used to study A–E associations and the role of effect anticipations for action control is the *response–effect (R–E) compatibility paradigm* (Kunde, 2001). Compatibility between actions and effects is induced by having both vary on a common dimension such as location (Ansorge, 2002; Kunde, 2001; Pfister, Kiesel, & Melcher, 2010; Pfister & Kunde, 2013), duration (Kunde, 2003; Pfister, Dignath, Hommel, & Kunde, 2013), or intensity (Kunde, 2001; Kunde, Koch, & Hoffmann, 2004). In the study of Kunde (2003), for example, participants pressed a response key for a short or a long period, and the response was followed contingently by either a short or a long tone. Facilitated responses with compatible relative to incompatible R–E relations indicated that the participants had learned which action produced which effect and that representations of intended action effects were activated during response selection. Moreover, Kunde (2003) observed a main effect of effect duration in this study. Response times were generally increased when a response was selected that produced a long (relative to a short) tone. These results suggest that action selection involves an anticipation of the effect duration that increased the time for response selection if the effect was long (for a related finding, see Kiesel & Hoffmann, 2004).

Temporal Contiguity Between Actions and Effects

Research in the induction paradigm and the R–E compatibility paradigm provided clear evidence that bidirectional A–E associations are acquired and that they are used for action control via

effect anticipations (Shin et al., 2010). But what actually is the mechanism behind A–E learning?

Theorists have proposed associative learning as a candidate mechanism for the automatic acquisition of A–E association (Elsner & Hommel, 2001, 2004). In the traditional associative learning framework, an association is regarded as a mental link between the representations of two events (Pearce & Hall, 1980; Rescorla & Wagner, 1972). For instance, after pairing a conditioned stimulus (CS) with an unconditioned stimulus (US), presenting the CS also activates the representation of the US. The strength of the link between both events is a result of contingency and temporal contiguity. That is, the better the CS had previously predicted the US and the closer in time the CS and the US were presented, the stronger is the link between representations of both events. It should be noted that, in this view of associative learning, temporal information is essential for the creation of an association, but the temporal information itself is not explicitly conceptualized to be part of the association (cf. Arcediano & Miller, 2002; but see Pavlov, 1927/1960, and the General Discussion for empirical evidence).

In contrast, other learning theories proposed that temporal information becomes a part of the association (e.g., Gallistel & Gibbon, 2000; Miller & Barnet, 1993). Miller and Barnet (1993), for instance, proposed that temporal information and associative strength can be viewed as two dimensions of the link between representations that influence behavior. A CS activates not only the representation of the US but also information about the time interval between both events. According to this temporal-coding hypothesis, temporal information is not only important for the formation of an association, but it is part and parcel of this association.

In a seminal study on the learning mechanism of ideomotor theory, Elsner and Hommel (2004) provided evidence that A–E learning shares some key features with classical associative learning principles. In this study, responses became associated with effects only when the contingency was high, that is, when performing an action predictably increased the likelihood of a corresponding effect. Furthermore, temporal contiguity between the responses and their effects was important: Learning effects were observed only when the temporal delay between actions and their effects was short (50 ms) but not when the delay was relatively long (2 s). This research suggests that actions and effects must be experienced closely together in time for A–E learning.

In line with classic learning theories, Elsner and Hommel (2004) proposed a critical time window for A–E integration. Only events that are registered within a specific time window can become associated with the response, whereas events that fall outside this time window become not linked with a response. Thus, temporal proximity is considered as a mechanism that fosters learning when the interval is relatively short.

However, there is also an alternative interpretation possible that appreciates the role of the temporal interval as a content of the acquired A–E association. Whereas faster RTs with consistent relative to inconsistent mappings were observed in conditions with short A–E delays (50 ms and 1,000 ms), the null effects in the conditions with long delays (2,000 ms) were interpreted as evidence for the absence of A–E learning. However, close inspection of their results shows a noticeable tendency for *longer* RTs with a consistent relative to an inconsistent response mapping. Although

these effects were not significant in either of two conditions (with eight participants each), the inconsistency benefit in the conditions with long delays approached significance in meta-analyzing both conditions ($N = 16$; $p = .083$).[1] One possible explanation for this unexpected finding is that a long action–effect delay was included into the associative action structure. In line with ideomotor theory, the information about a long action-effect delay was then automatically retrieved during response selection, explaining why responses producing a delayed action effect were initiated slower. The present experiments were conducted to test this hypothesis.

Opponent Processes of Automatic Interval Anticipation and Controlled Response Execution

According to ideomotor theory, the presentation or anticipation of an effect automatically activates the corresponding action via an associative link, which is retrieved from memory for response generation. Following associative theories on temporal interval learning, we conjecture that the bidirectional activation of the A–E association not only activates the events that were linked to each other but also the temporal information of this link. Consequently, this temporal information influences response generation in the same way as the duration of an intended effect influences response generation (as suggested by Kiesel & Hoffmann, 2004, and Kunde, 2003). The basic idea is that perceiving or anticipating an effect reactivates the previously experienced "action→delay→effect" episode in reverse order. During learning, an action is followed by a certain time delay, which is ultimately followed by a particular effect. After learning, the perception or anticipation of an effect automatically reactivates the associated time delay and the corresponding action in a reverse order. Assuming that all these representations are "images" in James' (1890/2011) terms, thus, perceptlike codes, the recollection of a long interval (or delay), should take more time than the recollection of a short interval. As a consequence, the time between the perception of the effect and the emission of the motor response should increase with the length of the retrieved time interval.

