Psychological Research (2012) 76:336–344
DOI 10.1007/s00426-011-0341-8

ORIGINAL ARTICLE

Time in action contexts: learning when an action effect occurs

Carola Haering · Andrea Kiesel

Received: 15 November 2010 / Accepted: 3 May 2011 / Published online: 17 May 2011

Abstract Action effects do not occur randomly in time but follow our actions at specific delays. The ideomotor principle (IMP) is widely used to explain how the relation between actions and contingently following effects is acquired and numerous studies demonstrate robust action-effect learning. Yet, little is known about the acquisition of temporal delays of action effects. Here, we demonstrate that participants learn that action effects occur at specific delays. Participants responded slower to action effects that occurred earlier than usual. In addition, participants often prematurely responded before the effect when it occurred later than expected. Thus, in contrast to biases of time perception in action contexts (e.g., Haggard, Trends Cogn Sci 9:290–295, 2005; Stetson et al., Neuron 51:651–659, 2006), participants learn and exploit temporal regularities between actions and effects for behavioral control.

Introduction

Human actions are mostly goal directed. We perform actions to produce specific effects. Effects often occur after specific temporal delays. For example, when the lever of a toaster is depressed, usually a toasted slice of bread will pop up after a minute. About 2 s after clicking a hyperlink, an Internet page will load, or when a stone is thrown into a well, we can hear it hitting the ground after 0.5 s. Goal-directed behavior requires that we learn relations between our own actions and the produced effects. Most likely, we also learn when these effects occur. Indeed, the acquisition of action–effect relations has been extensively studied. Yet, to our knowledge little is known about the acquisition of temporal relations in action contexts.

The ideomotor principle (IMP, cf. Herbart, 1825; for more recent reviews see Greenwald, 1970; Shin, Proctor, & Capaldi, 2010) is a framework that accounts for action-effect learning. It assumes that representations of actions and their contingently following effects are associated bidirectionally. Consequently, performing an action does not only lead to expectations of its effect, but vice versa, and anticipating an effect also accesses the action that usually brings about this effect.

Numerous recent studies have shown that experiencing contingent action–effect relations does indeed lead to the acquisition of action–effect associations using a paradigm first introduced by Elsner & Hommel, (2001). In an acquisition phase, participants pressed keys that contingently produced action-specific effect stimuli, which were irrelevant to the current task. In the test phase, the stimuli, which had served as irrelevant effects during the acquisition phase, preceded the action. Two measures have proven useful indicators for action-effect binding. First, responses to the former effects are faster, when the mapping of stimuli and keys is the same in the acquisition and test phase than when the assignment of keys and stimuli is reversed. Second, when participants freely choose responses after the presentation of one of the former effects in the test phase, they tend to choose the key that produced this stimulus during the acquisition phase more often (Dutzi & Hommel, 2009; Eenshuistra, Weidema, & Hommel, 2004; Elsner & Hommel, 2001, 2004; Hoffmann, Lenhard, Sebald, & Pfister, 2009; Hommel, 1996; Hommel, Alonso, & Fuentes, 2003; Pfister, Kiesel, & Hoffmann, 2011; but see also Herwig, Prinz & Waszak, 2007; Herwig & Waszak, 2009).

C. Haering (✉) · A. Kiesel
Department of Psychology, University of Wuerzburg,
Roentgenring 11, 97070 Würzburg, Germany
e-mail: haering@psychologie.uni-wuerzburg.de

Regarding time in the context of action-effect learning, it has been shown that besides the contingency of actions and effects, temporal contiguity adds to the acquisition of action–effect relations (Elsner & Hommel, 2004). To our knowledge, however, there are no studies on human action-effect learning that examine if a specific delay at which an action effect occurs is acquired. With a variation of the described paradigm, we tested whether the delay between an action and its effect is acquired and applied to optimize behavior.

At first sight, such a research question may seem trivial. First, there is evidence regarding learning of time intervals in animal learning studies. It has been shown that both delays between conditioned and unconditioned stimuli and delays between responses and contingently presented rewards are acquired (for an overview see Gallistel & Gibbon, 2000). For example, Swanton, Gooch, & Matell (2009) showed that rats learn that a conditioned stimulus A predicts that the unconditioned stimulus will appear in 10 s, while another conditioned stimulus B predicts the unconditioned stimulus to appear in 20 s. Based on these studies, we conclude that animals acquire information on time delays between two stimuli. Further, animals prefer response alternatives that bring forth a reward, i.e., an action effect, after short delays over response alternatives that bring forth a reward after longer delays (Rachlin & Green, 1972). Yet, it is unclear whether animals indeed acquire and apply precise information on delays between actions and action effects because animals usually prefer the response with early reward even when the amount of late reward largely exceeds the amount of early reward (Rachlin & Green, 1972).

