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Contiguity and contingency in action-effect learning

Abstract According to the two-stage model of voluntary action, the ability to perform voluntary action is acquired in two sequential steps. Firstly, associations are acquired between representations of movements and of the effects that frequently follow them. Secondly, the anticipation or perception of an acquired action effect primes the movement that has been learnt to produce this effect; the acquired action-effect associations thus mediate the selection of actions that are most appropriate to achieve an intended action goal. If action-effect learning has an associative basis, it should be influenced by factors that are known to affect instrumental learning, such as the temporal contiguity and the probabilistic contingency of movement and effect. In two experiments, the contiguity or the contingency between key presses and subsequent tones was manipulated in various ways. As expected, both factors affected the acquisition of action-effect relations as assessed by the potency of action effects to prime the corresponding action in a later behavioral test. In particular, evidence of action-effect associations was obtained only if the effect of the action was delayed for no more than 1 s, if the effect appeared more often in the presence than in the absence of the action, or if action and effect were entirely uncorrelated but the effect appeared very often.

These findings support the assumption that the control of voluntary actions is based on action-effect representations that are acquired by associative learning mechanisms.

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Introduction

The ability to perform goal-directed actions provides humans and other animals with a powerful instrument to control the environment, to create desired effects, and to avoid unpleasant events. To obtain this kind of control, an acting organism needs some sort of knowledge about the effects that are likely to follow a certain action under certain situational circumstances. It is this knowledge that allows a given action goal or a desired action effect to be easily translated into the behavioral pattern that is most likely to produce that effect and to reach the goal in a given situation. Once the knowledge is acquired, a person only needs to "think of an intended effect," to adopt the terminology of William James (1890), and the appropriate action will follow (more or less) automatically (Hommel, 1996, 1997; Kunde, Hoffmann, & Zellmann, 2002; Prinz, 1997). In view of the complexity and flexibility of human (and not only human) behavior under varying situational constraints it seems quite unlikely that knowledge about action-effect relations is innate, the more so as one of the variables to be considered in action planning is the developing and aging human body itself. Indeed, observation of infant behavior has indicated that the ability to perform goal-directed actions is based on exploration and continuous learning processes that accompany movements and that register the dependencies between actions and their consequences (Gergely & Watson, 1999; Piaget, 1952; Rochat, 1998). These learning processes are not restricted to the first years of life but still play a role in the control of adult action, as indicated in studies on choice reactions (Beckers, De Houwer & Eelen, 2002; Elsner & Hommel, 2001; Hommel, 1996; Stock & Hoffmann, 2002), or on the acquisition of stimulus-response

sequences (Hazeltine, 2002; Hoffmann, Sebald & Stoecker, 2001; Ziessler, 1998; Ziessler & Nattkemper, 2001, 2002).

Elsner and Hommel (2001; see also Hommel, 1997, 1998) have proposed a two-stage model of goal-directed action that is thought to capture the transition from the acquisition of knowledge about action-effect dependencies to the emergence of intentional action control. Stage 1 of the model—and it is this stage the present study focused on—is concerned with the acquisition of regularities between movements and effects. Firstly, it is assumed that, when a movement is carried out, all sensory events accompanying it are registered and coded within the cognitive system. Secondly, if a particular movement and a particular sensory event co-occur repeatedly—so that their cognitive codes are frequently co-activated—this leads to the automatic integration of these codes, i.e., to a bi-directional association of movement-related and effect-related codes. Accordingly, activating one of the integrated codes on later occasions will tend to activate the other associated codes too. This bi-directional activation is assumed to be important for Stage 2 of the model, which deals with how actions are recruited to achieve desired goals by anticipating the movements' effects. Thinking of a goal is claimed to activate the codes of its perceptual characteristics. If these perceptual codes have already become integrated with the codes of a movement, activating the codes of the goal will spread activation to the respective motor codes and thereby prime the movement that has produced the desired effects in the past. This allows the selection of actions by anticipating (i.e., activating the codes of) desired action effects.

First evidence supporting this model was provided by learning studies (Elsner & Hommel, 2001; see also Hommel, 1993, 1996) in which participants first worked through a learning phase by performing key presses that were followed by certain tones. For instance, one action produced a low-pitched tone (A1 → low) while another action produced a high-pitched tone (A2 → high). In a subsequent test phase, participants performed the same actions, but now in response to the same tones, which were presented as imperative stimuli. It turned out that an action was performed faster in response to a tone that it had previously produced (low → A1, high → A2) than to a tone that had been produced by the alternative action (low → A2, high → A1). Hence, an acquisition-consistent mapping of tone and action in the test phase allowed for better performance than an acquisition-inconsistent mapping. This observation has two important implications. Firstly, as the tones in Elsner and Hommel's (2001) learning phase were irrelevant to the task, producing a novel effect by performing an action automatically creates an association between the codes of the action and the codes of the effect. And, secondly, this association must be bi-directional, as effect tones primed the corresponding actions even though the sequence of events in the test phase reversed the sequence of action and tone experienced in the learning phase. Accordingly,

perceiving a learned action effect leads to a "backward" activation of the associated movement.

The present study was carried out to shed some more light on the conditions that support the acquisition of action-effect knowledge. According to Elsner and Hommel's (2001) model, such knowledge is accumulated by associative learning mechanisms. If so, action-effect learning would be expected to be influenced by factors that are known to affect associative instrumental learning. Some of these factors were already discussed by Hume (1739/1964), who sought to figure out which aspects of a relation between two given events lead us to assume that one event was causing the other. Hume's favorite "cues to causality" were, among others, the *contiguity* (i.e., temporal and spatial proximity) and the *contingency* (i.e., constant co-variation) of events. Indeed, later empirical studies have gathered considerable evidence that these factors are not only crucial for associative learning in animals and humans, but they also influence human perception of causality between movements and their consequences (see overviews by Shanks & Dickinson, 1987; Wasserman, 1990; Young, 1995). If so, and if action-effect acquisition really is a result of associative learning mechanisms, the ease of acquiring action-effect associations would be expected to depend on the contiguity and the contingency between actions and effects during the learning experience.

We tested this expectation in two experiments modeled after Elsner and Hommel's (2001) experiments. In the learning phase of Experiment 1, the temporal delay between key press and tone (i.e., *temporal contiguity*) was varied, while in the learning phase of Experiment 2, the covariation of key press and tone (i.e., *contingency*) was manipulated. The test phase was always the same. The former "action-effect" tones were presented as imperative stimuli, which, in separate blocks, were mapped onto key press responses in an acquisition-consistent or acquisition-inconsistent fashion. If action-effect learning depends on contiguity and contingency, the expected performance difference between acquisition-consistent and acquisition-inconsistent test blocks should increase with increasing temporal proximity and increasing co-variation of action and effect, i.e., we take performance differences between acquisition-consistent and -inconsistent test responses (i.e., the acquisition-consistency effect) to indicate the strength of the learned action-effect association.

Experiment 1: Contiguity

Since the beginning of the systematic study of animal learning, it has generally been accepted that the temporal contiguity between the conditioned and the unconditioned stimulus is a critical factor in classical conditioning (Pavlov, 1927). Later, Grice's (1948) study established that for instrumental learning, the temporal contiguity between response and reinforcement is also critical. Typically, learning performance decreases with

an increasing interval between response and reinforcement, i.e., with decreasing contiguity. The performance decline is commonly explained by the process of trace conditioning (Pavlov, 1927), which implies that the mental trace of the first event (i.e., the response in instrumental learning) extends beyond that event's actual presence in the environment, but is subject to continuous decay. If the second event (i.e., the reinforcer or effect) occurs at a time when the first trace is already weak, the learned association will also be weak. If the delay becomes too long, the activations of the two events will no longer overlap and no associations will be formed at all (Grice, 1948; Pavlov, 1927).

Recently, several researchers have demonstrated that contiguity affects conditioned responding in animals and ratings of causal effectiveness in humans in a comparable fashion, and thus, both phenomena may rely on the same mechanisms (e.g., Allan, 1993; Shanks & Dickinson, 1987; Wasserman, 1990).[1] In animals, delaying reinforcement reduces levels of conditioned responding (e.g., Reed & Reilly, 1990), and in humans, delaying the outcome of a movement reduces the perceived causal effectiveness of that movement. For instance, if participants are asked to estimate the extent to which pressing a key causes the flashing of a triangle, causality judgments match the actual dependency quite accurately when movement and effect are separated by delays of 0–2 s, but judgments become increasingly inaccurate with longer delays (Shanks, Pearson, & Dickinson, 1989). Thus, the effective action-effect integration window for simple key presses seems to be rather short.