While this process explains a general increase of RTs with long compared with short A–E intervals,[2] it cannot explain why with long time intervals RTs increase more with consistent A–E mappings relative to inconsistent ones. To explain this pattern of results, it is important to note that there are two sources of response activation in the test phase: (a) automatic response activation induced by the presentation of the associated effect and (b) a controlled selection of the correct response defined by the instructed effect–response mapping. With a consistent A–E mapping, the automatic response is the correct one; consequently, the full episode including the long A–E interval is retrieved during response selection. With an inconsistent A–E mapping, however, the automatic response is incorrect; as a consequence, retrieval of the full action episode is aborted by a controlled process, which saves time relative to the consistent mapping when the associated A–E interval is long. Hence, although the inconsistent condition might suffer from slowing due to an aborted automatic response tendency, it is not delayed by a retrieval of a long temporal interval. With time intervals of 2 s or more (derived from Elsner & Hommel, 2004), the response slowing induced by the retrieval of the time intervals in the consistent condition should be greater than the slow-down caused by response suppression in the inconsistent

condition, resulting in slower responses in the consistent relative to the inconsistent mapping condition (see Figure 1 for a graphical sketch of the model). Irrespective of associated time information, the model still expects a preference for effect-consistent responses over effect-inconsistent responses in a free-choice test situation. Hence, the model makes two predictions for a free-choice test when the A–E intervals are relatively *long*: (a) a slower initiation of effect-consistent responses (relative to effect-inconsistent responses) and (b) a preference for consistent over inconsistent responses.

The Present Research

The aim of the present research was to investigate whether the time interval between an action and its effect is bidirectionally learned and integrated into the A–E association. Three experiments were conducted to test this assumption. Experiments 1 and 2 used an *induction paradigm* with relatively long A–E intervals of 2 s (see Figure 2 for a schematic of the designs). Experiment 1 used a forced-choice acquisition phase followed by a free-choice test phase; Experiment 2 used a forced-choice test phase instead, replicating the original design of Elsner and Hommel (2004). Experiment 3 examined more directly a retrieval of time intervals during response selection by manipulating the time interval between response and effect experimentally.

Experiment 1

Given the present hypothesis that the interval between action and effect becomes part of a bidirectional A–E association, we conjectured that perceiving or anticipating an effect would activate both, the associated action and the associated interval. In Experiment 1, we tested this hypothesis with a forced-choice acquisition phase and a free-choice test phase. In the acquisition phase, participants pressed two different response keys, each producing a distinct acoustic effect (high vs. low tone). Crucially, presentation of the acoustic effect was delayed by 2 s. In a subsequent free-choice test, the tones were presented as cues in a go/no-go task, and participants could freely decide which key to press. Response choices were *effect-consistent* when participants responded to a tone (presented as go stimulus) with the response key that had produced this tone in the previous acquisition phase. Response choices were *effect-inconsistent* when the response key was paired with a different tone in the acquisition phase.

For RTs, we assumed two opposing processes whenever actions and effects are separated by a long delay (cf. Figure 1): For effect-consistent choices, facilitation of responses by activation of the corresponding action should be offset by activation of a long

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[1] For the meta-analysis, we used the "method of adding *t*s" suggested by Rosenthal (1978, p. 187): $Z = \dfrac{\sum t}{\sqrt{\sum \dfrac{df}{df-2}}}$, with Z being evaluated against a standard normal distribution.

[2] In the study by Elsner and Hommel (2004), RTs increased when the A–E interval increased from 50 ms to 1,000 ms but did not increase additionally when the interval was 2,000 ms. Given a between-subjects design with eight subjects per interval condition, however, one should be careful to draw strong conclusions from this observation.
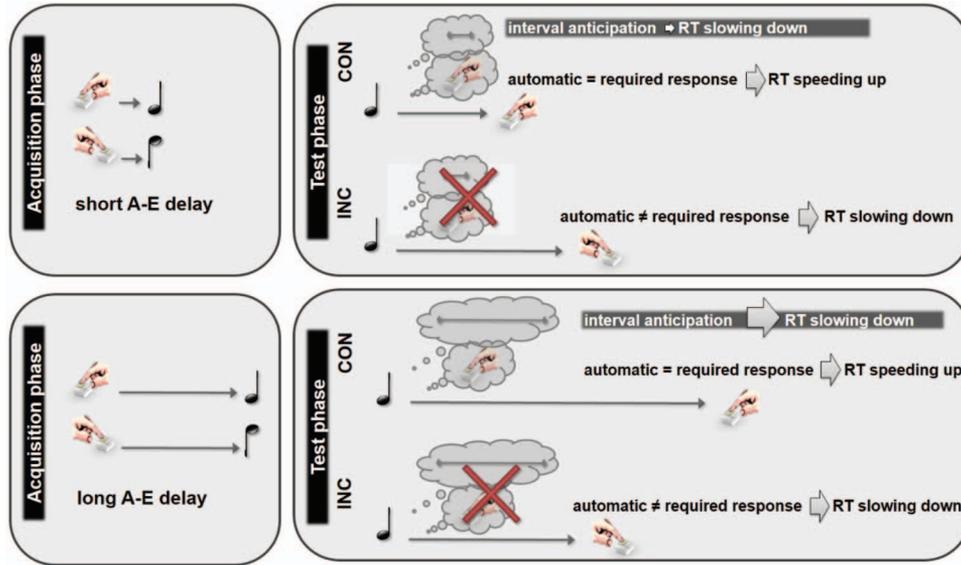
Figure 1. Illustration of the opponent processes model of temporal consistency effects. With short intervals (upper panel), suppression of the inappropriate response in the inconsistent condition takes more time than the (short) interval anticipation effect for the consistent condition. With long intervals (lower panel), suppression of the inappropriate response in the inconsistent condition takes less time than the (long) interval anticipation effect for the consistent condition. Line arrows indicate the duration of an interval (longer arrows indicate longer intervals), whereas block arrows indicate the strength of an influence (with bigger arrows corresponding to a larger impact). CON = effect-consistent actions, INC = effect-inconsistent actions. See the online article for the color version of this figure.

