

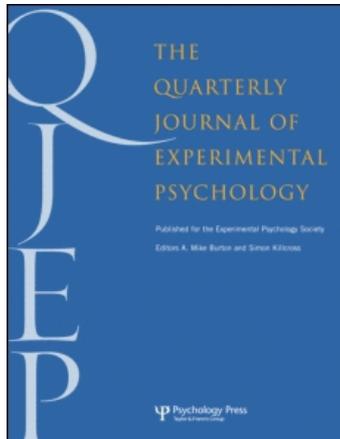
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Movements or targets: What makes an action in action-effect learning?

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Movements or targets: What makes an action in action–effect learning?

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According to ideomotor theory, actions become linked to the sensory feedback they contingently produce, so that anticipating the feedback automatically evokes the action it typically results from. Numerous recent studies have provided evidence in favour of such action–effect learning but left an important issue unresolved. It remains unspecified to what extent action–effect learning is based on associating effect–representations to representations of the performed movements or to representations of the targets at which the behaviour aimed at. Two experiments were designed to clarify this issue. In an acquisition phase, participants learned the contingency between key presses and effect tones. In a following test phase, key–effect and movement–effect relations were orthogonally assessed by changing the hand–key mapping for one half of the participants. Experiment 1 showed precedence for target–effect over movement–effect learning in a forced-choice RT task. In Experiment 2, target–effect learning was also shown to influence the outcome of response selection in a free-choice task. Altogether, the data indicate that both movement–effect and target–effect associations contribute to the formation of action–effect linkages—provided that movements and targets are likewise contingently related to the effects.

Keywords: Behavioural control; Motor learning; Ideomotor principle.

It takes years of training until a human being is able to control the movements of his body in a proper way. However, once learned, we use our limbs for whatever aims with impressive effortless-ness. Structures apparently have been formed that allow the right muscle commands to be evoked for any of the countless aims we strive for in our daily life. Anyhow, it is not yet well understood how the selection of the respective movements takes place.

An early speculation about the mental processes that evoke the appropriate movements to produce a

desired effect is the ideomotor principle (IMP; cf. Stock & Stock, 2004, for a historic overview). The IMP assumes that every movement becomes associated with its contingent sensory effects. This concerns more “proximal” sensations, coming from the moving limbs themselves, as well as more distal sensations, coming from changes caused by the movement in the environment. Second, it is assumed that anticipations of effects gain the power to evoke the corresponding movements (e.g., Herbart, 1825; James, 1890/1981; Lotze, 1852; see

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Greenwald, 1970a, 1970b; Hoffmann, 1993, 2003; Hoffmann et al., 2007; Hommel, 1998, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1987, 1990, 1992, 1997, for more recent versions of the IMP). As one and the same movement can produce varying distal effects it appears unlikely that movements and their effects are inherently connected. Rather, the assumed bidirectional relations between movements and at least their distal effects have to be learned (e.g., Held & Hein, 1963; Herbart, 1825). Thus, from the point of view of the IMP, learning of bidirectional movement–effect associations, or, in more general terms, bidirectional action–effect learning, is a fundamental process in the acquisition of behavioural competence.

Action–effect learning has already been studied intensively in animals. The integration of effects in the control of instrumental behaviour was first demonstrated by a facilitation of discrimination learning when responses produce differential outcomes (differential outcome effect; Trapold, 1970; see Urcuioli, 2005, for an overview). In accordance with the IMP, outcome–response theories (e.g., Trapold & Overmier, 1972) also assume that associations between outcomes (effects) and actions mediate instrumental behaviour in animals. This assumption is supported by a huge body of findings, including latent response–effect learning in rats (Meck, 1985), the impact of devaluated outcomes on response choices (Colwill & Rescorla, 1985, 1990), and congruency effects between imperative stimuli and outcomes (de Wit, Niry, Wariyar, Aitken, & Dickinson, 2007; Dickinson & de Wit, 2003).

Recently, numerous studies explored action–effect learning also in humans. Almost all studies are based on a suggestion made by Greenwald (1970a): As proximal effects of movements are difficult to manipulate experimentally, Greenwald proposed to use additional stimuli that are to be contingently presented after each of the required movements as their arbitrary distal effects. According to the IMP, bidirectional connections between the movements and their distal effects should be formed, so that the effect–stimuli subsequently exert influence on the selection of the movements they were formerly the effects of.

Meanwhile, influences of former effect–stimuli on response selection have been demonstrated in a variety of paradigms. For example, in serial reaction time tasks additionally presented contingent action effects substantially improve learning of the required action sequences (e.g., Hoffmann, Sebal, & Stöcker, 2001; Stöcker, Sebal, & Hoffmann, 2003), and sequence learning can at least partly be traced back to the learning of contingent action–effect relations (e.g., Ziessler, 1998; Ziessler & Nattkemper, 2001). Moreover, an acquired sequence of action effects facilitates learning of a sequence of new actions, provided that the same effect sequence is produced (Hazeltine, 2002). In reaction time tasks, action effects create compatibility phenomena like imperative stimuli—that is, participants respond faster if the required response is followed by a compatible than by an incompatible effect (e.g., Kunde, 2001, 2003; Kunde, Hoffmann, & Zellmann, 2002; Kunde, Koch, & Hoffmann, 2004). Finally, participants respond faster to stimuli that were experienced as effects of the currently required response than to stimuli that formerly were the effect of an alternative response (e.g., Elsner & Hommel, 2001, 2004; Greenwald, 1970a; Nattkemper & Ziessler, 2004). Altogether, the given evidence suggests that (a) voluntary actions indeed become connected to their contingent sensory effects and (b) that anticipations of these effects precede and affect the selection and initiation of voluntary actions.