Under conditions with long movement-effect delays, one method of improving learning is filling the temporal "gap" with irrelevant events that are contiguous with both the movement and the outcome (see Einhorn & Hogarth, 1986; Gruber, Fink, & Damm, 1957). In animal studies, Reed and Reilly (1990) demonstrated that a stimulus presented during a response-reinforcer delay ameliorates the deficit in conditioned responding that the delay would otherwise produce. Likewise, studies of human judgments have shown that a signal presented between movement and outcome will relieve the delay-induced deficit in ratings of causal effectiveness (Reed, 1992, 1999; Shanks, 1989). Kaplan and Hearst (1982) and Rescorla (1982) demonstrated that an intervening stimulus (IS) is most effective when it fills the interval between the two events completely. The influence of the IS is typically explained by conditioned reinforcement (Grice, 1948; Reed, 1999). It is assumed that due to the temporal contiguity of IS and effect (E), the participants learn an IS-E association. Because the IS is also contiguous to the response (R), an additional R-IS association may be formed. If this occurs, the response acquires causal efficacy with respect to the outcome via the R-IS-E association chain. An alternative explanation for the influence of the IS is that it helps to discriminate the movement-effect interval from the subsequent intertrial interval (ITI). This assumption is supported by the fact that the acquisition of response-outcome associations is not only facilitated by an IS presented in the response-effect interval, but also by an IS presented in the ITI (Kaplan & Hearst, 1982).

If we assume that the acquisition of novel action effects as investigated by Elsner and Hommel (2001) relies on associative learning mechanisms, we would expect the efficiency or likelihood of acquiring those effects to be sensitive to the same manipulations that were demonstrated to have an impact on more standard measures of response-outcome learning. Experiment 1 tested whether this is the case for the temporal contiguity between movement and effect. In the learning phase, participants were asked to respond to an imperative stimulus with one of four key presses (Fig. 1). After each key press, the participants heard a certain tone, so they were expected to acquire four action-effect associations. In five experimental groups, temporal contiguity was varied by manipulating the temporal delay between key press and tone, which should affect action-effect learning.

The impact of the contiguity variation was investigated in a subsequent test phase, which was similar for all participants. Here, the former effect tones were presented as imperative stimuli for a two-choice response task. The participants had to respond to each tone with a certain key press, and the key presses no longer produced auditory effects. The test phase consisted of two blocks. Participants responded in a consistent fashion in one of the test blocks, and in an inconsistent fashion in the other test block (see Fig. 1). If participants had acquired action-effect associations in the learning phase, perceiving a former effect tone should prime the associated movement, and the participants should perform better in the acquisition-consistent test block than in the acquisition-inconsistent test block.

In the learning phase of three contiguity groups (Group 50, Group 1000, and Group 2000), the tone

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[1]At first sight, causality ratings may seem to be more related to classical conditioning than to instrumental learning. Indeed, just like causal judgments, classical conditioning is about the relationship of, and the resulting association between two events, such as a perceived cause and a perceived effect. That such an association may be the basis for our perception of causality was the core of Hume's (1739/1964) approach. In contrast, original interpretations of instrumental learning did not assume that the effect of an action is actually learned; instead, an effect was claimed to only signal whether the response producing it is to be learned or strengthened (e.g., Thorndike, 1927). Thus, the original concept of instrumental learning treats action effects as merely providing the "glue" needed to associate responses and the stimuli preceding them (Walker, 1969) but not as elements of the resulting memory trace (Hommel, 1998). However, more recent studies have shown that even animals acquire knowledge about the content of action-effect relations (Brogden, 1962; Meck, 1985; Rescorla, 1992; Trapold, 1970; Urcuioli DeMarse, 1996; for an overview, see Elsner Hommel, 2001), which lends credit to Tolman, Hall, and Bretnall's (1932) view of action effects as information to be integrated, i.e., knowledge about action effects may well become a part of an action's representation (Hommel, 1998), which again may underlie our ability to perceive that action as causing the effect (Haggard, Aschersleben, Gehrke, Prinz, 2002). However, even though we tend to relate action-effect learning more to instrumental learning than to classical conditioning, nothing in our conclusions depends on this preference.

Fig. 1 Basic design of Experiments 1 and 2. Examples of the visual stimuli, responses (*curved arrow*: finger is moved, *cross in box*: finger is not moved), and effects in the learning phase and test phase for a participant under response effect mapping A

	Stimulus		Response		Effect
Learning phase: R-E mapping A	⇦	*	(curved arrow) □□□	□☒□	Low sinusoidal tone
	*	⇦	□☒□	(curved arrow) □□□	High sinusoidal tone
	⇨	*	(curved arrow) □□□	□☒□	Low bell tone
	*	⇨	□☒□	(curved arrow) □□□	High bell tone
Test block 1: Sinusoidal tones, inconsistent	Low sinusoidal tone		□☒□	(curved arrow) □□□	
	High sinusoidal tone		(curved arrow) □□□	□☒□	
Test block 2: Bell tones, consistent	Low bell tone		(curved arrow) □□□	□☒□	
	High bell tone		□☒□	(curved arrow) □□□	

appeared 50 ms, 1,000 ms, or 2,000 ms after key press onset. If action-effect learning is affected by temporal contiguity, we expect the acquisition-consistency effect in the test phase to decrease with increasing movement-effect delay in the learning phase. However, in Group 2000 the movement-effect interval and ITI both lasted 2,000 ms, and this may hamper the distinction between the intervals and thus affect action-effect learning. Therefore, we included a fourth contiguity group (Group 1000-ITI), in which both intervals lasted 1,000 ms. If the discriminability of the intervals has an impact on action-effect learning (Kaplan & Hearst, 1982), the test phase results in Group 1000-ITI should correspond to those of Group 2000. In the learning phase of a fifth group (Group 2000-IS), we presented an irrelevant stimulus that almost completely filled the 2,000-ms movement-effect delay. If the IS ameliorates the learning deficit that may be produced by the long delay (Reed, 1999), the consistency effect should be greater in Group 2000-IS than in Group 2000.

Method

Participants

Forty adults (27 female, 13 male; 1 left-handed, 39 right-handed) were paid to participate in the experiment. Their average age was 24 years. The participants reported having normal or corrected-to-normal vision and audition, and they were blind to the purpose of the experiment. For the contiguity variation, the participants were randomly assigned to five groups of eight participants each.

Stimuli and apparatus

The display and timing was controlled by a Hewlett Packard Vectra QS/20 computer, interfaced to an Eizo Flexscan monitor. The visual stimuli were displayed on a black background. A central white asterisk (*) served as fixation point, and a black arrow with white outline was presented 3.5° to the left or right of the fixation point to signal the response. From a viewing distance of about 60 cm, the arrow subtended a visual angle of 3° in width and 1.5° in height. The arrowhead pointed either to the left or to the right. The participants responded with their left and right index finger on a keyboard placed centrally in front of the monitor, which consisted of six 2-×-2-cm keys arranged in a horizontal row. The three left-hand keys and the three right-hand keys were 1 cm apart, and the two groups of three keys were separated by 22 cm. Auditory stimuli were sinusoidal tones or MIDI tones (i.e., bell tones; instrument Marimba) of 400 Hz (low pitch) or 800 Hz (high pitch), presented simultaneously through the left and right speaker of a headphone. The IS, which was only presented in Group 2000-IS, was a MIDI tone (instrument Flute) of 600 Hz.

Procedure

The experiment consisted of a single session of about 40–60 min, depending on the contiguity condition. The session was divided into a learning phase and a test phase.

Learning phase The subject's left and right index finger rested on the second and the fifth keys respectively, counting from left to right (Fig. 1). On appearance of the arrow, one index finger was to be moved from the home key to the adjacent left or right key as quickly as possible. The location of the arrow indicated the hand to be moved, i.e., an arrow left of the fixation point signaled the left hand, and an arrow on the right side the right hand. The direction of the arrowhead indicated the direction of the movement, thus, a left-pointing arrow signaled a leftward movement (touching key 1 with the left, or key 4 with the right index finger), and a right-pointing arrow a rightward movement (touching key 3 with the left, or key 6 with the right index finger). Each movement ended by moving the finger back to the home key.

Each key press triggered a particular tone. For all participants, presses of the left key (i.e., key 1 or key 4) triggered a sinusoidal tone, and presses of the right key (i.e., key 3 or key 6) triggered a bell (i.e., MIDI) tone. The pitch of the tone was mapped on the hand and was balanced across participants. For one half of the participants, the left index finger triggered the low tones and the right index finger triggered the high tones (action-effect mapping A), while the other half of the participants received the opposite action-effect mapping B. Participants were not informed about the action-effect mapping and were told that the tones were completely irrelevant to the task and should therefore be ignored.