A–E interval, leading to prolonged initiation of the associated action. For effect-inconsistent choices, inappropriate activation of actions and activation of a long A–E interval by the presented action effect are suppressed, leading to faster RTs than for consistent choices.

However, automatic retrieval of the time interval should only affect temporal features of the response (i.e., RTs), while response choices should be not affected by this information. For response choices, we therefore expected effect-consistent responses to be
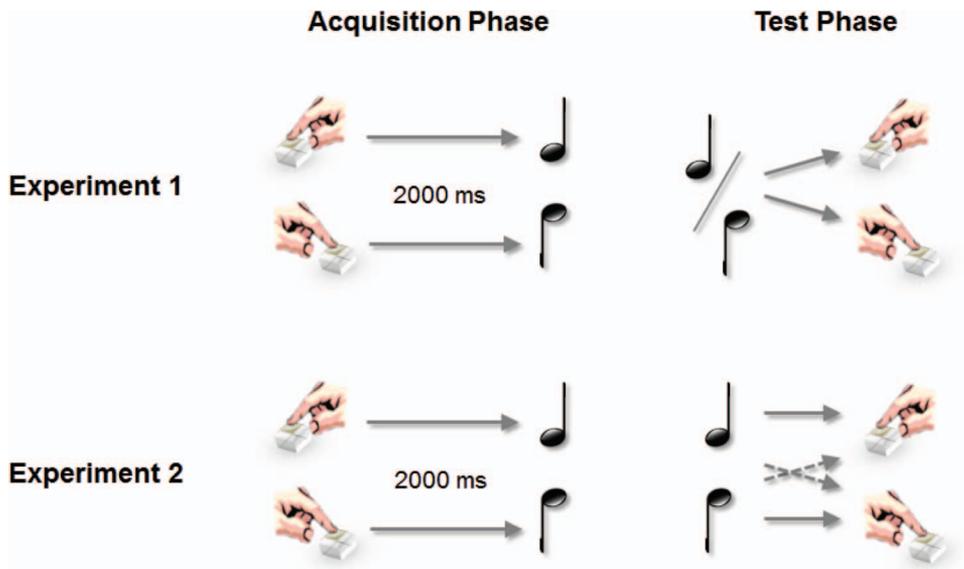

Figure 2. Design of Experiments 1 and 2. Both experiments used a forced-choice acquisition phase in which two key press responses produced different tones occurring after a delay of 2,000 ms. The acquisition phase was followed by a free-choice test phase in Experiment 1 and by a forced-choice test phase in Experiment 2. See the online article for the color version of this figure.

emitted more frequently than effect-inconsistent responses, replicating previous studies (Elsner & Hommel, 2001; Hoffmann et al., 2009; Pfister et al., 2011). The two different dependent variables thus provide a tool to disentangle the two dimensions of response identity and interval length within a single experiment.

Method

Participants. Forty-four students at the University of Würzburg were paid for participation (seven left-handed, 33 women, mean age = 27.5 years, age range = 17–60 years). Participants were naive to the purpose of the experiment. Data of two participants were excluded due to unusual high error rates ($M = 17\%$, > 3 SDs). Data of three participants were excluded because they did not comply with the instructions and pressed only a single key in the test phase.

Stimuli. A green or red asterisk was displayed at the center of a black screen during the acquisition phase. The asterisk subtended 1.15° of visual angle in width and height, measured from a viewing distance of 50 cm. Participants responded with their left and right index fingers by pressing the *d* and *l* keys of the keyboard, and the two keys were marked with color patches. Sinusoidal tones of 60 dB with a frequency of 400 Hz (low pitch) and 800 Hz (high pitch) were presented as auditory effects; an additional tone with a frequency of 600 Hz was used as a no-go tone in the test phase. All tones were presented via headphones. Key-tone and color-key mappings were counterbalanced across participants.

Procedure. The experiment consisted of two phases: an acquisition phase and a test phase.

Acquisition phase. For the acquisition phase, participants received the following instructions:

> At the beginning of each trial, a white star will appear on the screen. If the star changes to red, press the left [right] key as fast as possible. If the star changes to green, press the right [left] key as fast as possible. Each time you press a key, you will hear a tone. The tones are not important for the task and can be ignored. Try to respond as fast as possible without making too many errors.

A white asterisk was presented for 1,000 ms at the start of a trial. Then, the color of the asterisk changed to red or green, which prompted the participant to respond as quickly as possible. The assignment of left and right key presses to the color of the asterisk was counterbalanced across participants. Upon registration of a key press, a high or low tone (200 ms) was presented after a delay of 2 s. Key presses during the delay were logged to check whether participants shortened the time interval between action and effect with additional key presses. The next trial started after 1.5 s. We classified responses faster than 100 ms as anticipatory reactions and responses slower than 1,000 ms as omissions. In these cases, a visual warning signal appeared for 1 s on the screen. These trials were repeated. Participants worked through four blocks with 50 trials each.

Test phase. A go/no-go-task was used to minimize strategic response choices (for a similar procedure, see Elsner & Hommel, 2001, Experiment 3). Each trial started with the presentation of one of three tones for 200 ms. The high and low tones that were presented as action effects during the acquisition phase served as go signals (the high tone appeared in 25% of the trials, and the low tone appeared in another 25%). The neutral tone 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. They were explicitly instructed to decide spontaneously and not to use any kind of strategy. The next trial started after 1.500 ms. An error message appeared for 1,000 ms on the screen after a response anticipation (RT < 100 ms), a response omission (RT > 1,000 ms), or after a response in a no-go trial. Incorrect trials were repeated at the end of the experiment. In the test phase, key presses no longer produced tones. For the test phase, participants received 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.

Participants performed eight practice trials to familiarize them with the go/no-go task. These trials were not further analyzed (cf. Elsner & Hommel, 2001, 2004; Hoffmann et al., 2009; Pfister et al., 2011). Subsequently, participants work through five blocks with 20 go-trials and 20 no-go trials. After each block, a summary informed participants about their mean RT and error rate.