Second, there are a number of studies that show that people apply temporal information to optimize behavior. For example, people respond faster when an explicit temporal cue validly predicts at which time a stimulus will appear compared to a no-cue or an invalid cue condition (Correa, Lupiáñez, & Tudela, 2005; Correa, Lupiáñez, & Tudela, 2004; Coull, Frith, Büchel, & Nobre, 2000; Coull & Nobre, 1998; Kingstone, 1992; MacKay & Juola, 2007; Miniussi, Wilding, Coull, & Nobre, 1999; Nobre, 2001). Further, people adapt to variable foreperiods. If foreperiods vary blockwise, participants respond faster after shorter foreperiods. To account for this finding, it is assumed that participants predict the foreperiod that is realized in the block and this prediction is more accurate for shorter foreperiods (e.g., Bausenhart, Rolke, & Ulrich, 2008; Los & Van den Heuvel, 2001; Niemi & Näätänen, 1981). In contrast, when the foreperiod varies unpredictably within a block, participants respond faster the longer the foreperiods. This finding was explained in terms of aging probabilities (e.g., Niemi & Näätänen, 1981; Steinborn, Rolke, Bratzke, & Ulrich, 2009). The more time elapsed in the course of the foreperiod interval, the more probable the stimulus becomes.

In addition, several studies have shown that temporal regularities are learned when repeatedly presented without any information about those regularities given in advance (Albinet & Fezzani, 2003; Thomaschke, Wagener, Kiesel, & Hoffmann, 2011; Wagener & Hoffmann, 2010a, b). If, for example, target stimuli regularly occur after specific delays, participants acquire information about these covariations of delays and target identities (Wagener & Hoffmann, 2010b). However, these studies varied time intervals between two stimuli, a cue and the imperative target stimulus. None of these studies actually demonstrated that delays between actions and action effects are acquired and applied to optimize subsequent behavior.

Yet, some recent studies on time perception demonstrated biases of time perception in action contexts (e.g., Engbert & Wohlschläger, 2007; Haggard, Aschersleben, Gehrke, & Prinz, 2002; Haggard, Clark, & Kalogeras, 2002; Haggard & Cole, 2007; Obhi, Planetta, & Scantlebury, 2009; Tsakiris & Haggard, 2003; Wohlschläger, Engbert, & Haggard, 2003; Wohlschläger, Haggard, Gesierich, & Prinz, 2003). In a study of Haggard, Clark, et al., (2002), for example, participants pressed a key at a freely chosen time. At 250 ms after the action, a tone was presented as action effect. During the trial, participants saw a revolving clock hand (Libet, 1985; Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010; Wundt, 1887) and after each trial participants indicated the time of the action or of the effect tone. If participants knew in advance whether to judge the action or the effect, the action was perceived somewhat later in time and the effect was perceived somewhat earlier. Thus, there is a bias to perceive action and effect closer in time as they actually are. This bias is even more extreme when participants are instructed to attend to both the time of the action and the time of the effect. When participants are informed only after action and effect have happened whether to indicate the time of the action or the time of the effect, they judged the action and the effect to have happened at the same point in time (Haggard & Cole, 2007; for similar biases of time perception in action contexts observed with different methods see Engbert, Wohlschläger, & Haggard, 2008; Engbert, Wohlschläger, Thomas, & Haggard, 2007; Stetson et al., 2006).

Based on these studies, we wondered if participants represent time intervals between actions and effects such that they are able to behaviorally adapt to temporal regularities between actions and effects. To study this, we had participants perform actions which produced effects after action-specific delays. To facilitate learning of the task for our participants, we provided an (at least partially) ecologically valid design using drawings of light bulbs as stimuli and color changes of the light bulbs described as the light bulb being turned on. We reasoned that this resembled switching on a light by pressing a light switch and waiting for the light to turn on. We thought that such an everyday life association of action and effect might facilitate the acquisition of temporal delays in action contexts, yet it is beyond the scope of the study to test this assumption. In more detail, during the experiment, participants watched a light bulb and were asked to switch on the light bulb by pressing one of two possible keys. Each key press resulted in one of two possible color changes of the bulb that were described as "the light is switched on" to the participants.

The experiment consisted of a learning phase and a test phase. During the learning phase, we presented action-specific effects that occurred after action-specific delays. Participants first pressed one of two keys according to visual imperative stimuli. The key predicted the identity of the effect and the delay (see Fig. 1). For example, 400 ms after pressing the left key, the bulb turned blue and 1,200 ms after pressing the right key the bulb turned yellow. In 90% of all trials, no further response was required during the learning phase so that attention could be directed to the regularities of actions, delays and effects. Responses were only required to rare oddball effects that were included to make sure that the effects were attended to.

In the test phase, participants were asked to freely choose between the two response keys in each trial and they were required to detect the effect, i.e., the change of the color of the light bulb. They indicated the color change by pressing a central response key. Each left or right response predicted the delay and the identity of the effect in 80% of all trials, the valid trials. The remaining 20% of the trials, the invalid trials, were split into trials with an invalid delay, an invalid effect or both (see Table 1). Participants were not informed about the possibility of predicting the identity or delay of the effect so that any behavioral advantages in valid compared to invalid trials served as a measure for learning. We expected responses to valid effects after valid delays to be faster than if effect or delay was invalid. Additionally, predictions of delays should result in better preparation of the response and therefore in a higher probability of anticipatory responses when effects occurred later than predicted. Thus, we expected more anticipatory responses, i.e., responses before the effect had appeared, when an effect was predicted, but did not appear after the short delay than when it was validly predicted to appear after the long delay.