Each contiguity group consisted of four participants with action-effect mapping A and four with action-effect mapping B. The procedure in three of the five groups differed only according to the temporal delay between response and effect (R-E interval). Within each group, the temporal contiguity was the same for all four action-effect pairs. As shown in Table 1, three groups obtained a constant ITI of 2,000 ms, and the effect tone appeared 50 ms (Group 50), 1,000 ms (Group 1000), or 2,000 ms (Group 2000) after the key press. The design of Group 1000-ITI was identical to that of Group 1000, but the ITI was 1,000 ms. The design of Group 2000-IS was identical to that of Group 2000, but 50 ms after the key press the IS was presented for 1,950 ms, and directly after that, the effect tone appeared for 200 ms. Thus, the R-E interval in Group 2000-IS was almost completely filled by the IS.

Following the ITI, each acquisition trial started with a 500-ms display of the fixation point. After that, an arrow appeared for 200 ms to the left or right of the fixation point. From arrow onset, the program waited up to 1,000 ms for a key press. If the correct

Table 1 Experiment 1: Length of the intertrial interval (*ITI*) and of the delay between response and effect (*R-E interval*) in the learning phase of the five contiguity groups

Group	ITI (ms)	R-E interval (ms)	Filler tone
Group 50	2,000	50	No
Group 1000	2,000	1,000	No
Group 2000	2,000	2,000	No
Group 1000-ITI	1,000	1,000	No
Group 2000-IS	2,000	2,000	Yes

response key was pressed, the corresponding effect tone was presented for 200 ms, starting 50, 1,000, or 2,000 ms after the onset of the key press, depending on the contiguity condition. Trials with response latencies exceeding 1,000 ms were counted as missing, and responses faster than 100 ms were counted as anticipation errors. Incorrect key presses, response omissions, and anticipations were recorded, fed back to the participants by a 1,000-ms warning message, and repeated in a random position during the remainder of the block. Participants worked through eight practice trials and 400 valid acquisition trials (i.e., four action-effect pairs with 100 repetitions each).x

Test phase After completing the acquisition trials, participants were verbally instructed for the test phase, which was the same for the participants of all groups. In each test trial, one of the four effect tones was presented as an imperative stimulus, and the participants were asked to respond to this stimulus as quickly and as correctly as possible according to a fixed stimulus-response (S-R) mapping. The test phase was divided into two blocks, in which only the tones of one sound category were presented as imperative stimuli. Because the sound categories were previously mapped onto the keys, the participants responded with both hands in each block, but they used only the left keys (key 1 and key 4) in one block, and the right keys (key 3 and key 6) in the other. In the acquisition-consistent test block, the participants had to press the key that preceded the tone in the acquisition phase. For instance, participants who had experienced action-effect mapping A (left hand → low tone, right hand → high tone) were now to respond to the low tone with the left index finger and to the high tone with the right index finger. In the acquisition-inconsistent test block, the same participants were to respond to the low tone with the right index finger, and to the high tone with the left index finger. Half of the participants worked through the acquisition-consistent test block first, the other half worked through the acquisition-inconsistent block first. Additionally, half of the participants received the acquisition-consistent instruction for the sinusoidal tones, and the other half for the bell tones.

Each test trial started after a 1,500-ms ITI with a 200-ms presentation of a low or high tone. Then the program waited up to 1,000 ms for a key press. After the key press, no tone appeared, but the next ITI started immediately. Incorrect key presses, response omissions, and anticipations were treated as in the acquisition phase. Participants worked through 10 practice trials and 100 valid test trials in the first block. After that, a screen message informed the participants that only the tones of the other sound category would be presented in the next block, and instructed them for the new S-R mapping. The number of trials was identical in the two test blocks, so that the participants worked through a total of 20 practice trials and 200 valid test trials (two blocks with two effect-response pairs and 50 repetitions each).

Results

The significance criterion was set to $p < .05$ for all analyses (one-tailed for single contrasts of predicted effects).

Learning phase

After excluding response omissions (1.0%) and anticipations (0.1%), individual mean RTs were calculated. A one-way ANOVA did not reveal an effect of contiguity group, indicating that RTs in the learning phase were statistically comparable across groups (mean RT and standard error: Group 50: 450.3 [13.9], Group 1000: 487.8 [16.4], Group 2000: 485.9 [15.5], Group 1000-ITI: 483.9 [25.3], Group 2000-IS: 479.1 [22.1]).

Test phase

Trials with response omissions (0.7%) were excluded, and anticipations did not occur. Mean RTs and percentages of error were calculated and analyzed as a function of group and acquisition-consistency block (S-R mapping acquisition-consistent vs. -inconsistent).

As shown in Fig. 2, the participants of Group 50, Group 1000, and Group 1000-ITI responded faster in the acquisition-consistent block than in the acquisition-inconsistent block, and separate *t*-tests revealed that the acquisition-consistency effect was significant in each of these groups, *t*'s(7) = 2.58 ($p = .02$), 2.04 ($p = .04$), and 2.08 ($p = .04$) respectively. In Group 2000 and Group 2000-IS, the consistency effect was not significant (Group 2000: $t(7) = -1.01, p = .16$; Group 2000-IS: $t(7) = -1.31, p = .12$). Thus, a reliable effect of acquisition consistency was obtained in all groups with action-effect learning delays of up to 1,000 ms.

A 5 (contiguity group) × 2 (consistency block) analysis of variance (ANOVA) only revealed a significant interaction ($F(4,35) = 3.84, p = .01$), showing that the consistency effect differs between the contiguity groups. Separate analyses were conducted to investigate the group differences. For Group 50, Group 1000 and Group 2000, a separate 3 (contiguity group) × 2 (consistency block) ANOVA also yielded only a significant interaction ($F(2,21) = 4.5, p < .02$). As determined by
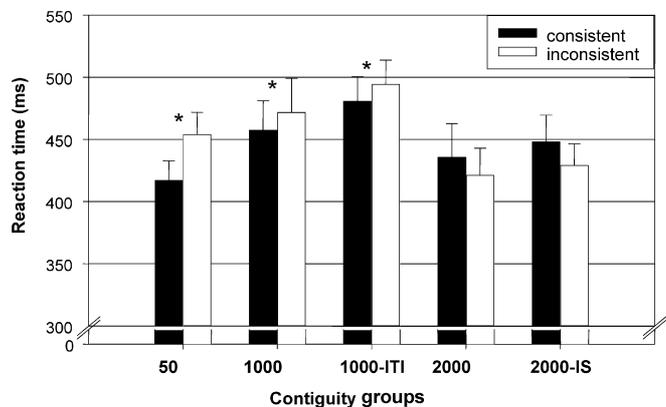

Fig. 2 Experiment 1: Mean reaction times and standard errors in the acquisition-consistent and -inconsistent test blocks in the five contiguity groups. *Asterisks* indicate a significant consistency effect within a group ($p < .05$)

Newman-Keuls tests, the critical difference between the consistency effects of two groups is 32.1 ms (*p* of .05 adjusted by a Bonferroni correction for 10 possible tests = .005). Thus, the consistency effects of the following groups differed significantly: Group 50 vs. Group 2000 (37.0 ms vs. -14.5 ms), Group 50 vs. Group 2000-IS (37.0 vs. -19.0 ms), Group 1000 vs. Group 2000-IS (14.3 vs. -f19.0 ms), and Group 1000-ITI vs. Group 2000-IS (13.6 vs. -19.0 ms). The reliable consistency effects in Group 50, Group 1000, and Group 1000-ITI did not differ, and neither did the non-reliable effects in Group 2000 and Group 2000-IS.

Incorrect key presses were rare (2.2% and 2.6% in the acquisition-consistent and -inconsistent blocks respectively) and did not produce any effect in an ANOVA.

Discussion

The results of Experiment 1 meet our expectation that the temporal contiguity between actions and their effects is an important prerequisite for acquiring associations between their cognitive representations. When participants have experienced that a key press movement is followed by a certain tone with a delay of 50 or 1,000 ms, they perform that key press faster after hearing the former effect tone than after hearing the alternative tone. However, when the tone occurs 2,000 ms after the key press, hearing the effect tone in the test phase does not lead to reliable performance differences under acquisition-consistent and -inconsistent effect-action mapping. The consistency effect of the Group 50 is only numerically higher than, but not statistically different from, the effect of the two groups with a 1,000-ms movement-effect interval. Although this may be caused by a lack of statistical power due to small group sizes (*n* = 8), our data point more to a critical time window for the integration of simple key press movements and following simple tones than to a gradual decrease in the strength of the acquired action-effect associations with decreasing contiguity. Being exposed to a particular action-effect mapping in the learning phase influenced subsequent test performance only if effects of key presses were delayed by no more than 1 s, whereas a 2-s delay was apparently too long to create sufficiently stable action-effect associations.

An alternative explanation for the lack of the consistency effect in Group 2000 is that the participants had problems in differentiating the 2,000-ms movement-effect interval from the 2,000-ms intertrial interval (Kaplan & Hearst, 1982). However, if this had been the case, the consistency effect should also be lacking in Group 1000-ITI, which also faced a R-E interval and ITI of equal length, and it should be present in Group 2000-IS, in which the intervening stimulus facilitated the discrimination of the R-E interval and ITI. But the data showed a significant consistency effect in Group 1000-ITI that was similar to that of Group 1000, but differed from that in Group 2000-IS. Thus, the

temporal contiguity of movement and effect seems to be more important for the acquisition of action-effect relations than the discriminability of the movement-effect interval and intertrial interval.