Results

Acquisition phase. The mean error rate was 2.2% ($SD = 1.5\%$), and the mean RT was 460 ms ($SD = 74.0$). The proportion of key presses during the response-effect interval was very low (< 2% of all trials).

Test phase. Trials with response anticipations (< 0.1%) or response omissions (0.8%) and trials with erroneous responses in no-go trials (2.3%) were excluded from the analysis, as were trials that followed such errors (3.4%). In addition, RTs were removed that deviated more than 3 SDs from the corresponding condition mean (0.8%). Mean choice frequencies and RTs were then analyzed with t tests for paired samples.

Choice frequencies. As shown in Figure 3, effect-consistent responses were selected more often ($M = 59.6\%$) than effect-inconsistent responses, $t(38) = 3.40$, $p = .002$, $d = 0.54$. To test whether participants have selected responses prior to effect presentation, we correlated the proportion of consistent responses with the proportion of errors in no-go-trials. This analysis did not show a significant correlation, $r = .005$, $p = .976$.

Reaction times. As expected, effect-consistent responses ($M = 462$ ms) took significantly longer to be initiated than effect-inconsistent responses ($M = 436$ ms), $t(38) = 2.90$, $p = .006$, $d = 0.46$.

Correlation analyses. We further correlated the percentage for effect-consistent response choices with the difference in RTs of effect-inconsistent responses and effect-consistent responses. Two outlier participants were excluded (> 2.5 SDs of the group mean).[3] As can be seen in Figure 4, participants who displayed a greater

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[3] When including the data of these participants, the correlation remained significant.
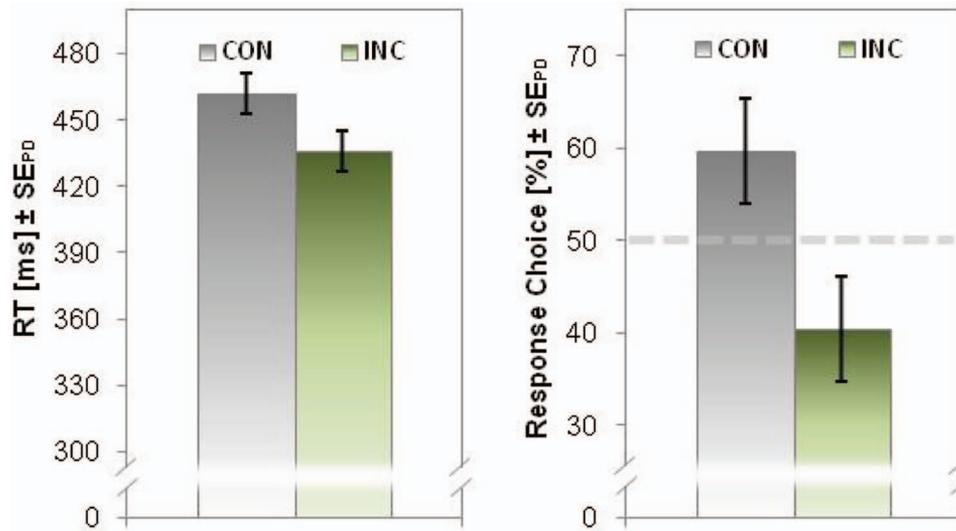
Figure 3. Mean reaction time (RT, left panel) and choice frequencies (in percentages, right panel) in Experiment 1 as a function of consistency (CON = consistent mapping; INC = inconsistent mapping). Error bars show standard errors of paired differences (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

bias for effect-consistent response choices showed also a greater slowing of RTs for effect-consistent responses, $r = .82$, $p < .001$.

Discussion

In Experiment 1, we investigated whether the time interval between actions and their perceived effects is integrated into the cognitive structure controlling the action. As noted earlier, if sensory effects become bound bidirectionally to the actions pre-

Figure 4. Correlation of the percentage of effect-consistent response choices and the consistency effect for reaction times (RTs; effect-consistent responses minus effect-inconsistent responses) across each participant. Scores exceeding 50% for response choices indicate a bias for the effect-consistent response choice. Positive difference scores for RTs indicate a slowing of effect-consistent responses. CON = consistent mapping; INC = inconsistent mapping.

ceding them, the presentation of the sensory effect should prime the associated action. The proportion of effect-consistent choices supported this prediction, as effect-consistent responses were chosen more frequently than effect-inconsistent responses. This finding replicates previous studies (Elsner & Hommel, 2001; Hoffmann et al., 2009; Pfister et al., 2011), yet with a long A–E interval (2 s). Even more important, participants needed more time to initiate an effect-consistent response than an effect-inconsistent response. This finding is in line with the present hypothesis that temporal information is included into action-effect associations and automatically retrieved during response selection. Furthermore, participants who particularly preferred effect-consistent responses were also slower to initiate these responses, providing an additional piece of evidence for the conclusion that temporal information about the action-effect interval was retrieved during response selection.