In view of the ample evidence for action–effect learning, the present experiments aimed at a further elucidation of the internal structure of the connections that are apparently formed. In the previously mentioned experiments, the employed actions typically did not differ only with respect to the required movements but also with respect to the aims or purposes they served, whereby almost always movements of fingers of the left or the right hand had to be performed in order to press certain keys. Consequently, contingencies between the required finger movements and the additionally presented distal effects were confounded with key–effect contingencies so

that action-effect learning may have been based on either of them or both. The present experiments were thus designed to explore the extent to which movement-effect and key-effect contingencies contribute to action-effect learning.

This issue is reminiscent of explorations of the internal structure of stimulus-response associations (S-R), where performed movements as well as movement targets have been shown to be involved. For example, numerous studies indicate that spatial S-R compatibility effects (Simon & Rudell, 1967) refer on the response side to both the anatomical-based distinction of left and right movements and the location of the movement targets (e.g., Buhmann, Umiltà, & Wascher, 2007; Guiard, 1983; Hasbroucq & Guiard, 1991; Heister, Schröder-Heister, & Ehrenstein, 1990; Hommel, 1993; Nattkemper & Prinz, 2001; Wallace, 1971; Wascher, Schatz, Kuder, & Verleger, 2001). Thus, in S-R associations features of the stimuli become related to features of the movements and to features of the targets the movements aimed at. Accordingly we expect that movement-effect and target-effect relations are both involved in the formation of action-effect associations as well.

The question of whether distal sensory effects of a voluntary action become associated to motor representations of the preceding movements or to sensory representations of the targets the movements aimed at is insofar of theoretical significance as it concerns the question to what extent the corresponding ideomotor linkages provide an account for motor control. Only if the effects become associated to the movements will they be able to evoke those motor patterns that have produced these effects in the past. However, if the effects become associated only with the targets, they will merely be able to facilitate target selection but not to determine the appropriate movements to achieve these targets.

EXPERIMENT 1

Experiment 1 is mainly based on a seminal study by Elsner and Hommel (2001). In this study

participants first were instructed to choose between pressing a left key with the index finger of the left hand or a right key with the index finger of the right hand in response to a unitary go-signal. During this acquisition phase, pressing the left key was contingently followed by a high-pitch tone, and pressing the right key was contingently followed by a low-pitch tone (or vice versa). In accordance with the IMP, the authors hypothesized that the finger movements by which the keys were pressed would automatically be associated to the following effect tones. Therefore, the perception of the effect tones should subsequently be able to prime the associated movements of the left or the right index finger.

These assumptions were examined in a test phase in which the effect tones were used as imperative stimuli, which required the left and right key presses that formerly were chosen freely. In a nonreversal group, each tone required the key press that had produced the respective tone in the acquisition phase, whereas in a reversal group, each tone required the key press that was formerly followed by the alternative tone. Participants in the nonreversal group responded more quickly than participants in the reversal group. In agreement with the IMP, the authors concluded that “perceiving several co-occurrences of a self-produced movement and a movement-contingent sensory event leads to an automatic association of the motor code representing the movement and the cognitive code representing the event—even if the event is completely irrelevant to the task at hand. Moreover, the emerging associations are bidirectional so that perceiving an event that resembles the acquired action effect will automatically prime the associated action” (Elsner & Hommel, p. 238, cf. also Elsner & Hommel, 2004; Hommel, 1996, 1998; Hommel, Alonso, & Fuentes, 2003).

Meanwhile, numerous studies have used the same experimental design. For instance, the “nonreversal advantage” has also been shown for 4- and 7-year-old children (Eenshuistra, Weidema, & Hommel, 2004) especially if the children were instructed to verbally label the relations between actions and effects (Kray, Eenshuistra, Kerstner,

Weidema, & Hommel, 2006). The design was enhanced by using nonauditory effects like category versus exemplar words instead of tones (Hommel et al., 2003), and it was applied to affective components of action effects (Beckers, De Houwer, & Eelen, 2002). Additionally, neuroimaging studies revealed the involvement of the supplementary motor area (SMA) and the hippocampus (Elsner et al., 2002; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008) in action–effect learning. All these studies consistently confirmed the nonreversal advantage (for an exception, see Herwig, Prinz, & Waszak, 2007). Thus, the available evidence is largely consistent with the basic claims of the IMP that first, voluntary actions become associated with contingently presented sensory effects, and that second, the formed associations are bidirectional in that they allow the effect stimuli to prime the actions they were formerly the effects of.

However, note that in all the experiments mentioned above participants were to press different keys with different fingers. Thus, in each trial a certain finger movement, represented by the corresponding motor pattern, always was performed in order to press a certain key. Consequently, any evidence in favour of action–effect learning can likewise be attributed to the formation of links between certain finger movements and their effects (movement–effect relations hereafter) as well as between certain target keys and the effects that were produced by pressing them (key–effect relations hereafter).