The importance of movement-effect contiguity is further supported by the comparison of Group 2000 and Group 2000-IS. The fact that neither of these groups showed a reliable consistency effect contradicts the expectation that an irrelevant stimulus presented in the R-E interval can compensate for low temporal contiguity. In view of the evidence of a positive impact of intervening stimuli on instrumental learning in humans and other animals (Einhorn & Hogarth, 1986; Gruber, Fink, & Damm, 1957; Reed, 1992, 1999) this is a somewhat surprising finding. However, the more convincing demonstrations of IS benefits come from studies of animal conditioning rather than studies on human causal judgments. And even though Reed's (1992, 1999) data support the assumption that "filling the gap" between action and effect facilitates the detection of a causal relation between the two, Davey (1983) showed that when a chain of stimuli is presented, participants acquire knowledge of the association between contiguous stimuli (i.e., between action and IS, or between IS and effect), but little knowledge of the relationship between more distal stimuli (i.e., between action and effect).

The failure to find a mediating effect of the intervening stimulus may also have something to do with our dependent variable. According to Reed (1999), the impact of the IS is based on secondary reinforcement. Thus, the detection of a relationship between action and effect is facilitated by learning processes that associate the IS with both the response and the effect, resulting in a R-IS-E association. In the present study, the occurrence of a consistency effect in the test phase is a rather indirect measure of the acquired action-effect associations. The lack of the consistency effect in Group 2000-IS may either be due to the fact that no R-IS-E associations have been learned, or to the fact that the activation spreading "backwards" on R-IS-E associations is too weak to allow an activation of the action (i.e., Associate 1) by activating the representation of the effect (i.e., Associate 3). If so, the lack of a behavioral effect in Group 2000-IS would not be due to the absence of learning, but instead due to learning that is insufficient to affect overt performance. Further studies are required to clarify this issue.

Taken together, the results of Experiment 1 show that the temporal proximity of movement and effect is a critical factor for the acquisition of action-effect knowledge. Only if the delay between key presses and effects was no longer than 1 s, the acquired action-effect associations had an impact on the selection and execution of subsequent actions. This supports and extends the assumption of Elsner and Hommel's (2001) two-stage model claiming that voluntary action control is based on acquired action-effect associations. Indeed, such associations seem to be formed on the occasion of mere co-occurrences of a movement and a subsequent

sensory event, provided that the latter is perceived within a window of about 1 s after movement onset. This suggests that trace conditioning is at work here, i.e., associations between the codes of a movement and a perceptual effect are created when their activations overlap in time (Hommel, 2003). If we assume that the activation of codes decays over time (Hommel, 1994) such an overlap is less likely the more the effect is delayed. In view of our present results, it would need to be assumed that the decay of the codes of simple key presses takes longer than 1 but shorter than 2 s.

Experiment 2: Contingency

Although temporal contiguity is an important mechanism in human and animal associative learning, a mechanism relying solely on the contiguity of movement and effect would often not obtain valid results. Let us imagine a tone that is produced by pressing a piano key and a telephone ring that happens to co-occur with a hit on the computer keyboard. Both tones may be perfectly contiguous with the action and yet only the former is actually produced by it. Hence, valid judgments of the relation between action and effect would require an organism to experience several situations in which a movement and a following sensory event have the chance to co-occur frequently, which would point to a causal relation, or to appear separately. There is ample evidence that humans (Allan & Jenkins, 1980; Chatlosh, Neunaber, & Wasserman, 1985; Shanks & Dickinson, 1987) and other animals (Dickinson & Charnock, 1985; Hammond, 1980) use information about probabilistic contingencies to detect relations between movements and effects. Contingency detection is usually investigated in the "free-operant" paradigm (Dickinson & Charnock, 1985; Hammond, 1980; Shanks & Dickinson, 1991; Wasserman, 1990), in which participants may perform (R) or may not perform (−R) a particular response. If they do perform the response, an effect does (E) or does not (−E) occur according to a fixed probability $p(E|R)$. If they do not perform the response, the effect appears with another fixed probability $p(E|\text{-}R)$. Using this paradigm, Dickinson and Shanks (1985) noted that for a given $p(E|R)$, increasing $p(E|\text{-}R)$ decreases attributions of causal effectiveness regarding the response in humans.

In the classical definition by Rescorla (1967), the degree of contingency between response and effect is expressed by the difference between the two probabilities (i.e., Delta-p), which again are calculated from the relative frequencies (F) of the presence or absence of response and effect:

$$\Delta p = p(E|R) - p(E|{-}R)$$
$$= \frac{F(E|R)}{F(E|R) + F(-E|R)} - \frac{F(E|{-}R)}{F(E|{-}R) + F(-E|{-}R)}$$

A positive Delta-p value expresses that the effect occurs more often in the presence than in the absence of a given response. Under positive contingency, animals learn excitatory associations, and humans judge the response as the cause of the effect (Shanks & Dickinson, 1987; Wasserman, 1990; Young, 1995). Typically, the strength of the learned association increases with increasing positive contingency. Under non-contingency, i.e., when Delta-p equals zero, the effect appears equally often in the presence and in the absence of a response, and thus, action and effect are independent of each other. Animals respond to non-contingencies with learned irrelevance (Seligman, Maier, & Solomon, 1971). They become inactive because their behavior has no impact on the appearance of a reinforcer. For humans, non-contingencies are more difficult to judge than positive contingencies (Shanks, 1993).

Rule-based or statistical models of instrumental learning (see Allan, 1993; Shanks, 1993; Waldman & Holyoak, 1992; Wasserman & Miller, 1997) take the interdependence between behavior and contingency as evidence that organisms adapt their behavior according to the Delta-p rule. However, the application of the Delta-p rule makes strong demands on cognitive abilities. Firstly, the calculation of relative probabilities requires a retrospective evaluation of the presence or absence of all actions and sensory events in all relevant situations, and thus calls for high memory and attentional capacities. Secondly, the calculation requires an accurate perception of the co-occurrence of the two events, which is, among other things, dependent on the temporal limits of the contingency analysis (Wassermann, 1990). For instance, if an effect appears 5 s after the movement, a 6-s analysis interval would result in adding 1 to $F(E|R)$, but a 2-s interval would result in adding 1 to $F(-E|R)$, 1 to $F(-E|{-}R)$, and 1 to $F(E|{-}R)$.

Given the high demands of Delta-p calculation, some researchers doubt that humans and other animals actually use this rule to determine the relationships between events, and favor associative models instead (e.g., Allan, 1993; Shanks, 1993; Wasserman & Miller, 1997). Shaklee and Wasserman (1986) showed that causality judgments that apparently matched the Delta-p rule could well result from other, simpler learning processes. Shaklee and colleagues found that the process participants use to determine the dependence of two events is determined, among other things, by their age and memory load. Elementary-school children seem to rely on frequency-based associative mechanisms, whereas university students prefer the Delta-p rule (Shaklee, Holt, Elek, & Hall, 1988). However, adults also tend to shift to simpler processes under high memory load (Shaklee & Mims, 1982).

Deviations from the Delta-p rule are also common in non-contingent conditions (Shanks & Dickinson, 1987; Wasserman & Shaklee, 1984). Chatlosh et al. (1985) reported that the overall frequency of the effect $F(E)$ has an impact on causality judgments, especially

Stimulus	Response	Effect	F	p	Contingency
⇦ *(green)	◰ ▢▢▢ ▢⊠▢	Low Sinus	$F(E|R) = 40$	$p(E|R) = .80$	Delta p = .60
⇦ *(green)	◰ ▢▢▢ ▢⊠▢	--	$F(-E|R) = 10$		
⇦ *(red)	▢⊠▢ ▢⊠▢	Low Sinus	$F(E|-R) = 10$	$p(E|-R) = .20$	
⇦ *(red)	▢⊠▢ ▢⊠▢	--	$F(-E|-R) = 40$		

Fig. 3 Experiment 2: Possible combination of the presence (R) or absence of a key press (−R) and of the presence (E) or absence (−E) of an effect for one of the four responses in the learning phase. Frequency (*F*) of every combination in 100 learning trials, probability (*p*) and contingency (Delta-*p*) for one contingency group

in non-contingent situations with aversive effects. Thus, the participants made higher causality ratings when $p(E|R)$ and $p(E|-R)$ were equally high (e.g., .80 and .80) than when they were equally low (e.g., .20 and .20), although Delta-*p* was zero in both conditions. The overall frequency of the effect is also important when participants have to judge the causality of several actions at the same time, such as when two keys cause the appearance of a light with different contingencies (Jenkins & Ward, 1965). Probably, the concentration on overall frequency of the effect makes lower demands on memory and attention and is therefore used in situations with high cognitive load.