Experiment 2

Given the methodological difference in the test phase between our design (free-choice test) and the study by Elsner and Hommel (2004; forced-choice test), the aim of Experiment 2 was to replicate the reversed A–E consistency effect in using a design that is more similar to Elsner and Hommel's. Additionally, to come up with a better understanding of why the reversed A–E consistency effect in Elsner and Hommel's study was considerably weaker than in our Experiment 1 and did not significantly differ from zero, we wanted to check whether they observed nonsignificant differences (individually tested) due to insufficient power. Therefore, we recruited a large sample to get a better estimate of the true population effect size. For practical reasons, we tested two independent samples at different times. Thus, we treated them as independent experiments (2a and 2b), although the experimental procedures were identical.
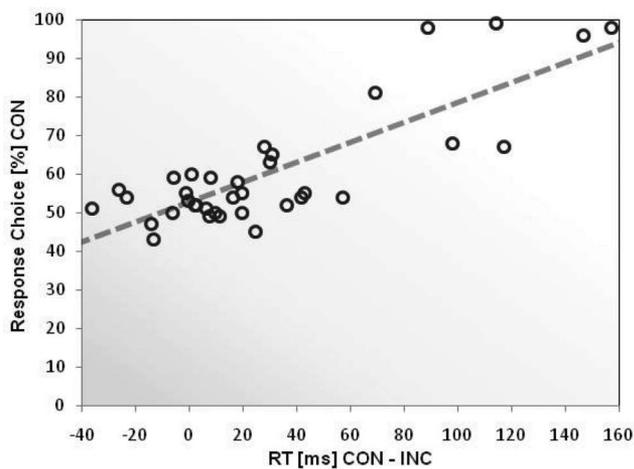
Contingencies between responses, acoustic effects and the A–E time interval were as in Experiment 1. In the test phase, however, the previous effects were now presented as response-imperative stimuli. For half of the participants, the mapping between the tones and the responses was consistent with the acquisition phase (consistent group); for the other half, the mapping was reversed (inconsistent group). In the consistent-mapping group, activation of a long A–E interval should lead to prolonged RTs (in line with the hypothesis that ideomotor priming of a response is offset by the time-costly retrieval of a long A–E time interval; see Figure 1). For the inconsistent-mapping group, it was hypothesized that incorrect response tendencies induced by ideomotor processes are suppressed, rendering a time-costly retrieval of the associated time interval less effective or likely.

Method

Participants. Forty-six students participated in Experiment 2a (three left-handed, 40 women, $M = 25.7$ years, age range = 18–46 years) and another 40 students participated in Experiment 2B (three left-handed, 33 women, $M = 21.8$ years, age range = 18–42 years). Data of one participant in Experiment 2a were lost due to a technical failure. Data of one participant in Experiment 2b were removed due to an unusually high error rate ($M = 24\%$, > 3 SDs). Participants were randomly assigned to consistent and inconsistent groups in the test phase.

Procedure. The acquisition phase was identical to Experiment 1.

Test phase. Participants received the following instructions (assignments of tone and responses were counterbalanced):

It is your task to press the left [right] key if you hear a high tone and to press the right [left] key if you hear a low tone. Try to be as fast as possible and avoid errors.

The tones presented as action effects during the acquisition phase served as response-imperative stimuli. The consistent group responded to the tones with response keys that were consistent with the key-effect relations of the acquisition phase, whereas the inconsistent group received opposite tone-response instructions. At the start of each trial, a tone was presented for 200 ms. High and low tones were presented equally often and in random order. The next trial started 1,500 ms after a correct response. A warning message appeared on the screen if the response was too fast (RT < 100 ms), too slow (RT > 1,000 ms), or incorrect. Incorrect trials were repeated at the end of the experiment in random order.

Participants performed eight practice trials and five blocks of 20 test trials. After each block, a block summary informed about the mean RT and error rate.

Results

Acquisition phase. Response errors occurred in $M = 3.2\%$ ($SD = 2.4\%$) and $M = 2.6\%$ ($SD = 2.0\%$) of the trials and response speed for correct responses was M = 450 ms ($SD = 95$ ms) and M = 418 ms ($SD = 74$ ms) in Experiments 2a and 2b, respectively. The frequency of key presses during the delay interval was very low in both experiments (<1% of all trials).

Test phase. Trials with anticipations (Experiment 2a: 0.1%; Experiment 2b: 1.1%), omissions (0.4%; 0.2%), or erroneous responses (4.6%; 5.2%) were discarded from RT analyses, as were trials following such errors (5.5%; 6.0%). In addition, RTs were removed that deviated more than 3 SDs from the corresponding condition mean (0.9%; 0.7%). Mean RTs and percentage of errors were analyzed with t tests for independent samples.

As shown in Figure 5, responses of the inconsistent group were significantly faster than responses of the consistent group in Experiment 2a ($M = 324$ ms vs. 356 ms), $t(43) = 2.41$, $p = .020$, $d = 0.73$, and Experiment 2b ($M = 314$ ms vs. 350 ms), $t(37) = 2.25$, $p = .030$, $d = 0.72$. Error rates of the inconsistent and the consistent groups were not different in Experiment 2a ($M = 4.9\%$ vs. 6.0%) and Experiment 2b ($M = 5.0\%$ vs 6.0%), both $|ts| < 1$.
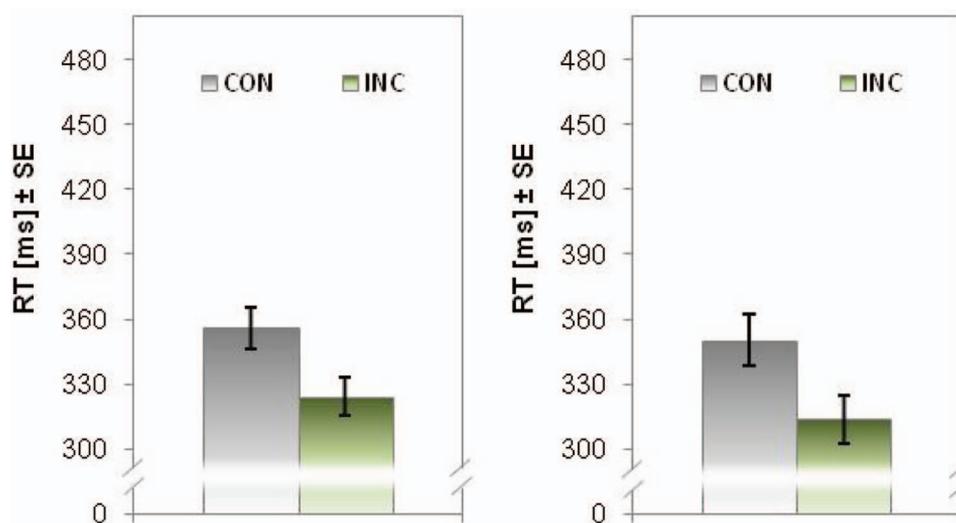

Figure 5. Mean reaction time (RT) in Experiment 2a (left panel) and Experiment 2b (right panel) as a function of consistency (CON = consistent mapping; INC = inconsistent mapping). Error bars show standard errors of the between-subjects difference. See the online article for the color version of this figure.