In order to disentangle the influence of movement–effect and key–effect contingencies on action–effect learning, keys and movements have to be orthogonally combined. For this reason, in Experiment 1, the reversal versus nonreversal variation of the movement–tone relation (reversal vs. nonreversal) used by Elsner and Hommel (2001, Experiment 1) was supplemented by an additional variation of the hand–key mapping. For half of the participants the hand–key mapping of the acquisition phase remained unchanged whereas for the other half the hand–key mapping was inverted in the test phase. In order to allow a comfortable change of the hand–key mapping the keys

were vertically arranged so that the index finger of one hand pressed the distant key, and the index finger of the other hand pressed the near key. Accordingly, participants performed the same finger movements producing the same proximal effects, like the feeling of the movement and of the pressure exerted on the key, as in the acquisition phase. However, after changing the hand–key mapping each of the finger movements was now executed in order to press the other key.

As a result, in four experimental groups the reversal versus nonreversal of the movement–tone and the reversal versus nonreversal of the key–tone assignments were orthogonally varied, allowing a separate assessment of the extent to which movement–tone and key–tone associations contribute to the general nonreversal advantage (see Figure 1).

According to the findings of Elsner and Hommel (2001), we expect the participants who did not change the hand–key mapping to respond faster for nonreversed than for reversed movement–tone mappings. If this nonreversal advantage would rely solely on acquired movement–tone associations, participants who changed the hand–key mapping from the acquisition to the test phase should yield an equally strong nonreversal advantage—even though the finger movements now aimed at the key that formerly produced the alternative tone. If however, key–tone associations also contribute to action–effect learning, the nonreversal advantage is expected to diminish as a result of the changed hand–key mappings.

Method

Participants

A total of 64 undergraduate students at the University of Würzburg (54 females, 10 males) participated in exchange for course credit and were randomly assigned to the four experimental groups. The mean age was 21.9 years ($SD = 4.7$). The participants reported having normal or corrected-to normal vision and hearing and were naive as to the purpose of the experiment.

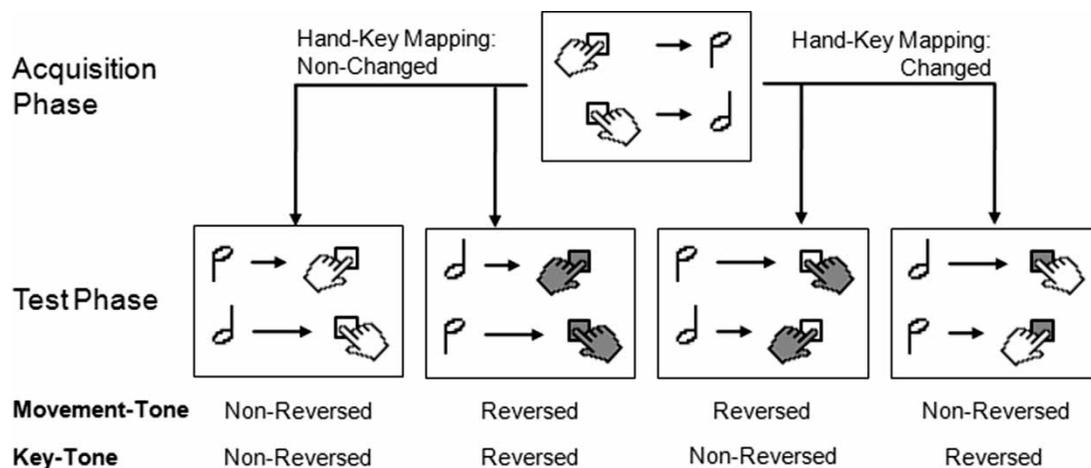


Figure 1. Design of Experiment 1. In an acquisition phase, participants learned a key/movement-tone mapping by pressing two vertically arranged keys. In the following test phase, these effect tones served as imperative go-signals in a forced-choice reaction time task. Hand-key mapping as well as movement-tone mapping were independently varied, thus creating four subgroups with reversed versus nonreversed movement-tone mapping (grey vs. white hands) and reversed vs. nonreversed key-tone mapping (grey vs. white keys).

Apparatus and stimuli

In the acquisition phase, a white square was displayed in the centre of a black 17" monitor. The square subtended a visual angle of 2.3° in width and height, measured from a viewing distance of about 50 cm, and served as a visual go-signal. Participants responded by pressing one of two response keys with the index fingers of the left and the right hand. The keys measured 18×18 mm each. They were mounted on the table in front of the participants at a vertical distance of 250 mm. As auditory effects, sinusoidal tones of 60 dB with a frequency of 400 Hz (low pitch) and 800 Hz (high pitch) were presented via two loudspeakers to the right and left of the monitor.

Procedure

Acquisition phase. Participants were instructed to respond as quickly as possible to the onset of the white square with a keystroke of the index finger of the right or left hand. They were told to choose freely which hand to use in each trial but to use both hands about equally often and in random order. They were also asked to keep their index fingers on the respective keys. Half of

the participants were to press the distant key with the left and the near key with the right hand; the remainder followed the opposite hand-key mapping. The key/hand-tone assignments were balanced across all participants.

At the beginning of each trial, the white square was presented for 200 ms. When the response was made, the appropriate tone was presented for 200 ms starting 50 ms after the onset of the keystroke. Like Elsner and Hommel (2001), we considered responses faster than 100 ms as anticipations and responses slower than 1,000 ms as omissions. In these cases, a 1,000-ms warning signal appeared on the screen. Both types of invalid trial were repeated at the end of the block. There was an interval of 1,500 ms between trials. Participants started with 8 practice trials and continued with four blocks of 50 valid trials each. After each block, a message on the screen informed participants about the relative frequencies of right- and left-hand responses and encouraged them to improve their performance.