Taken together, studies on instrumental learning in humans and other animals imply that a positive contingency facilitates the detection of a relationship between action and effect. However, the same observable behavior may be based on different processes, such as the calculation of relative probabilities (i.e., Delta-*p*), or the concentration on the overall frequency of the effect. Taking aside the processes that underlie the observable behavior, the appearance of an effect in the absence of a response is important for the causal power of a response, and models that rely solely on the temporal contiguity of action and effect are not well equipped to take this information into account.

If the acquisition of action effects is based on associative learning mechanisms, it should be influenced not only by the temporal contiguity of movement and effect, as investigated in Experiment 1, but also by action-effect contingency. The first evidence of the impact of contingency on latent action-effect learning comes from studies using serial response tasks (Hoffmann et al., 2001; Ziessler, 1998). However, these studies did not directly address whether a given action-effect association is weaker if the effect occurs frequently in

the absence of the movement. This was tested in Experiment 2, in which the action-effect contingency in the learning phase was varied in five groups. Because computing Delta-*p* requires that responses are sometimes performed (R) and sometimes not (−R), we designed a go/no-go version of our task. We presented green or red arrows and participants were instructed to respond only to a green, and not to a red arrow (Fig. 3). Whenever participants responded to a green arrow, the corresponding action effect appeared with the fixed probability $p(E|R)$, and whenever the subject did not respond to a red arrow, the effect appeared with the fixed probability $p(E|-R)$. If contingency has an impact on action-effect learning, the acquisition-consistency effect in the test phase should be more pronounced the higher the Delta-*p* in the learning phase, i.e., the more the probability of an effect given the action $p(E|R)$ exceeds the probability of the effect given the absence of the action $p(E|-R)$.

In three groups, Delta-*p* contingencies were varied by keeping $p(E|R)$ constant and increasing the probability of $p(E|-R)$: Group .60, Group .30, and Group .00/.80 (Table 2). To test whether the overall frequency of an effect $F(E)$ has an impact on the test behavior under non-contingency, we added two further groups in which Delta-*p* equals zero: Group .00/.50 and Group .00/.20. In Group .00/.80, the effect occurred in 80% of the learning trials, in Group .00/.50 in 50%, and in Group .00/.20 in 20%. To allow for a comparison of the results of Experiment 2 with the data on causality judgments (cf. Shanks & Dickinson, 1991), and to test for the possible impact of perceived causality on the consistency effect, we also asked the participants, after the learning phase, to rate the amount to which the occurrence of the tones has been dependent on the key presses. The test phase was identical for all participants and corresponded to that of Experiment 1. Again, performance differences between the acquisition-consistent and -inconsistent test block were taken as evidence that action-effect associations had been acquired in the learning phase, and group differences in the acquisition-consistency

Table 2 Experiment 2: Frequencies (*F*) and probabilities (*p*) of the presence (*E*) or absence (−*E*) of an effect tone given the presence (*R*) or absence (−*R*) of a key press in the learning trials of the five contingency groups

	$F(E|R)$	$F(-E|R)$	$p(E|R)$	$F(E|-R)$	$F(-E|-R)$	$p(E|-R)$	Delta p	$F(E)$
Group .60	40	10	.80	10	40	.20	.60	50
Group .30	40	10	.80	25	25	.50	.30	65
Group .00/.80	40	10	.80	40	10	.80	.00	80
Group .00/.50	25	25	.50	25	25	.50	.00	50
Group .00/.20	10	40	.20	10	40	.20	.00	20

effects were taken as evidence that the contingency between movement and effect influenced action-effect learning.

Method

Participants

Forty adults (28 female, 12 male; 33 right-handed, 6 left-handed, 1 ambidextrous) were paid to participate in the experiment. Their average age was 28 years. They fulfilled the same criteria as in Experiment 1. The participants were randomly assigned to five groups of eight participants each.

Stimuli and apparatus

These were as in Experiment 1, with one exception. The arrow that served as imperative stimulus in the learning phase had either a red or a green outline.

Procedure

The experiment consisted of a single session of about 45 min, divided into a learning phase and a test phase.

Learning phase The procedure of the learning phase was identical to that of Experiment 1, with the following exceptions: After a green arrow, participants were to press the corresponding key, just as in Experiment 1. After a red arrow, however, they were to leave their fingers on the home keys (key 2 and key 5).

Similar to Experiment 1, each key was mapped onto one of four tones. However, the tones did not always and not only occur after a key press, hence, sometimes a key press did not produce a tone, and sometimes a tone appeared without a key press. In the five contingency groups, the relative frequencies of the presence or absence of the tones given the presence or absence of the corresponding key press varied as shown in Table 2. Within each group, the contingency was constant for all four action-effect pairings. In three groups, $p(E|R)$ was set to .80, and the contingency was varied by increasing the probability of $p(E|-R)$. As displayed in Table 2, this resulted in three groups with different Delta-p contingencies: Group .60 ($\Delta p = p(E|R) - p(E|-R) = .80 - .20$), Group .30 (.80 − .50), and Group .00/.80 (.80 − .80). In two further groups with a Delta-p contingency of .00, the overall frequency of an effect $F(E)$ was varied. In Group .00/.80, the effect occurred in 80% of the learning trials, in Group .00/.50 (.50 − .50) in 50%, and in Group .00/.20 (.20 − .20) in 20%.

Each learning trial started after an intertrial interval of 1,000 ms with the presentation of the fixation point and the arrow as described in Experiment 1. After a green arrow, the program waited up to 1,000 ms for a key press. When the correct key was pressed within this interval, the corresponding tone was either presented for 200 ms, with an action-effect interval of 50 ms, or was not presented. In the latter case, the key press triggered the next ITI directly. After a red arrow, the program waited up to 700 ms for a response. If no key was pressed in this interval, the corresponding tone was either presented for 200 ms, or was not presented. Errors, anticipations, and omissions were defined and treated as in Experiment 1. Additionally, key presses following a red arrow were counted as false alarms, and were treated like the other errors. The participants worked through 24 practice trials and 400 valid learning trials (four R-E pairs with 100 replications).

Participants were informed that a tone may or may not appear after a key press, and that tones may or may not appear when no key had been pressed. We asked the participants to attend to the dependency of the effect on the key press in the learning phase,[2] and after completing this phase they were to judge this dependency on a scale similar to that used by Shanks and Dickinson (1991), which ranged from 0 (the key press was never followed by a tone) to 100 (the key press was always followed by a tone). To ease the judgment task, the learning phase was divided into seven blocks in which either one, two, or all four of the key presses were required. The succession of the blocks was balanced across participants.

Test phase The procedure of the test phase was identical to that of Experiment 1.

Results

Learning phase

Response omissions (0.3%), anticipations (0.02%), and false alarm responses (0.01%) were excluded from the analysis. The remaining data were treated as in Experiment 1. Again, the reaction times of the contingency groups did not differ significantly (mean RT and standard error: Group .60: 445.3 [12.2], Group .30: 434.2 [11.5], Group .00/.80: 428.3 [19.6], Group .00/.50: 448.3 [20.1], Group .00/.20: 439.2 [15.9]).

Causality judgments

The causality judgments were calculated for each group and each key. A 5 (contingency group) × 4 (key) ANOVA revealed only a significant main effect of contingency ($F(4,35) = 7.57$, $p < .001$). The mean causality judgments for each group are shown in Fig. 4. On the given scale, a "no dependency" judgment would result in a rating of 50. The causality judgments of Group .60 ($t(7) = 3.45$, $p = .005$), Group .30 ($t(7) = 3.45$, $p = .015$), and Group .00/.80 ($t(7) = 5.95$, $p < .001$) were significantly higher than this value, the judgments of the