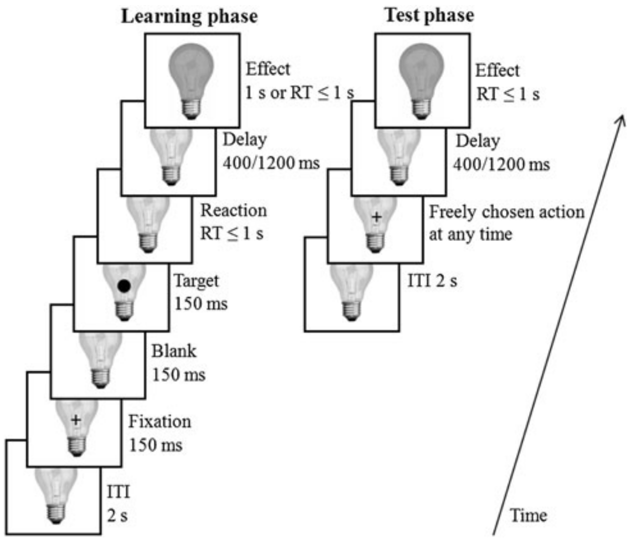


Fig. 1 Schematic layout of trials in the learning phase (*left*) and test phase (*right*). Effects, here represented by a *light bulb colored gray*, could be a color change to yellow or blue in learning and test phase and additionally to *dark gray* in the learning phase

In addition, we expected two results typical for studies entailing more than one delay and temporal expectations, which are not critical for our research question. First, we expected participants to respond faster after long compared to short delays because of the variable foreperiod effect (e.g., Bertelson & Tisseyre, 1968; Correa et al., 2004; Correa & Nobre, 2008; Elithorn & Lawrence, 1955; Karlin, 1959; Näätänen & Merisalo, 1977; Niemi & Näätänen, 1981). Second, we expected temporal validity effects only for effects that occur earlier but not for effects that occur later than expected, because in the latter case attention can be reoriented to the later point in time when the expectation of the effect occurring early was not met (e.g., Correa et al. 2004, 2006; Miniussi et al., 1999).

Method

Participants

A total of 24 participants (4 male) between 16 and 26 years old (mean 21 years) took part in the experiment. All were right-handed. Data of six further participants were excluded and replaced because the number of their left and right free choice responses in the test phase differed significantly (chi-square, $p \leq 0.05$)[1]. Participants reported having

---

[1] Participants who showed a bias for left or right responses were excluded as an unbalanced choice of left and right actions resulted in an unbalanced number of short and long delays. For example, the participant with the most extreme bias pressed the left key almost three times more often than the right key and as a result experienced the action-effect delay of 400 ms 280 times in the valid delay condition (296 times overall) and the delay of 1,200 ms 104 times in the valid delay condition (148 times overall). We assume that this bias may hamper the acquisition of the long delay and thus excluded participants with a significant bias toward one key. Nevertheless, we repeated the same within-subject analyses conducted in the results section including the six excluded participants. ANOVAs on RTs and anticipatory responses revealed that including the six participants did not change any main effects or interactions. That is, both analyses on RTs and anticipatory responses showed significant main effects of delay and validity of delay as well as an interaction of delay and validity of delay (all *ps* ≤ 0.002) and no other significant main effects or interactions.

Table 1 Number of trials

	Delay in ms	400		1,200		400	1,200	Sum
	Effect color	Blue	Yellow	Blue	Yellow	Gray	Gray	
Learning phase	Square → left key	72	0	0	0	9	0	81
	Circle → right key	0	0	0	72	0	9	81
Test phase	Left key	180*	15*	15*	15*	–	–	225
	Right key	15*	15*	15*	180*	–	–	225

The numbers marked with asterisks can differ according to the actually chosen responses of participants (see text). The table presents one possible stimulus, response, effect and delay assignment. Stimulus–response mappings, delays and effects were counterbalanced across participants

normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Participants took part due to course requirements or in exchange for payment.

Apparatus and stimuli

For stimulus presentation and data collection, the software E-Prime (Schneider, Eschman, & Zuccolotto, 2002) was run on an IBM-compatible PC. The experiment was presented on a 19″ CRT screen with a resolution of 768 × 1,024 pixels and a refresh rate of 100 Hz. During all experimental blocks, a photographic picture of a switched-off light bulb (260 pixels high, 155 pixels wide) was shown in the middle of the screen. The bulb was surrounded by a white rectangle, 379 pixels high and 192 pixels wide, on a gray background. The light bulb's color was white and changed either to yellow, blue or dark gray. At the beginning of a trial, a fixation cross was presented (1.3 cm wide and high) in the middle of the bulb. A filled black circle (diameter ca. 1.2 cm) and a black square (diameter ca. 1 cm) served as imperative stimuli in the learning phase. Three response keys were attached in a triangular pattern on the table in front of the participant. The middle key was placed in equidistance to the other two keys but a bit closer to the participant than the other keys. Keys could be rearranged for each participant so that the index fingers and the dominant thumb could rest on the keys comfortably at the same time. Standard headphones were used to present tones that signaled errors.