Test phase. The two different effect tones were now used as imperative stimuli. Participants were informed about the current tone-hand mapping

and were instructed to respond to each tone with the corresponding finger movement as quickly and as correctly as possible. Again, participants were asked to keep their index fingers on the respective keys in order to respond as fast as possible. Furthermore, keeping the index fingers on the keys ensured that after a change of the hand–key mapping the same finger movements were to be performed as in the acquisition phase before, irrespective of the keys to press. Each participant was randomly assigned to one of four equally sized experimental groups (see Figure 1). The two subgroups with unchanged hand–key mapping represent a replication of Experiment 1 of Elsner and Hommel (2001) whereas the two groups with changed hand–key mapping allow disentangling of movement–tone and key–tone associations.

At the beginning of each trial, the white square was presented together with one of the two tones for 200 ms. The tones appeared equally often in random order. The next trial started 1,500 ms after a correct response. In case of anticipations (reaction time, $RT < 100$ ms), omissions ($RT > 1,000$ ms), or wrong keystrokes a warning message appeared on the screen. All three kinds of invalid trials were repeated at random positions during the same block. Participants performed 8 practice trials and 100 valid test trials.

Results

Acquisition phase

Response omissions or anticipations occurred in 4.2% of the trials and were excluded from further analysis. Then, relative frequencies of left and right finger movements (i.e. distant and near key strokes) were computed for each participant. In order to ensure that participants in all groups had chosen both response alternatives about equally often a ratio of 89:111 (respectively, 44.5% to 55.5%) or more extreme was considered as a deviation from equal distribution. This ratio corresponds to the application of a two-category chi-square goodness-of-fit test performed at a significance level of $\alpha = .15$ for each participant. (Note that α was raised to reduce Type II errors.

For all other analyses the significance level was set to $\alpha = .05$.) A total of 2 participants were replaced because their response ratios deviated from equal distribution. All other participants used both response alternatives about equally often (on average 49.9% vs. 50.1%, $SD = 1.7$). The mean RTs amounted to 213 ms, and RTs did not differ between the four groups, $F(3, 60) = 1.39, p = .255$.

Test phase

Response omissions or anticipations (0.3%) were excluded from further analyses. Then, error rates and mean RTs of valid responses were determined for each participant and block of 20 valid trials each. Figure 2 shows the mean RTs plotted across blocks for all four groups.

To replicate the data evaluation of Elsner and Hommel (2001), we performed an analysis of variance (ANOVA) with block (1 to 5) as within-subjects factor and movement–tone mapping (reversal vs. nonreversal) as the between-subjects factor, but added hand–key mapping (changed vs. nonchanged) as additional between-subjects factor.

The ANOVA of RTs revealed a main effect of block, $F(4, 240) = 5.47, p < .001, \eta_p^2 = .08$, with mean RTs increasing from 343 ms in Block 1 to 365 ms in Block 5. Furthermore, the interaction of movement–tone mapping and hand–key mapping was significant, $F(1, 60) = 4.32, p = .042, \eta_p^2 = .07$. All other effects did not reach significance (all $ps > .19$).

The corresponding ANOVA of error rates only yielded a significant main effect of block, $F(4, 240) = 4.01, p = .003, \eta_p^2 = .06$, which was due to a higher error rate in Block 1 than in Blocks 2, 3, 4, and 5 (8.9% vs. 5.2%, 5.8%, 5.4%, and 5.2%, respectively). No other effect approached significance (all $ps > .18$).

In order to disentangle the interaction of movement–tone mapping and hand–key mapping concerning RTs, we performed separate ANOVAs with block (1 to 5) as within-subjects factor and movement–tone assignment (reversal vs. nonreversal) as the between-subjects factor for the two groups, which either did change or did not

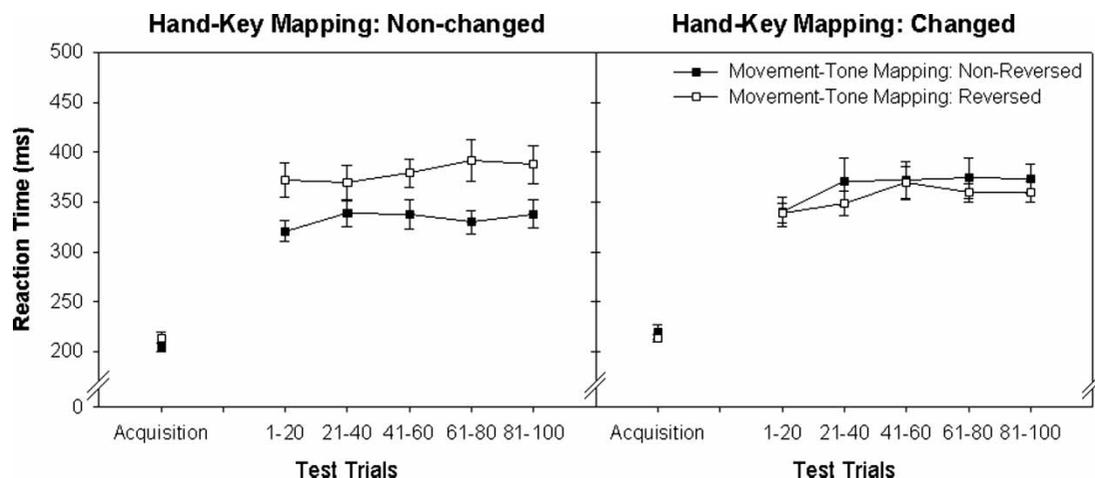


Figure 2. Mean reaction times in the acquisition phase and in blocks of 20 valid trials of the test phase of Experiment 1 as a function of the reversal of the movement–tone relation, separately for participants who either did not (left) or did change the hand–key mapping (right).