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[2]It may be a concern that asking participants to attend to the action-effect relationship may have rendered the learning more "explicit" than in Experiment 1 and, thus, may have engaged a different learning mechanism. We have no evidence that would support this consideration. Firstly, Hommel, Alonso, and Fuentes (2001) investigated action-effect learning under an "implicit" instruction in a large sample and sorted their participants according to whether they were able or were not able to recall the response-effect mapping of the learning phase after the test phase. There was no evidence that learning was any different in these two groups, suggesting that the impact of action-effect associations does not depend on, and is not even modified by, explicit knowledge. (We made the same observation in a number of pilot studies where we systematically manipulated the emphasis given to the action-effect relation.) Secondly, if an "explicit" instruction would really engage a different, more intentional learning mechanism, this would be expected to increase the correlation between the consistency effects and the causality judgments; and yet, we will see that this correlation is anything but impressive. Thirdly, we will see that the effective conditions in Experiment 2 produced effects that are very comparable in size to the effects obtained in Experiment 1, which does also not support the assumption that different learning mechanisms were at work.
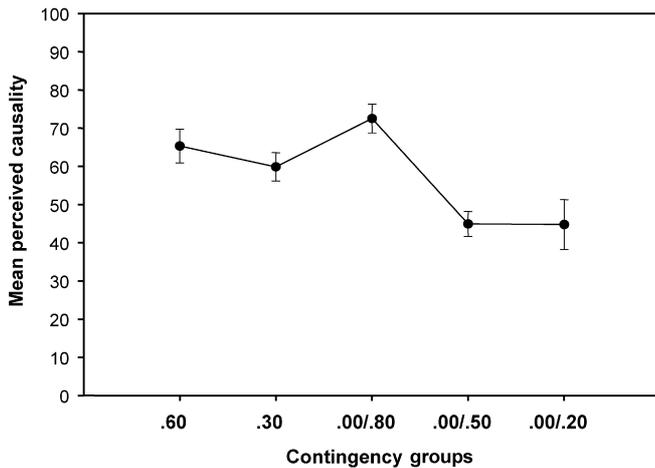
Fig. 4 Experiment 2: Means and standard errors of the contingency judgments, averaged over the four keys, in each of the five contingency groups. The judgments were obtained on a scale ranging from 0 (the tone *never* appeared after a response) to 100 (the tone *only* appeared after a response)
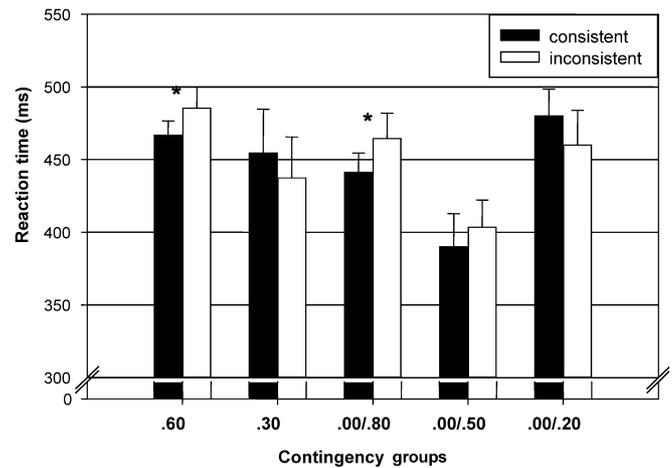

Fig. 5 Experiment 2: Mean reaction times and standard errors in the acquisition-consistent and -inconsistent test blocks in the five contingency groups. *Asterisks* indicate a significant consistency effect within a group ($p < .05$)

two other groups did not differ from 50 (p's > .08). Newman-Keuls tests yielded a critical difference between the mean causality judgments of two groups of 17.4 (p adjusted for 5 tests = .01), and thus, the judgments of Group .00/.80, Group .60, and Group .30 did not differ from each other (72.5 vs. 65.3 vs. 59.8), but the judgments of Group .00/.80 and Group .60 were significantly higher than those of Group .00/.50 and Group .00/.20, which also did not differ from each other (44.9 vs. 44.8).

Test phase

Response omissions (0.9%) were excluded from the analysis, and anticipations did not occur. For the remaining trials, mean RTs and error rates were calculated for each group and for both blocks (i.e., acquisition-consistent and -inconsistent mapping of tone and key press).

As shown in Fig. 5 and confirmed by separate *t*-tests, Group .60 and Group .00/.80 responded significantly faster in the acquisition-consistent test block than in the acquisition-inconsistent test block, t's(7) = 2.24 (p = .03) and 3.08 (p = .009). In all other groups, the consistency effect did not reach the significance level (Group .30: $t(7)$ = −1.09, p = .16; Group .00/.50: $t(7)$ = .79, p = .23; Group .00/.20: $t(7)$ = −1.74, p = .06).

For the RTs, a 5 (contingency group) × 2 (consistency block) ANOVA yielded a significant main effect of contingency group ($F(4,35)$ = 2.58, p = .05), which was due to a significant higher overall RT in Group .60 than in Group .00/.50. Additionally, the ANOVA yielded a significant interaction ($F(4,35)$ = 2.70, p = .05), showing that the consistency effect differs between the contingency groups. A separate 3 (contingency group) × 2 (consistency block) ANOVA for the groups in which $p(E|R)$ was set to .80 and the contingency was varied by

increasing the probability of $p(E|−R)$ (i.e., Group .60, Group .30, and Group .00/.80) also revealed a significant interaction ($F(2,21)$ = 3.93, p = .04). The critical Newman-Keuls difference between the consistency effects of two groups is 28.2 ms (p adjusted for 3 tests = .017) and thus the consistency effects of Group .00/.80 and Group .60 (23.1 vs. 18.7 ms) did not differ significantly, but both groups differed from Group .30 (-17.2 ms).

For the non-contingent groups (i.e., Group .00/.80, Group .00/.50, and Group .00/.20), another separate 3 (contingency group) × 2 (consistency block) ANOVA yielded a significant main effect of contingency group ($F(2,21)$ = 4.44, p = .03), caused by the fact that Group .00/.50 responded faster than the other groups. The ANOVA also showed a significant interaction ($F(2,21)$ = 3.27, p = .05). The critical difference between the consistency effects of two groups is 32.3 ms (adjusted p = .017), and thus the consistency effects of Group .00/.80 and Group .00/.50 (23.1 vs. 13.5 ms) did not differ significantly, but both groups differed from Group .00/.20 (-19.9 ms).

Errors were rare (2.5% vs. 2.8% in acquisition-consistent and -inconsistent blocks) and did not produce a reliable effect.

To test for a possible impact of perceived causality on the acquisition-consistency effect we calculated individual consistency effects (i.e., acquisition-inconsistent mean RT minus acquisition-consistent mean RT) and correlated them with the individual mean causality judgments. However, as shown in Fig. 6, and indicated by the perfectly flat regression line, there was no hint of any dependency between these measures. Indeed, the Pearson correlation across all groups was very small (r = .15) and far from significance (p = .35), and this picture did not change when the correlations were run for each group separately (p's > .49).
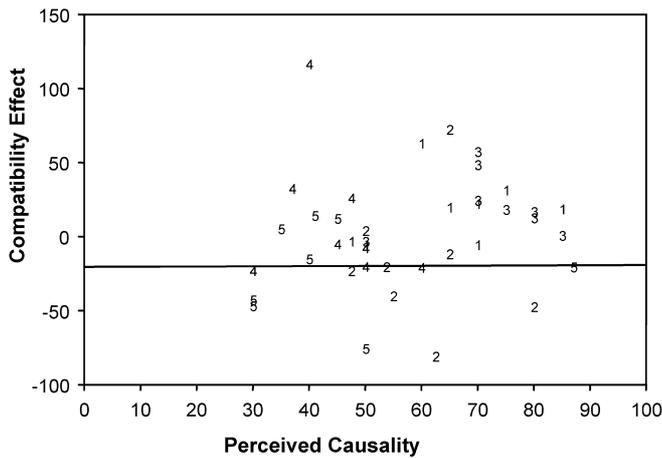
Fig. 6 Experiment 2: Relation between individual perceptions of causality between key presses and their auditory effects (mean percentage, averages across the four keys) and the size of the acquisition-consistency effect (mean RT in inconsistent block minus mean RT in consistent block). Numbers refer to the five contingency groups: *1* Group .60; *2* Group .30; *3* Group .00/.80; *4* Group .00/.50; *5* Group .00/.20

Discussion

Experiment 2 yielded three important outcomes. First of all, as expected, the acquisition-consistency effect in the test phase was affected by the contingency of action and effect in the learning phase. Thus, our studies confirm the results of Hoffmann et al. (2001) and Ziessler (1998) in showing that action-effect learning is sensitive to both the presence and the absence of a given action and its perceived effects. Which action effects are acquired depends on both temporal contiguity of, and probabilistic contingency between, actions and their effects. Secondly, consistency effects and causality judgments showed both commonalities and differences. On the one hand, both measures seem to be affected by the contingency manipulations, and they seem to be affected in similar ways, a point we will get back to below. On the other hand, however, commonalities were restricted to group means only, whereas the individual causality judgments did not predict the individual size of the consistency effect. This means that the perceived causality of an action-effect relation and the impact of an acquired relation on later performance are unlikely to be pure measures of the same underlying factor, such as an action-effect association. We will take up this issue in the General discussion section. Thirdly, the patterns of RT effects and causality judgments across the contingency groups indicate that not all groups behaved according to the Delta-*p* rule. If they had, we would have expected consistency effects and causality judgments to be most positive in the group with the highest positive Delta-*p* contingency (i.e., Group .60), somewhat less pronounced in the group with low but still positive contingency (i.e., Group .30), and small and comparable in the non-contingent groups (i.e., Group .00/.80, Group .00/.50, and Group .00/.20). Instead, the results

indicate that two contingency groups stick out by showing both significant consistency effects and high causality judgments: Group .60 and Group .00/.80. Let us discuss the results for the separate groups in turn.