Discussion

In the forced-choice test phase of Experiments 2a and 2b, participants responded significantly *slower* when the response instructions were consistent with the learned key-effect relations of the acquisition phase than when the instructions were inconsistent with the corresponding key-effect relations. This finding provides further evidence that a long time interval between responses and effects was automatically retrieved during response selection. Furthermore, the present results suggest that the null effects obtained by Elsner and Hommel (2004) were caused by insufficient statistical power to detect an inconsistency benefit. In line with this argument, a post hoc power analyses (using G–Power3; Faul, Erdfelder, Lang, & Buchner, 2007) showed that the Elsner and Hommel study would have needed a minimum effect size of $d = 1.29$ for a sufficient power of .80 with a sample size of $n = 8$. Given the moderate effect sizes obtained in Experiment 2A ($d = 0.73$) and Experiment 2b ($d = 0.72$), it is thus plausible that statistical power in the study of Elsner and Hommel was not sufficient to detect a reversed A–E consistency effect.

Experiment 3

A third experiment was conducted to provide a more conclusive test of our hypothesis that temporal information about A–E intervals is retrieved during action selection. As argued previously, the delay of response initiation should be a function of the interval length. Therefore, the length of the A–E interval was manipulated systematically in Experiment 3.

In line with previous research on R–E compatibility effects (Kiesel & Hoffmann, 2004; Kunde, 2003), we hypothesized that previously experienced time intervals between action and effects are anticipated during response selection. Short and long A–E intervals should hence affect the speed of response initiation differently, because long intervals should require more time to anticipate and thus should prolong response initiation more than short intervals. One response key triggered an acoustic effect after a long delay (2,000 ms) like in the experiments before. Most critically, however, the other response triggered a tone after a relatively short delay (50 ms). It was expected that responses associated with a short A–E delay are initiated faster than responses associated with a long delay in a free-choice test (Experiment 3a) and in a forced-choice test situation (Experiment 3b).

Method

Participants. Twenty-three students participated in Experiment 3a (no left-handers, 16 women, $M = 24.3$ years, age range = 18–56 years), and an additional 23 students participated in Experiment 3b (two left-handed, 17 women, $M = 27.5$ years, age range = 19–46 years). Data of one participant in Experiment 3a were excluded due an exceptionally high error rate ($M = 16\%$, >3 SDs).

Stimuli and procedure. For Experiment 3a (free-choice test), each trial started with the presentation of a white asterisk. Instructions stated that participants could choose freely between both response keys with the only restriction that both keys should be used about equally often during the experiment. They were encouraged to decide spontaneously and not strategically. For Ex-

periment 3b (forced-choice test), 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 when a green (red) asterisk appeared and to press the right key when a red (green) asterisk appeared on the screen (for detailed instructions, see the test phases of Experiments 1 and 2).

In both experiments, a key press triggered a high (800 Hz) or low tone (400 Hz) after a short (50 ms) or a long (2,000 ms) time interval (with counterbalanced assignment of tones and delays to the response keys). The next trial started 1,500 ms after a correct response. A warning message appeared on the screen when the response was too fast (RT < 100 ms) or incorrect (only Experiment 3b). Participants worked through eight practice trials, which were not further analyzed, and five blocks with 40 trials each. After each block, a summary informed participants about the proportion of response choices (Experiment 3a) or about the RT level and error rate in the last block (Experiment 3b).

Results

Experiment 3a (free-choice test). Trials with latencies below 100 ms and above 1,000 ms (2.5%) and trials following a warning message (2.6%) were discarded from the RT analyses. In addition, RTs were removed that deviated more than 3 SDs from the condition mean (2.3% of all trials). Relative frequencies of left and right key presses were computed for each participant; a response proportion of 44.5%–55.5% (in absolute numbers: 89–111) or more extreme was classified as a significant deviation from an equal response distribution (corresponding to a two-category chi-square goodness-of-fit test with a significance level at $\alpha = .15$; cf. Hoffmann et al., 2009). Two participants were excluded from further analyses based on this criterion.

Participants chose both response keys about equally often, irrespective of the response-effect delay (short delay: 51%), $|t| < 1$. Most important, key presses were faster when the effect appeared after a short delay ($M = 327$ ms) relative to a long delay ($M = 351$ ms), $t(20) = 3.24$, $p = .004$, $d = 0.71$ (see Figure 6).

Experiment 3b (forced-choice test). Trials with RTs below 100 ms and above 1,000 ms (0.5%), trials with erroneous responses (2.2%) and trials following any error (2.3%) were discarded for the RT analyses. In addition, RTs were removed that deviated more than 3 SDs from the corresponding condition mean (1.7%).

Like in Experiment 3a, key presses were faster when the response-effect delay was short ($M = 398$ ms) relative to long ($M = 419$ ms), $t(21) = 4.86$, $p < .001$, $d = 1.03$ (see Figure 6). Error rates were not different for short-delay responses ($M = 1.9\%$) and long-delay responses ($M = 2.3\%$), $t(21) = 1.18$, $p = .248$, $d = 0.25$.