change the hand–key mapping. The ANOVA for the two groups with unchanged hand–key mapping revealed a significant effect of movement–tone mapping, $F(1, 30) = 5.73$, $p = .023$, $\eta_p^2 = .16$. Participants responded faster to nonreversed than to reversed tone–movement assignments (333 ms vs. 380 ms). This result replicates the nonreversal advantage of Elsner and Hommel (2001). The ANOVA for the two groups with changed hand–key mapping, however, yielded no significant effect of movement–tone mapping, $F(1, 30) = .30$, $p = .588$, $\eta_p^2 = .01$. Participants in the nonreversal condition even tended to respond slower than participants in the reversal conditions (366 ms vs. 355 ms). Thus, changing the hand–key mapping caused the nonreversal advantage to disappear. The changed hand–key mapping thereby specifically affected the reversal effect and not the overall performance. Consequently, a 2×2 split-plot ANOVA with the within-subjects factor of experimental phase (acquisition vs. test) and the between-subjects factor of hand–key mapping showed neither a significant main effect of hand–key mapping nor a significant interaction (both F s < 1).

The initial ANOVA revealed a significant influence of the change of hand–key mapping on the nonreversal advantage, thus suggesting a contribution of key–tone relations. As the study also aimed at an assessment of the relative impact of key–tone and movement–tone contingencies on the nonreversal advantage, the data of all four groups were reassessed by an ANOVA again with block (1 to 5) as within-subjects factor but now with key–tone mapping (reversal vs. nonreversal) and movement–tone mapping (reversal vs. nonreversal) as between-subjects factors.

The ANOVA of RTs showed the already reported main effect of block, $F(4, 240) = 5.47$, $p < .001$, $\eta_p^2 = .08$, and a significant main effect of key–tone mapping, $F(1, 60) = 4.32$, $p = .042$, $\eta_p^2 = .07$.¹ All interactions with the block variable failed to reach significance (all p s > .39). RTs increased from 344 ms with a nonreversed to 373 ms with a reversed key–tone mapping. There was also an increase of RTs from nonreversed to reversed movement–tone mapping (350 ms vs. 368 ms), which, however, failed to reach significance, $F(1, 60) = 1.70$, $p = .198$, $\eta_p^2 = .07$. The interaction of key–tone mapping

¹ This effect corresponds to the interaction of movement–tone mapping and hand–key mapping in the former ANOVA.

and movement–tone mapping did not reach significance either ($F < 1$).

The corresponding ANOVA of error rates only yielded the already reported main effect of block, $F(4, 240) = 4.01$, $p = .003$, $\eta_p^2 = .06$. No other effect approached significance (all $ps > .17$).

Discussion

First of all, changing the hand–key mapping influenced neither the overall reaction times in the test phase nor the increase from acquisition to test phase so that the manipulation is unlikely to influence the finger movements per se. Thus, conditions with changed and unchanged hand–key mapping can be directly compared. Considering the conditions that replicated the Elsner and Hommel (2001) design—that is, the two groups who did not change the hand–key mapping from the acquisition to the test phase—participants again responded more quickly if the imperative tones had previously been experienced as the effect of the currently required finger movement, replicating the nonreversal advantage. However, if in the test phase the very same tone–finger mappings required pressing of another key, the nonreversal advantage disappeared. Thus, the data suggest that during the acquisition phase not only the performed finger movements but also the respectively pressed target keys became associated with the subsequently presented effect tones. Sensory features of the pressed keys, presumably in particular their different locations, seem to constitute an indispensable part of the action representations. Accordingly, in the test phase the tones prime not only the finger movements but also the selection of the target keys by which they were produced formerly. If the hand–key mapping is not changed, both priming tendencies privilege the required response in the nonreversal condition and/or jointly hamper the required response in the reversal condition, producing the nonreversal advantage. If the hand–key mapping is changed, however, both tendencies outweigh each other in the reversal condition and in the nonreversal condition as well: When the tone primes moving the one finger concurrently it

primes pressing the other key (and vice versa) so that the nonreversal advantage disappears.

EXPERIMENT 2

Experiment 2 was conducted in order to reassess the findings of Experiment 1, this time focusing on the outcome rather than the speed of response selection. Elsner and Hommel (2001, Experiments 2–4) already performed experiments in which participants were to respond to presentations of the former effect tones not by a forced but by a free choice between the two movement alternatives in the test phase. They found a general preference for the movement that was consistent with the previously experienced movement–tone relation—that is, participants preferably chose the movement that formerly produced the current tone. The finding confirmed the notion that during the acquisition phase bidirectional associations between the performed finger movements and the contingently following effect tones had been established so that the effect tones evoke the movements they were the effects of. However, again it might be that the preference for the “consistent” response resulted at least partly also from experienced key–tone contingencies.