The results for the two groups with positive contingency (i.e., Group .60 and Group .30) may be taken to reflect the Delta-*p* rule. Given equal probabilities of an effect given a response $p(E|R)$, increasing the probability of an effect in the absence of a response $p(E|-R)$ seems to work against creating an association between action and effect, so that acquisition-consistency effects decrease. Even though Group .30 shows no consistency effect, the mean causality judgment in this group is still quite high and does not differ from that of Group .60. Apparently, under positive Delta-*p* contingency, the participants perceive effect tones to be more dependent on their actions than under non-contingency and low overall frequency of the effect (i.e., in Group .00/.50 and Group .00/.20). Thus, the participants of four out of our five groups were able to judge the relative relationship between the presence or absence of an effect given the presence or absence of a response quite appropriately, and this perception mirrors the acquisition of action-effect associations. If Group .00/.80 is excluded from the analysis, the impression may indeed be given that participants' performance in the test phase is based on the Delta-*p* rule.

However, the results of the non-contingent Group .00/.80 indicate that the participants of this group have acquired sufficiently strong action-effect associations in the learning phase, in spite of Delta-*p* non-contingency, thus producing a reliable consistency effect in the test phase. This is also reflected by the causality judgment of this group, which is the numerically highest of all the groups. The participants of this group did not detect the non-contingency but instead had the impression of actively producing the tones. But if the behavior of Group .00/.80 is not consistent with the Delta-*p* rule, what other learning processes may it reflect? According to Chatlosh et al. (1985), the overall frequency of the occurrence of an effect $F(E)$ has an impact on participants' behavior under non-contingent conditions. Indeed, Group .00/.80 experienced the highest $F(E)$ rate in Experiment 2 (cf. Table 2). In 80% of the learning trials, one of the effect tones appeared whether an action was performed or not. In Group .30, an effect appeared in 65% of the learning trials, in Group .60 and Group .00/.50 in 50%, and in Group .00/.20 in 20%. Most probably, the high overall frequency of the effect in Group .00/.80 led to the acquisition of strong action-effect associations in the learning phase that mediated the high causality judgments and the reliable RT effects in the test phase. Indeed, if Group .30 is excluded from the analysis, the impression may be given that participants' performance in the test phase is based on the overall frequency of the effect, or $F(E)$.

The impact of $F(E)$ may be due to the fact that associations between key presses and effects are not

only learned in the go trials, but also in the no-go trials. This could happen if the participants in the no-go trials planned the response to a certain degree, so that the effect tone could be integrated with the action plan. Such learning was demonstrated by Ziessler and Nattkemper (2002) in an experiment in which participants had to prepare a movement to a white stimulus S1, but to postpone movement execution until S1 changed its color to yellow (GO signal). In half of the trials, S1 turned red (NOGO signal), and the prepared movement was not to be performed. In all go and no-go trials, effect letters were presented. The results showed clear response-effect learning in the no-go trials when the time between the onset of S1 and the color change was long enough to allow full response preparation. However, this learning effect was dramatically reduced with a preparation time of only 100 ms. Thus, in the no-go trials, participants related the effects to the prepared, but not executed, response, but only when there was elaborate response planning. In the present study, the no-go signal appeared at the same time as the imperative stimulus, and it thus seems unlikely that participants have prepared key presses in the no-go trials. Still, these trials may have contributed to action-effect learning in the non-contingent groups, leading to the impact of $F(E)$.

Additionally, the participants' tendency to rely on the overall frequency of the effect may be fueled by the high attentional and memory demands of the task of monitoring the contingencies of four key presses and four effects. Although we tried to facilitate the detection of Delta-p contingencies by introducing the four action-effect pairs step by step, the task may still have been too difficult for the participants, leading them to shift to simpler processes such as those in the study of Jenkins and Ward (1965). If the fact that participants usually experience non-contingent conditions as more demanding than positive contingent conditions is taken into account (Allan, 1980; Allan & Jenkins, 1980; Seggie, 1975), the results of Experiment 2 resemble those of Shaklee and Mims (1982). Especially under more demanding non-contingencies, the participants concentrated on the overall frequency of the effect to detect the dependencies between action and effect. Taken together, the results of Experiment 2 indicate that action-effect learning is influenced by the occurrence of the effect in the absence of an action. However, the question whether participants rely on the calculation of Delta-p or on an evaluation of the overall frequency of the effect when determining the dependencies of actions and effects calls for further investigation.

General discussion

The present study was conducted to test the hypothesis that the learning of relationships between actions and their perceptual consequences is accomplished by associative learning processes. This is a central assumption in the first stage of Elsner and Hommel's (2001) two-stage model of the emergence of action control. The basic idea is that performing an action requires an action plan that consists of codes that specify, among other things, that action's characteristics (Hommel, 1997; Stoet & Hommel, 1999). If activation of these codes frequently overlaps in time with activation of codes representing the perceived consequences of the action, action-related and effect-related codes become associated with each other due to a sort of trace conditioning (see Hommel, 2003). If so, learning should depend on the temporal contiguity and the probabilistic contingency of action and effect, because these factors determine the activation overlap of the codes.

Moreover, the model claims that the emerging associations are bi-directional, so that being exposed to an acquired action effect will prime the associated action. As the degree of response priming should vary with the strength of the acquired association, the amount of priming should decrease with decreasing action-effect contiguity and contingency. And this is what the present experiments show. Evidence of response priming, as indicated by acquisition-consistency effects, was most pronounced:

1. When action and effect were separated by less than 2 s
2. When the effect only rarely occurred in the absence of the action
3. When the overall frequency of an effect was high

Thus, our results indicate that the frequent co-occurrence of an action and an effect is a critical factor for the acquisition of action-effect knowledge, and hence for the degree to which this knowledge affects the planning and execution of future actions.

Some more specific implications of our findings relate to the mechanism of action-effect acquisition and the utilization of action-effect knowledge, which we now discuss in turn.

The mechanism of action-effect acquisition

We assume that being exposed to the frequent co-occurrence of an action and a following sensory event induces the creation and incremental strengthening of an association between the motor pattern driving the action and the codes representing the perceived event. Note that, taken in isolation, the present data do not unequivocally prove this assumption to be correct. In particular, our data do not address the issue of how direct the association between action codes and effect codes really is. For instance, the action-contingent tones may well have been associated with the arrow stimuli preceding them in the learning phase (a stimulus-effect association), which again became associated with the actions they signaled (stimulus-response association).

Then, in the test phase, presenting a tone may have retrieved the memory of the corresponding arrow (as arrows did not appear in the test phase), which again primed the associated response. Hence, the consistency effects we observed may reflect the operation of E-S-R association chains rather than the more direct E-R associations we assume. Alternatively, the emerging associations may not have linked effect codes and action codes directly but, instead, consist of a cluster of associations between effect tones and response locations, and response locations with the responses proper.

Even though these possibilities cannot be ruled out on the basis of the present results we do not consider this to undermine our arguments. First of all, any of those possible scenarios assumes that, one way or the other, actions and their effects do become part of the same cognitive structure, which is exactly what we have claimed here and elsewhere (Elsner & Hommel, 2001; Hommel, 1997). How complex these structures are and which elements they include is an interesting issue, but it does not affect the general idea that actions and effects are integrated. Secondly, there is no evidence that using the same target stimuli in the learning phase and the test phase would increase the impact of action effects; if anything, the opposite seems to be true (cf. Hommel, 1996, and Elsner & Hommel, 2001). In our view, this at least rules out an account in terms of E-S-R associations. Thirdly, we have provided neurophysiological evidence that merely perceiving a learned action effect in a task that requires no response leads to the activation of the human supplementary motor area (SMA; Elsner et al., 2002). Moreover, the only other brain area whose activity covaried with the frequency of previous action effects was the right hippocampus, which does not support the idea that the retrieval of the (in this case visual) target stimuli from the learning phase or of the locations of the response keys were necessary mediators of action priming. All in all, we think that it makes sense to assume that perceiving an action-effect sequence results in the integration of action-related and effect-related codes into a structure that allows for bi-directional (i.e., action $\rightarrow$ effect and effect $\rightarrow$ action) priming.

But how might such structures emerge? In more general terms, Hebb (1949) proposed that the frequent co-activation of two or more neural structures leads to changes in the synaptical connections between them, which again are thought to facilitate the transmission of electrical impulses from one to the other. Applied to action-effect learning this would imply linking neural patterns in motor areas to neural patterns of sensory areas in the brain. Although a direct association of primary motor codes to primary sensory codes seems unlikely, there is increasing evidence that certain brain areas integrate sensory and motor codes, such as the intraparietal sulcus (Murata, Gallese, Luppino, Kaseda, & Sakota, 2000) or the areas containing "mirror neurons", e.g. the prefrontal cortex (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Together with the observations of Elsner et al. (2002), these findings bolster the view that actions and their effects are integrated into sensorimotor (or perception-action) structures that can be characterized as "action concepts" (Elsner & Hommel, 2001; Hommel, 1997).