Comparison of Experiments 3a and 3b. For a cross-experimental comparison, we submitted the data to a 2 (experiment) $\times$ 2 (long delay vs. short delay) split-plot analysis of variance. Only main effects reached significance, that is, participants in the free-choice condition responded faster (Experiment 3a, $M = 357$ ms) than participants in the forced-choice condition (Experiment 3b, $M = 412$ ms), $F(1, 41) = 13.07$, $p < .001$, $\eta_p^2 = .24$. In line with the single comparisons of each experiment, responses producing effects after a short delay were emitted faster ($M = 374$ ms) than responses producing effects after a long delay
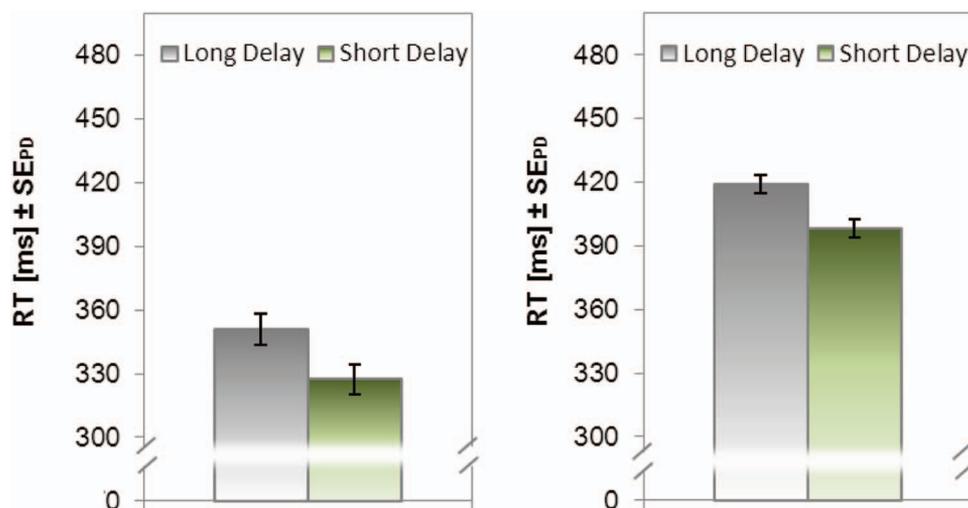
Figure 6. Mean reaction time (RT) in Experiment 3a (free choice, left panel) and Experiment 3b (forced choice, right panel) as a function of delay duration between action and effect. Error bars show standard errors of paired differences (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

($M = 395$ ms), $F(1, 41) = 19.55$, $p < .001$, $\eta_p^2 = .32$. This effect was not further modulated by experiment ($F < 1$).

Discussion

In Experiment 3, we investigated an endogenous activation of short and long A–E intervals during response selection. Results showed a prolonged initiation of responses that produced an effect after a long (2,000-ms) delay in comparison with responses that produced an effect after a short (50-ms) delay. Results provide clear evidence that the time interval between the response and its effect was anticipated during response selection, affecting the time that was needed to initiate a corresponding response.

Experiments 3a and 3b also examined whether information about the A–E interval is activated differently in forced-choice versus free-choice situations. This was motivated by recent findings suggesting that both forms of action control rely on different forms of control modes (Herwig et al., 2007; Herwig & Waszak, 2009, 2012; Kühn, Elsner, Prinz, & Brass, 2009; Pfister et al., 2010; Pfister, Melcher, Kiesel, Dechent, & Gruber, 2014). Based on this research, it was expected that the endogenous activation of response effects (and the associated information about the R–E interval) is elevated in a free-choice action mode (Experiment 3a) relative to a forced-choice action mode (Experiment 3b). However, the cross-experimental comparison did not yield any evidence for this prediction (see Pfister & Kunde, 2013, for similar findings).

General Discussion

This study examined whether temporal information about the interval between actions and effects is integrated into a cognitive action structure and automatically retrieved during response selection. The results were very clear: Long effect delays prolonged response initiation relative to short delays in conditions in which the anticipation of an action effect was cued exogenously (Experiments 1 and 2) or endogenously (Experiment 3). These results

suggest that the time linking an action to an effect is integrated into cognitive action structures. After integration, the interval is automatically reactivated as a response feature during action preparation.

More precisely, the results of Experiments 1 and 2 suggest that suppression of inappropriate response tendencies also affects the representation of temporal information. The length of the A–E interval determines whether suppression of inappropriate responses (and intervals) in the inconsistent condition dominates over anticipation of temporal information in the consistent condition or the other way around. With short intervals, suppression of the inappropriate responses in inconsistent conditions takes more time than the (short) interval anticipation effects for consistent conditions. With long intervals, however, suppression of the inappropriate A–E association in inconsistent conditions takes less time than the (long) interval anticipation for consistent conditions. Thus, long intervals may yield an RT advantage for inconsistent mappings: the reversed A–E consistency effect.

Inhibition as Alternative Explanation

Alternating patterns of consistency that vary as a function of temporal intervals between stimuli have also been reported for prime-target effects. Eimer and Schlaghecken (1998) presented arrows pointing to the left or right direction, and participants had to indicate the direction of the arrow. It should be noted that masked prime arrows preceded the target arrow. With short intervals between prime and target, a usual compatibility effect emerged; that is, participants were faster in identifying compatible compared with identifying incompatible prime–target pairs. With longer intervals, however, the compatibility effect reversed, and participants were faster with incompatible prime–target pairs (see also Kiesel, Berner, & Kunde, 2008). Eimer and Schlaghecken explained this effect with an inhibition of the primed response. With longer intervals, primed response activation has to be inhibited to avoid premature responding. Compatible trials require a

reactivation of the inhibited response, leading to a disadvantage for compatible prime–target pairs (Eimer & Schlaghecken, 1998, 2003). Although the negative compatibility effect bears a resemblance to the reversed A–E learning effect reported here, the mechanisms underlying the negative compatibility effect cannot explain our data. First, the compatibility effect in the prime–target paradigm is a measure of response activation due to brief visual exposure of a stimulus, whereas the consistency effect in the induction paradigm is a measure of response activation due to previously learned A–E associations. This theoretical difference becomes important when considering procedural differences of both paradigms. In the prime–target paradigm, participants respond to the target but withhold responses to the prime, whereas participants in the induction paradigm are explicitly instructed to respond to the action–effect tone, and no further stimulus is presented. Second, any inhibition account fails to explain why Experiment 1 showed evidence for A–E learning in the response frequencies. Assuming that the learning of A–E associations is inhibited for longer intervals would lead one to predict the same inconsistency effect for both dependent variables and not opposing effects for RT and choice frequencies as reported.