Procedure

For each participant, the experiment consisted of two phases, a learning and a test phase. The learning phase was identical for both groups. During the blocks of the learning phase, the outline of the light bulb remained on the screen and stimuli were presented centrally in the bulb. A trial started with the presentation of the fixation cross (150 ms) followed by the plain bulb for 150 ms. Then the imperative stimulus (circle or square) appeared for 150 ms.

Participants were instructed to respond to the imperative stimulus as fast as possible by pressing a left or a right key with the index finger of the respective hand. There was a time window of 1,000 ms to collect responses. If participants did not respond within this time window, the trial was considered an omission error. Each key press triggered one effect after a specific delay. For example, the circle required to press the left key and 400 ms after pressing the left key the light bulb turned blue, whereas the square required to press the right key and 1,200 ms after pressing the right key the light bulb turned yellow. The assignment of delays, color of light bulbs and imperative stimuli to keys were counterbalanced across participants. In 11% of all trials, the light bulb turned dark gray. This effect was included as an oddball, equally probable for both keys and always after the response-specific delay. When the light bulb turned gray, participants were required to press the middle key with their dominant hand's thumb as fast as possible. This third effect was introduced to make sure that participants attended to the effects. In all other trials of the learning phase, no further response was required after the effect had appeared. In cases of errors, a tone accompanied by a message appeared that indicated the type of error, i.e., whether participants pressed a wrong key according to the imperative stimulus ("Fehler!"), did not respond to the imperative stimulus within 1,000 ms ("Bitte schneller!"), pressed any key after their initial reaction to the imperative stimulus but before an effect ("Nur einmal drücken!"), responded erroneously to a blue or yellow effect ("Nicht bestätigen!") or did not respond to a dark gray effect ("Bitte bestätigen!").

In the test phase, each trial started with the presentation of the fixation cross that remained on the screen until participants pressed the left or right key. Participants were instructed to freely choose between the two keys from trial to trial after the fixation cross had appeared. We asked participants to randomly choose the response key and not to use any strategy like alternating trialwise or blockwise. They were asked to try to press the two keys equally often, but if they did not apply to this instruction, they were not instructed to equalize response choice. Participants were not informed about the existence of different delays or about any relation between responses, effects and delays.

In the second part of each test trial, i.e., after the delay of 400 or 1,200 ms, the light bulb turned yellow or blue. In 80% of all trials, the color of the effect and its delay were the same for an action as in the learning phase (valid trials). The remaining 20% of all trials, the invalid trials, were split up into trials with invalid delay, invalid effect or invalid delay + invalid effect (see Table 1). To assess whether participants had learned the assignment of action, delay and effect, participants had to respond to the color change of the light bulb by pressing the middle key with the thumb as fast as possible.

Left and right keys were freely chosen for each trial by participants, thus, the order of left/right actions could not be assigned randomly to participants. The order of valid and invalid trials, however, was randomly assigned.

Written error feedback and a tone were presented in case of anticipatory responses ("Zu früh!"), when the middle key was chosen as free choice action ("Falsche Taste!"), when the left or right key was pressed after the effect had occurred ("Falsche Taste!") or when a response was required but not given within 1,000 ms ("Bitte schneller!"). When a participant executed an anticipatory response before the effect had appeared, an error message ("Zu früh!") was presented instead of the effect.

The learning phase started with 20 practice trials followed by three blocks of 54 trials. The test phase consisted of 30 practice trials followed by five blocks of 90 trials. After each block, written feedback informed the participant about the mean RT, the number of anticipatory responses before the effect had occurred, the number of erroneous responses, and in the action group of the number of left and right actions.

Data analysis

Only data from the test phase were analyzed. Dependent variables were response times (RTs) to the color change of the light bulb and anticipatory responses, i.e., responses that occurred before the light bulb and up to 100 ms after the light bulb changed its color. Please note, that the criterion to judge responses with RTs shorter than 100 ms as anticipatory responses is arbitrary, yet such short RTs probably do not indicate a response to the effect stimulus, but these responses are most likely initialized before the effect stimulus has occurred. Practice trials were excluded from analyses. Furthermore, trials were excluded when participants pressed the middle key (0.98%) instead of choosing one of the two action keys. For the analysis of RTs, additionally anticipatory responses were excluded, i.e., when participants responded before the color change (4.91%) or when participants responded within the first 100 ms after the color change (2.0%), as well as omission errors, i.e., when participants did not respond within 1,000 ms after the effect (1.28%), and trials with erroneous (that is left or right) responses to the effect (0.17%).

Mean RTs for correct responses were separately computed for each participant and each combination of the factors delay, validity of delay and validity of effect. Mean percentages of anticipatory responses were separately computed for each participant and each combination of the factors delay and validity of delay. The validity of effect was hereby not taken into account as anticipatory responses are per definition initialized or committed in advance of the effect, and thus the validity of the effect was then not known to the participant. In principle, participants did not know the delay of the effect for these trials, either, but acquired knowledge about the delay could be used to prepare the response to the effect before it occurred. Thus, we considered anticipatory responses as all responses that occurred before the effect or during the first 100 ms of effect presentation and coded the delay as the delay that would have been presented if the participant had not responded early, i.e., within the 399 ms before the effect in short delay trials and within 1,199 ms in long delay trials.