In Experiment 2 we first replicated the settings used by Elsner and Hommel (2001) in their Experiment 3b. After an acquisition phase, which was identical to Experiment 1, a go/no-go paradigm was applied in the test phase: A white square was presented together with either one of the two former effect tones or with a new third tone. The two former effect tones indicated go trials, whereas the new third tone indicated a current no-go trial. In go trials, participants had to choose freely whether to perform a key press with the index finger of the left or the right hand, whereas in no-go trials, participants had to withhold any response and to wait until the next trial started. The no-go trials were inserted in order to reduce a possible tendency of making response decisions prior to the presentation of one of the go-tones (cf. Elsner & Hommel, 2001, p. 236). Again we explored whether a

change of the hand–key mapping from the acquisition to the test phase would affect the choices of the left or the right index finger in response to presentations of the former effect tones. Therefore, another group of participants were examined who were asked to change the hand–key mapping from the acquisition to the test phase as described in Experiment 1.

According to the findings of Elsner and Hommel (2001), we expect participants who did not change the hand–key mapping to prefer that finger movement by which a current go-tone was formerly produced—that is, we expect a bias in favour of the movement consistent choices due to the acquired movement–tone association. If this “consistency preference” would rely solely on movement–tone associations, participants who changed the hand–key mapping from the acquisition to the test phase should yield an equally strong consistency preference despite the fact that this time the alternative key (that is, the inconsistent key) is pressed by the respective consistent finger movement. If, however, key–tone associations also contribute to action–effect learning, the consistency preference is expected to diminish as a result of the changed hand–key mapping.

Method

Participants

Another 24 (8 male) paid participants were recruited for Experiment 2 and fulfilled the same criteria as those in Experiment 1. The mean age was 23.6 years ($SD = 3.1$).

Task, apparatus, stimuli, and procedure

Stimulus, apparatus, and procedure were almost the same as those in Experiment 1, except that in the test phase the forced choices were replaced by free choices under go/no-go conditions. The tones were presented by the loudspeakers of headphones. The test phase consisted of two blocks of 50 go trials and about 50 no-go trials (erroneous go trials were repeated whereas no-go trials were randomly inserted with a probability of .5). In go trials one of the two former effect tones were

presented equally often and in random order. Participants were to decide freely which finger to use after the current effect tone was presented. They were instructed to react as fast and as spontaneously as possible and to adopt no conscious strategy. No-go trials were indicated by presenting a metallic sound in about 50% of the trials. The sound had a mean frequency of 600 Hz and was of a distinct quality. In no-go trials participants were instructed to withhold any response and to wait until the next trial.

Results

Participants with more than 10% responses in no-go trials were excluded from analysis, and their data were replaced by the data of another participant. For this reason 2 participants had to be replaced. Another participant explicitly declared that he made up response decisions prior to the onset of the effect tones so that his data also had to be replaced. All participants fulfilled the same equal distribution criterion for the acquisition phase that had been used in Experiment 1.

Acquisition phase

Response omissions or anticipations occurred in 2.7% of the trials and were excluded from further analysis. The relative frequency of response choices was analysed by a paired-samples t test and did not deviate from chance (49.1% vs. 50.9%), $t(23) = -0.23$, $p = .821$.

Test phase

Trials with response anticipations or response omissions were excluded from analysis (1.7%). The mean response rate in no-go trials (errors) amounted to 5.2%.

Mean response frequencies and RTs were analysed as a function of consistency and the change of the hand–key mapping. The relative frequency of tone-consistent choices was analysed by separate t tests for both mapping conditions, with consistency being defined as performing the finger movement that had produced the current go-tone in the acquisition phase (see Figure 3). Thus, if a key press with the index finger of the left hand had

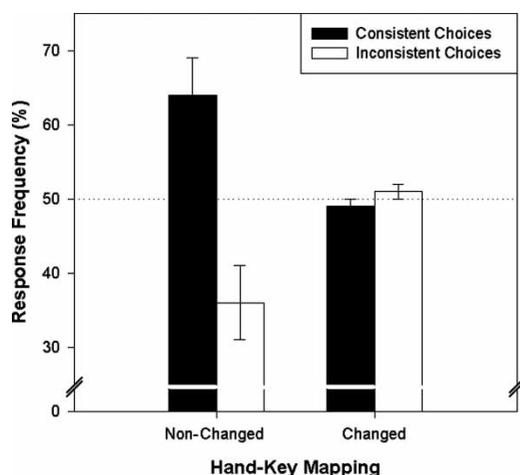


Figure 3. Mean frequencies of consistent and inconsistent choices in Experiment 2. Participants could choose freely which key to press after a former effect tone was presented. Consistent choices are coded movement based, and error bars represent standard errors.

produced a high-pitch tone in the acquisition phase, a consistent choice would be using the left index finger when a high-pitch tone was encountered as a go-signal—irrespective of which particular key was pressed.

For participants who did not change the hand-key mappings, the relative frequency of consistent choices significantly exceeded chance level (64% vs. 50%), $t(11) = 3.11$, $p = .01$, $d = 1.27$ —that is, the participants showed a clear preference to perform the finger movement that had produced the current go-tone as an effect in the acquisition phase. These results replicate the consistency preference reported by Elsner and Hommel (2001). In contrast, the relative frequency of consistent choices did not deviate from chance for participants who changed the hand-key mapping (49% vs. 50%), $t(11) = -1.71$, $p = .12$, $d = -0.70$. Instead, inconsistent choices were slightly preferred, but this difference was of negligible magnitude. A direct comparison of both groups reveals a significant difference between the relative frequencies of consistent choices, $t(11.42) = 3.31$, $p = .007$, $d = 1.35$ (Welch-adjusted to account for unequal variances), indicating that the change

of the hand-key mapping from the acquisition to the test phase causes the consistency preference to disappear.