Empirical Evidence for Temporal Interval Learning

In animal research, the phenomena of inhibition of delay in classical conditioning describes withholding of the response until the end of a long CS just before the US is presented (Drew, Zupan, Cooke, Couvillon, & Balsam, 2005; Pavlov, 1927/1960; Rescorla, 1967; for evidence on response timing, see Sears, Baker, & Frey, 1979). In operant conditioning. it has been reported that animals learn to exploit temporal regularities to maximize reward. In these studies, animals learned to press different levers at specific point in time to achieve a reward (Arantes & Machado, 2008; Church & Deluty, 1977). Analogous results have been reported in research with human participants in the so-called "foreperiod" paradigm (e.g., Los & van den Heuvel, 2001; see Niemi & Näätänen, 1981, for a review). Typically, a first noninformative stimulus is presented, and after a specific delay, a second stimulus is presented to which participants must respond. With fixed durations of the delay, RTs increase with the duration of the delay. This is explained with impaired accuracy of duration judgments for long intervals. Participants form expectancies over the correct point in time for their response, but the duration judgment for long intervals is less accurate than for shorter intervals (Allan & Gibbon, 1991). This leads to systematic timing errors with longer intervals.

First, suggestive evidence for learning of temporal information between individuals' own actions and effects comes from a study of Haering and Kiesel (2012). In this study, participants were faster to detect the onset of an action effect when this effect appeared after a regular delay compared with an earlier onset than they had experienced previously. This study, however, did not obtain evidence for an automatic integration of the delayed effects themselves into cognitive action structures; possible reasons for these results might be the use of an acquisition phase with reduced contingency between actions and effects or, alternatively, the detection task that was used to probe for A–E associations. Furthermore, it has been suggested that expectations about upcoming action effects mainly reflect monitoring processes and do not necessarily imply bidirectional A–E associations (Band, van

Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; Verschoor, Spapé, Biro, & Hommel, 2013). Thus, this research does not allow for strong conclusions about whether the interval between an action and a sensory effect becomes part of the associative structure controlling the action.

Learning A–E Intervals: Possible Mechanisms and Contents

The present results show that learning effects can be observed even with long action-effect delays. At a first glance, this may seem surprising. Since Hume's (1739/2003) seminal work on causality, it has been well known that the time interval between an action and its effect is a major determinant for the perception of causality and for the efficiency of knowledge acquisition and learning (Grice, 1948). However, while all contemporary learning theories acknowledge the critical role of timing for learning, different theories have proposed different explanations for the impact of delays on learning.

According to traditional association models, an association between two events (here:, an action and its sensory effect) is only formed during a brief critical integration window. With longer intervals, the associative link is weakened, resulting in decreased or no learning (Dickinson, 2001; Shanks, Pearson, & Dickinson, 1989). This traditional assumption of associative learning theory, however, is challenged by new studies showing that causal learning is observed even with long delays of action consequences (Buehner & May, 2004; Greville, Cassar, Johansen, & Buehner, 2013; Schmidt & De Houwer, 2012). According to cognitive perspectives on causal learning (Greville et al., 2013), learning is impaired with delayed effects because a delay places more demand on memory and increases uncertainty. The availability of high-level knowledge (e.g., knowledge about the mechanisms of a system (Buehner & May, 2004) or cues that structure the sequence of events, however, reduces memory load and increases certainty about causal effects even with long delays. A trial structure with two exclusive responses and two response-contingent outcomes may have provided such structural cues in the present study, facilitating causal learning even with a substantial delay of the action effects.

As described previously, temporal contiguity is traditionally considered as a mechanism that fosters learning. However, some theoretical accounts explicitly focus on temporal interval as a content of learning (Gallistel & Gibbon, 2000; Honig, 1981; Matzel, Held, & Miller, 1988; Miller & Barnet, 1993). Although quite different in their assumptions and predictions, both Gallistel and Gibbon's rate expectancy theory and Miller and Barnet's temporal coding hypothesis explicitly state that representations of events and their temporal information are stored in memory and subsequently exploited for behavioral control. The present results apply this theoretical notion of temporal interval learning to A–E learning by showing that temporal information is also the content of action-related knowledge structures.

From Mechanisms to Content

The role of intervals linking actions to effects also has been the focus of research on the phenomenon of intentional binding (Haggard, Clark, & Kalogeras, 2002; for a review, see Hughes, Desan-

tis, & Waszak, 2013). Haggard et al. (2002) showed in a number of experiments that intentionally produced action effects are perceived as closer in time than incidentally produced effects. A functional interpretation of their results emphasized the importance of binding actions to effects for coherent conscious experience. Clearly, in order to come up with a subjective estimate of time intervals, participants have to base their judgments on a representation of this interval. An integration of A–E intervals in cognitive action structures is a potential mechanism for this representation. It is tempting to speculate whether the subjective compression of time for voluntary action is inferred from an unbiased interval representation or whether voluntary actions cause distorted interval representation already during learning.

Summary

The present research shows that responses become associated not only with perceived effects but also with the time interval that passes until the appearance of the effect. The time interval is then retrieved during action planning like other features of action effects. Thus, bidirectional associations of actions and their effects do not only encode a sequence of two events but also the temporal relationship between these events.

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