In addition, we analyzed the proportion of left and right key presses that were chosen by each participant. Participants not choosing left and right responses equally often (assessed by chi-square tests) were excluded from the analysis because these participants experienced a specific effect and the corresponding delay more often than the alternative effect and delay.

Results

RTs

The results are depicted in Table 2. An ANOVA was conducted with the within-subject factors delay (400, 1,200 ms), validity of delay (valid delay, invalid delay) and validity of effect (valid effect, invalid effect).

Table 2 Mean response times in milliseconds

Delay in ms	Validity of effect			
	Valid		Invalid	
	Validity of delay			
	Valid	Invalid	Valid	Invalid
400	391 (19)	438 (18)	400 (21)	430 (19)
1,200	332 (12)	342 (14)	334 (15)	333 (14)

Numbers in brackets indicate standard errors

The analysis revealed significant main effects for the factors delay, $F(1, 23) = 82.29$, $p < 0.001$, and validity of delay, $F(1, 23) = 14.46$, $p < 0.001$. Furthermore, there was a significant within-subject interaction between delay and validity of delay, $F(1, 23) = 10.20$, $p = 0.004$. No main effect or interaction was found for the factor validity of effect.

Post hoc t tests showed that RTs were generally faster for effects presented after 1,200 ms than after 400 ms (valid delay: $t(23) = 5.85$, $p < 0.001$, invalid delay: $t(23) = 9.69$, $p < 0.001$). The interaction of delay and validity of delay revealed that the valid delays led to shorter RTs than invalid delays only after short delays, $t(23) = -3.78$, $p < 0.001$, but not after the long delays, $t(23) = -0.95$, $p = 0.35$.

Anticipatory responses

The results are depicted in Table 3. An ANOVA on percentages of anticipatory responses was conducted with the within-subject factors delay (400, 1,200 ms) and validity of delay (valid delay, invalid delay). It revealed main effects for the factors delay, $F(1, 23) = 47.67$, $p < 0.001$, and validity of delay, $F(1, 23) = 17.80$, $p < 0.001$, as well as a significant interaction between the factors delay and validity of delay, $F(1, 23) = 19.94$, $p < 0.001$ (see Fig. 2). Subsequent t tests revealed that participants responded more often anticipatorily before the long delay (that is before 1,200 ms) during invalid compared to valid delays, thus when the action predicted a short rather than long delay, $t(23) = 4.39$, $p < 0.001$. Furthermore, participants responded less often anticipatorily during the short delay (that is in the time window 1–399 ms before an effect) for valid compared to invalid delays, thus when the action predicted a short rather than long delay, $t(23) = -2.63$, $p = 0.015$.

Table 3 Mean percentage of anticipatory responses

	Validity of delay	
Delay in ms	Valid	Invalid
400	2.0 (0.4)	0.9 (0.3)
1,200	11.3 (1.1)	23.6 (3.8)

Numbers in brackets indicate standard errors

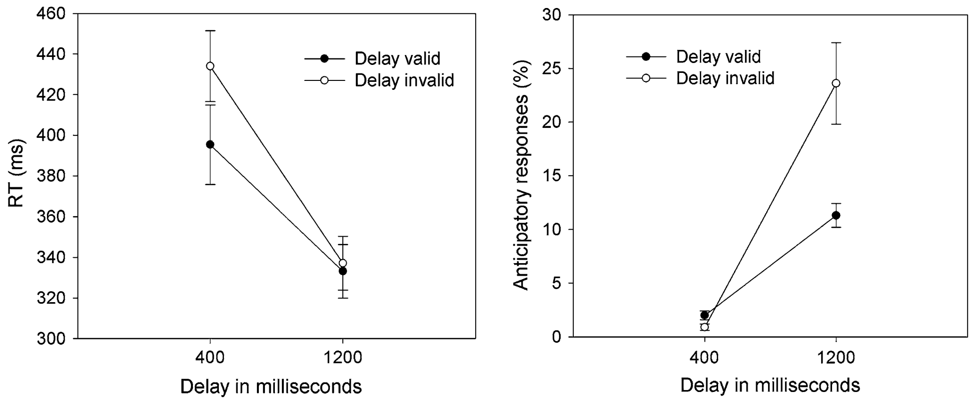
Discussion

In the current study, we explored whether participants learn that effects occur after action-specific delays. Participants pressed left or right response keys to turn on a light bulb. The identity of the response predicted the identity of the effect and its delay. Data revealed that participants adapt to these temporal regularities because participants respond faster to an effect that occurs at its regular delay. Before discussing this finding in detail, we present an overview of the obtained results.