If integration depends on overlapping activation of perception- and action-related codes, it should be constrained by code decay. In the context of this assumption, the results of Experiment 1 can be taken to indicate that the activation of action-related codes decays rather quickly. Indeed, after only 2 s the activation of the codes of a manual key press seems to have decreased to a level that no longer creates or strengthens action-effect associations, at least not to a degree that would influence performance on a later occasion (i.e., in the test phase). This observation fits with the findings of Stoet and Hommel (1999), which showed that maintaining an action plan impairs the planning of another feature-overlapping action. However, the interference disappears less than 1 s after the execution of the maintained plan, which suggests that the codes making up the plan (and producing the interference) decayed to a level that does not influence concurrent processes any longer. In other words, used action plans are short-lived.

The assumption of a Hebbian learning mechanism stresses the importance of temporal contiguity and probabilistic contingency for action-effect learning. As there is evidence of associative action-effect learning not only in adults, but also in human infants (see Elsner & Aschersleben, in press; Gergely & Watson, 1999), cats (Brogden, 1962), rats (Meck, 1985; Rescorla, 1992), and pigeons (Urcuioli & DeMarse, 1996), the underlying learning mechanism is unlikely to be overly complex or to put high demands on memory capacities. If so, it may be doubted whether the calculation of relative probabilities according to the Delta-p rule—which requires the storage of information about all occurrences and non-occurrences of an action and its effects—is a reasonable candidate to underlie action-effect learning. In contrast, contiguity-based learning would only require that the cognitive system registers the co-occurrence of two events on-line, and automatically forms an association between their codes. By increasing or updating the strength of the emerging association at every subsequent experience of the co-occurrence (or non-occurrence) of the same events, random co-occurrences of an action and an event may eventually be filtered out. However, the data reported here do not provide sufficient evidence for a final answer to the issue whether action-effect learning is based on temporal contiguity or on probabilistic contingency.

The utilization of action-effect knowledge

The present study was mainly concerned with the first stage of Elsner and Hommel's (2001) two-stage model, i.e., with the question of how knowledge about actions and their effects is learned. In order to demonstrate that learning actually took place, we made a rather strong assumption, namely, that presenting an effect stimulus to someone who had acquired a particular action-effect

association primes the associated action to a degree that facilitates the selection of the corresponding action and/ or hampers the selection of another action. Only if this strong assumption holds, acquisition-consistency effects can be expected to show up in the RTs of the test phase.

On the one hand, there are a couple of reasons to believe that actions can indeed be activated by presenting people with the perceptual effects of that action. For instance, Hommel (1996) instructed participants to perform choice reactions to visual stimuli while being presented with previously learned auditory action effects. Even though the auditory stimuli were entirely irrelevant to the task, performance was better if they had previously been associated with the currently correct key press than with the alternative key press. Likewise, Beckers et al. (2002) found that the task-irrelevant affective value of stimulus words facilitates the selection of responses that had previously been followed by a value-congruent electrocutaneous feedback (presence or absence of a mild electro-shock). Elsner and Hommel (2001, Experiments 2–4) instructed participants to perform free-choice responses timed by a tone signal that had been presented as an action effect in a previous part of the session. Even though participants were encouraged to ignore the pitch of the tones, they were more likely to choose the movement that had previously produced the tone. The perhaps most direct evidence of the activation of action tendencies was obtained by the study by Elsner et al. (2002) already discussed, where the presentation of learned action effects in a listening task was found to increase activation of the SMA.

On the other hand, however, there is some evidence that acquisition-consistency effects are not necessarily a pure measure of the presence and strength of action-effect associations. One piece of evidence comes from our own observation that individual causality judgments are not a valid predictor of the individual size of the acquisition-consistency effect. First of all, this implies that these two measures do not reflect exactly the same thing. Indeed, it would be a plausible assumption that experiencing the frequent occurrence of an action and an effect induces an association between action- and effect-related codes, and that this association drives both the causality judgments and the response priming responsible for the consistency effect. Given the close correspondence of findings from instrumental conditioning in animals and causal judgments of action-effect relations in humans (Shanks & Dickinson, 1987; Wasserman, 1990; Young, 1995) it is in fact not unreasonable to assume that the strength of action-effect associations and the degree of causality attributed to the corresponding action-effect relation are mirror-images of each other—even though learning theorists and cognitive researchers may argue about the causal relation between these two measures (i.e., whether judgments are driven by associations or whether learning depends on causal perception). But if so, the discrepancy between individual causal judgments and consistency effects would suggest that the

former represent a purer measure of association strength than the latter. The available evidence suggests two, in no way exclusive reasons for why this may be the case.

One has to do with inter-individual differences in relative and absolute processing speed. Hommel's (1996) study provides evidence that the degree to which an irrelevant action-effect stimulus affects response performance to a target stimulus depends on the relative processing speed for the features of the two stimuli. Firstly, priming was increased if the action effect stimulus preceded the target stimulus by 100 ms (Experiment 5b), suggesting that priming an action takes some time. Secondly, priming was also increased by decreasing the discriminability of target stimuli (Experiment 5a). As this manipulation made the task more difficult and, thus, increased the RT level, it can be assumed that response priming had more time to unfold before response selection was completed. Indeed, thirdly, analyses of the RT distributions revealed that the priming effect was restricted to the slow tail of the distribution. The first two of these observations are based on data that were averaged across participants, but their processing logic also applies to inter-individual differences. Most importantly, the time needed to process stimuli of particular modalities or to complete response selection may differ between individuals, which would introduce variance in the interval in which response-priming can unfold. Because these factors are likely to influence the size of acquisition-consistency effects but not the judgments of causality between action and effects, they may provide at least part of an explanation why the latter are imperfect predictors of the former.

A second reason why acquisition-consistency effects may not always mirror the strength of action-effect associations has to do with the current task goals. Consider the study of Hommel (1993), who investigated the impact of irrelevant spatial stimulus location on the speed of selecting spatial responses (i.e., the so-called Simon effect). Under the standard instruction to "press a left and a right key" in response to a particular stimulus (e.g., to the color of a visual patch), people are known to show better performance when the spatial locations of stimulus and response key correspond (e.g., Simon & Rudell, 1967). Hommel (1993) first showed that this is also the case if the two keys produce light flashes on the opposite side, i.e., if pressing a left key produces a right-side flash and vice versa. However, when the same task was carried out under the slightly different instruction to "flash the right and left light" in response to the target stimulus, performance was best if the locations of stimulus and light corresponded—even though this implied non-correspondence of stimulus and response key. This means that task intentions can select particular action effects (here: referring to key or finger location versus light location) and thereby influence the way a given action is cognitively coded in a given situation. This does not necessarily eliminate non-selected action

effects from action control entirely but it drastically reduces their impact on overt behavior (Hommel, 1993, 1996).

This assumption is fostered by the recent findings of Hommel (2003b). He instructed participants to respond manually to the color of words with a congruent or incongruent meaning (i.e., Stroop-type stimuli). In two groups, each response produced a visual patch of a particular color on a screen. In one group, the effect was always of the same the color as the stimulus, in the other group, the effect was of a different color. In a third group, the responses produced no effects. If the impact of action effects on response selection were entirely automatic, the benefit of the compatible-mapping group over the no-effect group should be mirrored by a comparable disadvantage in the incompatible-mapping group. However, overall performance in the compatible-mapping group was better than in the other groups, which did not differ. Because the compatible-mapping group was the only group in which the stimulus and effect color were identical, the members of this group may have profited from *intentionally* changing the coding of their actions from location to color. Thus, for example, they performed the *green* response after the *green* stimulus, whereas the other groups performed the *left* response (which caused a blue effect or no effect). According to this interpretation, the current intention determines which action effects are selected to cognitively represent a particular action. If so, the automatic impact of action effects that are unrelated to the current task goal is necessarily weak, and it may be unreliable or even absent in overt behavior. Moreover, the automatic impact may vary depending on the participants' strategies, on the subjective salience of the action effects, and so forth. In other words, acquisition of action effects may well be automatic, but the impact of acquired action effects on action control may depend on subjective utility, which again depends on the relevance of the action effects to the task at hand.

To conclude, the two experiments of this study provide evidence that action-effect acquisition depends on the temporal proximity of action and effect and on the contingency or on the frequency of their co-occurrence. These observations and their correspondence with findings from instrumental conditioning in animals and causal perception in humans support the assumption that acquiring action effects is accomplished by well-known associative learning mechanisms. However, whether or not the emerging action-effect associations produce a measurable impact on action control is likely to depend on task intentions and on individual processing characteristics.

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