The RTs were evaluated by an ANOVA with the between-subjects factor of hand-key mapping (changed vs. nonchanged) and the within-subjects factor of consistency (consistent choices vs. inconsistent choices). None of the effects approached significance (all $F_s < 1$) indicating that the change of the hand-key mappings did not cause any delay in response choices.

Discussion

Experiment 2 was conducted to reassess the conclusion of Experiment 1 that key-tone as well as movement-tone relations contribute to the formation of action-effect associations. For this purpose participants were to choose freely between a movement of the index finger of the left hand and a right-hand movement in order to press a near or a distant key in response to a go-tone that was formerly a contingent effect of either one of the two finger movements. Furthermore, the mapping of the hands to the keys was either changed or not changed from the acquisition to the test phase. If the hand-key mapping was kept constant, participants reliably preferred the finger movement that formerly had produced the current go-signal, replicating the findings of Elsner and Hommel (2001). However, if the hand-key mapping was changed, the preference for the tone-consistent finger movement disappeared.

The data support the notion that in the acquisition phase the effect tones become likewise associated to the finger movements as well as to the keys by which they are contingently produced. Consequently, in the subsequent test phase the presentation of the effect tones as go-signals tends to evoke representations of the respective tone-consistent finger movement and of the respective tone-consistent key. If the hand-key mappings are not changed, both tendencies privilege the same response alternative so that a reliable preference for tone-consistent responses results. After a change of the hand-key mapping,

however, the tendencies are contradictory: The tones tend to evoke the representation of the one finger movement, and concurrently they tend to provoke the representation of the other key to press so that neither of the response alternatives is preferred.

GENERAL DISCUSSION

According to ideomotor theory, voluntary actions become associated with the sensory effects they produce, and anticipations of these effects gain the power to evoke actions that have been experienced as bringing them about (e.g., Greenwald, 1970a; Herbart, 1825; James, 1890/1981; Lotze, 1852). However, prior investigations of these bidirectional action-effect associations yielded a confound of movement-effect and key-effect contingencies so that the relative contribution of both associations remained uncertain (e.g., Elsner & Hommel, 2001, 2004; Hoffmann, Stöcker, & Kunde, 2004; Hommel, 1996, 2003; Hommel et al., 2003; Kunde, 2001, Kunde et al., 2004). The present experiments indicate that both components are involved in action-effect learning.

In Experiment 1, different tones were first experienced as contingent effects of pressing a distant or near key with the index finger of the left or right hand. In a subsequent test phase, these tones were used as imperative signals to trigger distant or near keystrokes with the left or right index finger, with either changed or unchanged hand-key mapping. When the tones required pressing the same key to which they had previously been assigned to as effect, RTs were significantly reduced when compared to the reversed tone-key mapping. When the tones required the same finger movements to which they had previously been assigned to as effect, RTs also were numerically but nonsignificantly reduced in comparison to the reversed tone-movement mapping. In the conditions with unchanged hand-key mapping, both effects complemented one another, producing a substantial nonreversal advantage. However, if the

hand-key mapping was changed, both effects outweighed each other, cancelling any nonreversal advantage. Thus, the data indicate that both movement-tone and key-tone contingencies are involved in action-effect learning.

Experiment 2 extended the findings of Experiment 1 to the outcome rather than the speed of response selection. In an acquisition phase, different tones were experienced as contingent effects of pressing a distant or near key with the left or right index finger. In the following test phase, participants could choose freely which index finger to use after one of the two effect tones was presented as a go-signal. If participants responded with the same hand-key mapping as that in the acquisition phase, the finger movement was preferred that had produced the respective tone in the acquisition phase. However, when the hand-key mapping was changed from the acquisition to the test phase the preference for the tone-consistent finger movement disappeared. This discrepancy again suggests that both movement-tone and key-tone associations are formed: With unchanged hand-key mapping both associations promote the same response, which accordingly is preferably chosen, whereas with changed hand-key mapping the key-tone association and the movement-tone association refer to contradictory response choices so that neither of them is preferred.

The data of both experiments consistently suggest that not only the movements to perform but also the keys to press contribute to the formation of bidirectional action-effect associations. Thus, the "action" in an action-effect relation seems not only to refer to the corresponding motor patterns but rather is to be imagined as a bundle of features, comprising the sensory features of the keys to press as well as their location (see Chaminade & Decety, 2001; Hommel et al., 2001; Prinz, 1992). All these features of an action may become associated to following sensory effects to the extent to which they contribute to the discrimination between current response alternatives (cf. Ansorge & Wühr, 2004; Buhmann et al., 2007; Heister et al., 1990; Hommel et al., 2001) and in dependence on

their contingency to subsequently presented effect stimuli.²

However, there is a possible alternative account of our results that avoids the involvement of target keys in action–effects associations: Movement–effect associations could be highly context dependent in particular with regard to the postures under which the movements are performed. Accordingly, an association acquired under a certain posture would be abolished under a different posture, possibly because the proprioceptive feedback of the movement is altered. In the present experiments, the arm postures changed with the hand–key mappings, so that, if postures would really matter, the formed movement–tone associations would no longer be effective after the hand–key mappings were changed. Thus, the failure of a nonreversal advantage in the changed hand–key mapping condition would have been due to a context change instead of contradictory movement–tone and key–tone associations. The present findings do not allow such a contextual account to be ruled out. As we discuss in more detail, posture-dependent movement–effect associations would, however, be of little use for behavioural control as postures almost always change continuously. On the contrary, target objects remain largely stable even if they are attained by steadily changing movements and postures, so that they are predestined to form stable associations with contingently following effects.