First, RT data showed the well-known foreperiod effect for randomly varying delays. Participants responded faster after the long delay than after the short delay. This effect has been demonstrated in many studies (Correa et al., 2004; Correa & Nobre, 2008; Elithorn & Lawrence, 1955; Karlin, 1959; Näätänen & Merisalo, 1977; Niemi & Näätänen, 1981) and is often explained by conditional probabilities (Elithorn & Lawrence, 1955; Näätänen & Merisalo, 1977; Niemi & Näätänen, 1981). When the stimulus does not occur at the early delay, participants can expect the stimulus to occur at the late delay. Thus, probability for stimulus appearance increases during the trial.

More importantly, we found validity effects for both RTs and anticipatory responses. As expected, these validity effects were asymmetrical. For RTs, we observed an effect of the validity of delay for short delays, but not for long delays. This was expected due to the ability to orient and reorient attention in time (e.g., Correa et al. 2004, 2006; Miniussi et al., 1999). When a short delay was expected, but this delay had passed and no effect occurred, temporal attention was shifted to a later point in time. Therefore, no

Fig. 2 The interaction of delay and validity of delay in response times (*left*) and anticipatory responses (*right*)



validity effect can be seen in RT data for long delays. Yet, for short delays participants responded faster if the effect occurred at a valid than at an invalid delay demonstrating that participants learned when an effect usually occurred.

The result pattern for anticipatory responses was also asymmetrical. For anticipatory responses, we observed an effect of validity of delay for long delays and a seemingly reversed effect for short delays. We conjecture that anticipatory responses reflect response preparation that cannot be withheld. For short delays, therefore, the overall number of anticipatory responses was low. For invalid short delays, that is when a long delay was predicted by the action, there were even fewer anticipatory responses than for valid short delays. This shows that response preparation was higher early during a trial when an effect was to be predicted after 400 ms than when it was predicted after 1,200 ms. During long delays, there were more anticipatory responses when the action predicted a short delay than when it predicted a long delay. This provides evidence that participants used the predictive meaning of the action to prepare a response. When the effect was expected early in a trial, but did not occur (that is in invalid long delay trials), participants were not able to withhold responding of the prepared response and responded prematurely.

In contrast to the validity of the delay, the validity of the effect did not influence RT data. Due to the compelling evidence on action-effect learning it is not reasonable to assume that actions' consequences are not acquired (e.g., Allan, 1993; Alloy & Abramson, 1979; Dickinson, Shanks, & Evenden, 1984; Dutzi & Hommel, 2009; Eenshuistra et al., 2004; Elsner & Hommel, 2001; Gibbon, Berryman, & Thompson, 1974; Hoffmann & Sebald, 2005; Hommel, 1996; Hommel et al., 2003; Pavlov & Anrep, 1927; Rescorla & Wagner, 1972; Shanks, 1985). Instead, we conjecture that the test task was unsuitable to demonstrate action-effect learning. As the effect had to be detected but not discriminated to accomplish the task, the identity of the effect was not important in the test phase.

We were further interested in whether participants' knowledge of the action-specific delay was explicit. To assess explicit knowledge, we asked participants if they had observed any temporal regularities, and more specifically if they had observed any regularities between their actions and delays. Participants were rated to be aware of the relation when they had realized that after one action, effects were usually later than after the other. Of the 24 participants, 17 were rated to be aware of the temporal regularities. We repeated the ANOVAs on RTs and anticipatory responses and added awareness of delay as between-subjects factor. These analyses revealed no difference between aware and unaware participants regarding any experimental factors or interactions thereof. The post hoc calculated statistical power of the interaction of the validity effect and the between-subjects categorization into recognizers and non-recognizers was above .99 for both analyses (computed with G*Power, Faul, Erdfelder, Lang, & Buchner, 2007). This provides evidence that in most cases the relation of actions and delays can be described explicitly. Yet, it seems that the knowledge on actions and delays of effects can remain implicit but nevertheless influence behavior. So participants who acquired explicit knowledge on delays of action effects did not additionally profit from this knowledge in terms of temporal preparation compared to participants whose knowledge on the predictive meaning of their actions for the delay of the effect remained implicit. This seems to add evidence to the notion that temporal knowledge about when an effect presumably occurs need not be applied in an intentional, strategic way, but can as well be acquired and applied unintentionally (for a detailed overview of the two accounts see Los & van den Heuvel, 2001).

Taken together, the current study demonstrates that in the context of actions, the delays of effects are acquired so that an effect is expected after its typical delay. This shows that in spite of systematic distortions of the temporal perception of actions and effects (i.e., Haggard 2005; Haggard, Aschersleben, et al., 2002) that are even more pronounced if participants have to attend to actions and effects (e.g., Haggard & Cole, 2007, Stetson et al., 2006), participants learn and exploit temporal regularities between actions and effects for behavioral control. Future research has to show whether time perception and usage of temporal information in action contexts reflect dissociable processes.

Acknowledgments We thank Arvid Herwig and an anonymous reviewer for their helpful remarks. We also thank Joachim Hoffmann and Annika Wagener for their helpful discussions.

References

Albinet, C., & Fezzani, K. (2003). Instruction in learning a temporal pattern on an anticipation-coincidence task. *Perceptual and Motor Skills, 97*(1), 71–79.

Allan, L. G. (1993). Human contingency judgments—rule-based or associative. *Psychological Bulletin, 114*(3), 435–448.

Alloy, L. B., & Abramson, L. Y. (1979). Judgment of contingency in depressed and nondepressed students: Sadder but wiser? *Journal of Experimental Psychology: General, 108*(4), 441–485.

Bausenhart, K. M., Rolke, B., & Ulrich, R. (2008). Temporal preparation improves temporal resolution: Evidence from constant foreperiods. *Perception & Psychophysics, 70*(8), 1504–1514.

Bertelson, P., & Tisseyre, F. (1968). Time-course of preparation with regular and irregular foreperiods. *Quarterly Journal of Experimental Psychology, 20*, 297–300.

Correa, A., Lupiáñez, J. M. B., & Tudela, P. (2004). Endogenous temporal orienting of attention in detection and discrimination tasks. *Perception & Psychophysics, 66*(2), 264–278.

Correa, A., Lupiáñez, J., & Tudela, P. (2005). Attentional preparation based on temporal expectancy modulates processing at the perceptual level. *Psychonomic Bulletin & Review, 12*(2), 328–334.

Correa, A., Lupiáñez, J., & Tudela, P. (2006). The attentional mechanism of temporal orienting: determinants and attributes. *Experimental Brain Research, 169*(1), 58–68.

Correa, A., & Nobre, A. C. (2008). Neural modulation by regularity and passage of time. *Journal of Neurophysiology, 100*(3), 1649–1655.

Coull, J. T., Frith, C. D., Büchel, C., & Nobre, A. C. (2000). Orienting attention in time: behavioural and neuroanatomical distinction between exogenous and endogenous shifts. *Neuropsychologia, 38*(6), 808–819.

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience, 18*(18), 7426–7435.

Dickinson, A., Shanks, D. R., & Evenden, J. (1984). Judgment of act-outcome contingency: The role of selective attribution. *Quarterly Journal of Experimental Psychology, 36A*, 29–50.

Dutzi, I. B., & Hommel, B. (2009). The microgenesis of action–effect binding. *Psychological Research-Psychologische Forschung, 73*(3), 425–435.

Eenshuistra, R. M., Weidema, M. A., & Hommel, B. (2004). Development of the acquisition and control of action–effect associations. *Acta Psychologica, 115*(2–3), 185–209.

Elithorn, A., & Lawrence, C. (1955). Central inhibition—some refractory observations. *Quarterly Journal of Experimental Psychology, 7*, 116–127.

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 229–240.

Elsner, B., & Hommel, B. (2004). Contiguity and contingency in action-effect learning. *Psychological Research-Psychologische Forschung, 68*(2–3), 138–154.

Engbert, K., & Wohlschläger, A. (2007). Intentions and expectations in temporal binding. *Consciousness and Cognition, 16*(2), 255–264.

Engbert, K., Wohlschläger, A., & Haggard, P. (2008). Who is causing what? The sense of agency is relational and efferent-triggered. *Cognition, 107*(2), 693–704.

Engbert, K., Wohlschläger, A., Thomas, R., & Haggard, P. (2007). Agency, subjective time, and other minds. *Journal of Experimental Psychology: Human Perception and Performance, 33*(6), 1261–1268.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Gallistel, C. R., & Gibbon, J. (2000). Time, rate, and conditioning. *Psychological Review, 107*(2), 289–344.

Gibbon, J., Berryman, R., & Thompson, R. L. (1974). Contingency spaces and measures in classical and instrumental conditioning. *Journal of the Experimental Analysis of Behavior, 21*(3), 585–605.

Greenwald, A. G. (1970). A double stimulation test of ideomotor theory with implications for selective attention. *Journal of Experimental Psychology, 84*, 392–398.

Haggard, P. (2005). Conscious intention and motor cognition. *Trends in Cognitive Sciences, 9*(6), 290–295.

Haggard, P., Aschersleben, G., Gehrke, J., & Prinz, W. (2002). Action, binding, and awareness. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action: attention & performance XIX* (pp. 266–285). Oxford: Oxford University Press.

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience, 5*(4), 382–385.

Haggard, P., & Cole, J. (2007). Intention, attention and the temporal experience of action. *Consciousness and Cognition: An International Journal, 16*(2), 211–220.

Herbart, J. F. (1825). *Psychologie als Wissenschaft neu gegründet auf Erfahrung, Metaphysik und Mathematik. Zweiter, analytischer Teil*. Königsberg: August Wilhelm Unzer.

Herwig, A., Prinz, W., & Waszak, F. (2007). Two modes of sensorimotor integration in intention-based and stimulus-based actions. *Quarterly Journal of Experimental Psychology, 60*, 1540–1554.

Herwig, A., & Waszak, F. (2009). Intention and attention in ideomotor learning. *Quarterly Journal of Experimental Psychology, 62*(2), 219–227.

Hoffmann, J., Lenhard, A., Sebald, A., & Pfister, R. (2009). Movements or targets: what makes an action in action-effect learning? *Quarterly Journal of Experimental Psychology, 62*(12), 2433–2449.

Hoffmann, J., & Sebald, A. (2005). When obvious covariations are not even learned implicitly. *European Journal of Cognitive Psychology, 17*(4), 449–480.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research-Psychologische Forschung, 59*(3), 176–186.

Hommel, B., Alonso, D., & Fuentes, L. (2003). Acquisition and generalization of action effects. *Visual Cognition, 10*(8), 965–986.

Karlin, L. (1959). Reaction-time as a function of foreperiod duration and variability. *Journal of Experimental Psychology, 58*(2), 185–191.

Kingstone, A. (1992). Combining expectancies. *The Quarterly Journal of Experimental Psychology Section A, 44*(1), 69–104.

Libet, B. (1985). Unconscious cerebral initiative and the role of conscious will in voluntary action. *Behavioral and Brain Sciences, 8*, 529–566.

Los, S. A., & Van den Heuvel, C. E. (2001). Intentional and unintentional contributions to nonspecific preparation during reaction time foreperiods. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 370–386.

MacKay, A., & Juola, J. F. (2007). Are spatial and temporal attention independent? *Perception & Psychophysics, 69*(6), 972–979.

Miniussi, C., Wilding, E. L., Coull, J. T., & Nobre, A. C. (1999). Orienting attention in time—modulation of brain potentials. *Brain, 122*, 1507–1518.

Näätänen, R., & Merisalo, A. (1977). Expectancy and preparation in simple reaction time. In S. Dornic (Ed.), *Attention and performance VI* (pp. 115–138). Hillsdale: Elrbaum.

Niemi, P., & Näätänen, R. (1981). Foreperiod and simple reaction-time. *Psychological Bulletin, 89*(1), 133–162.

Nobre, A. C. (2001). Orienting attention to instants in time. *Neuropsychologia, 39*(12), 1317–1328.

Obhi, S. S., Planetta, P. J., & Scantlebury, J. (2009). On the signals underlying conscious awareness of action. *Cognition, 110*(1), 65–73.

Pavlov, I. P., & Anrep, G. V. (1927). *Conditioned reflexes; an investigation of the physiological activity of the cerebral cortex*. London: Oxford University Press, Humphrey Milford.

Pfister, R., Kiesel, A., & Hoffmann, J. (2011). Learning at any rate: action-effect learning for stimulus-based actions. *Psychological Research, 75*(1), 61–65.

Rachlin, H., & Green, L. (1972). Commitment, choice and self-control. *Journal of the Experimental Analysis of Behavior, 17*(1), 15–22.

Rescorla, R. A., & Wagner, A. R. (1972). Inhibition in Pavlovian conditioning: applications of a theory. In R. A. Boakes & M. S. Halliday (Eds.), *Inhibition and learning* (pp. 64–99). London: Academic Press.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime User's Guide*. Pittsburgh: Psychology Software Tools.

Seifried, T., Ulrich, R., Bausenhart, K. M., Rolke, B., & Osman, A. (2010). Temporal preparation decreases perceptual latency: evidence from a clock paradigm. *Quarterly Journal of Experimental Psychology, 63*(12), 2432–2451.

Shanks, D. R. (1985). Continuous monitoring of human contingency judgment across trials. *Memory & Cognition, 13*, 158–167.

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A Review of contemporary ideomotor theory. *Psychological Bulletin, 136*(6), 943–974.

Steinborn, M. B., Rolke, B., Bratzke, D., & Ulrich, R. (2009). Dynamic adjustment of temporal preparation: shifting warning signal modality attenuates the sequential foreperiod effect. *Acta Psychologica, 132*(1), 40–47.

Stetson, C., Cui, X., Montague, P. R., & Eagleman, D. M. (2006). Motor–sensory recalibration leads to an illusory reversal of action and sensation. *Neuron, 51*(5), 651–659.

Swanton, D. N., Gooch, C. M., & Matell, M. S. (2009). Averaging of temporal memories by rats. *Journal of Experimental Psychology: Animal Behavior Processes, 35*(3), 434–439.

Thomaschke, R., Wagener, A., Kiesel, A., & Hoffmann, J. (2011). The scope and precision of specific temporal expectancy: evidence from a variable foreperiod paradigm. *Attention, Perception & Psychophysics, 73*, 953–964.

Tsakiris, M., & Haggard, P. (2003). Awareness of somatic events associated with a voluntary action. *Experimental Brain Research, 149*(4), 439–446.

Wagener, A., & Hoffmann, J. (2010a). Behavioural adaptations to redundant frequency distributions in time. In J. T. Coull & K. Nobre (Eds.), *Attention and Time*. Oxford: Oxford University Press.

Wagener, A., & Hoffmann, J. (2010b). Temporal cueing of target-identity and target-location. *Experimental Psychology, 57*, 1–10.

Wohlschläger, A., Engbert, K., & Haggard, P. (2003a). Intentionality as a constituting condition for the own self- and other selves. *Consciousness and Cognition: An International Journal, 12*(4), 708–716.

Wohlschläger, A., Haggard, P., Gesierich, B., & Prinz, W. (2003b). The perceived onset time of self- and other-generated actions. *Psychological Science, 14*(6), 586–591.

Wundt, W. (1887). *Grundzüge de physiologischen Psychologie* (3rd ed.). Leipzig: Wilhelm Engelman.