Further evidence for the involvement of targets in action–effect associations was also provided by a recent study by Rieger (2004, Experiment 4). In this study, skilled typists responded to the colour of letters that were presented on a computer screen. When participants responded with crossed hands on an ordinary computer keyboard, the relation of the irrelevant identity of the letters

not only to the currently required finger movement but also to the currently required key to press had a significant impact on RTs: In comparison to neutral conditions participants responded faster with the letter-consistent finger although an inconsistent key was to be pressed, and they also pressed the letter-consistent key faster although they used an inconsistent finger. Because letters are imperative signals as well as contingent effects of keystrokes on a computer keyboard, the findings probably likewise refer to the participation of movements and keys in stimulus–response associations (see also Buhlmann et al., 2007; Heister et al., 1990; Hommel, 1993) as well as in action–effect associations.

The involvement of movements and targets in action–effect associations is also supported by neuroimaging studies. In a study using positron emission tomography (PET), Elsner et al. (2002) found an activation of the supplementary motor area (SMA) after participants simply heard tones that were previously experienced as contingent effects of voluntary key presses. They concluded that due to the formed action–effect associations the tones activate motor representations of the key presses that they were the effects of. However, the conclusion can be expanded in the light of new findings: The SMA has been found to comprise not only movement-related neurons but also target-related neurons and even neurons that are both target and movement related (Crutcher, Russo, Ye, & Backhus, 2004). Thus, SMA activity in response to the presentation of effect stimuli might refer to movement–effect as well as to target–effect associations.

Note that in the present study and in almost all previous studies on action–effect learning the keys were to be pressed under highly standardized conditions, mostly with the fingers resting on the respective keys. Accordingly, pressing a certain

² The assumed representation of actions by a bundle of sensory features is consistent with the theory of event coding (TEC; Hommel et al., 2001), which also assumes that actions are represented by their sensory consequences. However, TEC focuses: “on ‘early’ cognitive antecedents of action that stand for, or represent, certain features of events that are to be generated in the environment (=actions). TEC does not consider the complex machinery of the ‘late’ motor processes that subserve their realization (i.e., the control and coordination of movements)” (Hommel et al., 2001, p. 849). In contrast, the present experiments explicitly deal with the question of to what extent representation of distal action–effects gain the power to address concrete movements—see later.

key always required almost identical hand or finger movements. The same holds, for example, for professional typing or for playing a musical instrument where almost identical movements are performed in order to type a certain letter or to produce a certain sound (e.g., Drost, Rieger, Brass, Gunter, & Prinz, 2005a, 2005b; Drost, Rieger, & Prinz, 2007; Rieger, 2004, 2007). Under such conditions contingently appearing additional sensory effects can be likewise related to the various targets (keys to press, letters or sounds to produce) as well as to the almost uniform movements that serve to attain these targets. These conditions, however, are anything but typical for tracking everyday objectives.

If we think of the thousands of keys we press in order to switch a device on or off, to enter a PIN-code at a cash machine, to dial, or to send a text, and so on, it soon becomes apparent that in no case do we always use the same or even a similar movement under the same postures in order to press the various keys. In contrast, depending on the current circumstances, we typically use different movements and even different limbs if necessary in order to press the appropriate key. And what holds for key presses holds to a much greater extent for tracking other everyday objectives like opening a door, grasping an object, filling a glass, and so on: Whereas the targets we strive for remain relatively constant, the movements to attain them vary tremendously from case to case. This is the well-known redundancy problem of motor control—that is, that almost every behavioural target can be and typically is reached by an innumerable number of different body movements (e.g., Bernstein, 1967; Butz, Herbort, & Hoffmann, 2007; Jordan & Rumelhart, 1992).

If under such more ecological conditions certain distal sensory effects appeared along with attaining certain targets, these effects would be contingently related to the constant targets but not to the varying movements by which the targets are attained. Thus, it appears that everyday actions provide good conditions for the formation of target-effect associations but impeding conditions for the formation of movement-effect

associations. For example, if pushing the handle of a certain door is always somewhat creaky, the “creak” will be most likely associated to the door handle but less likely to the various movements by which the door handle is pushed. Thus, we have to admit that the involvement of both movement-effect and key-effect relations in action-effect associations is probably restricted to the infrequent cases in which the target keys are always pressed by the same movements and may be expanded to similar cases in typing or playing a musical instrument. In the majority of cases, however, where behavioural targets are achieved by ever-changing movements, the formed action-effect relations most likely rely on the experienced contingencies between the aspired targets and the effects.

The preceding considerations are crucial with regard to the functions that ideomotor linkages can serve. If movement-effect associations are involved, the activation of the corresponding effect representation—that is, its idea—would be able to evoke the movement that has been learned to go along with the appearance of the activated effect. This is presumably the case if the appearance of the effect always or at least mostly goes along with almost the same movement. If however, the ideomotor linkage refers primarily to target-effect relations, sensory effects could only prime associated behavioural targets—for example, the key to press or the handle to push—but not the movements to achieve these behavioural targets. Under this condition sensory effects might merely activate an initial movement (Adams, 1971) or a motor schema (Schmidt, 1975), which has to be further instantiated by subsequent processes about which the IMP remains silent. Accordingly, the IMP does not provide a general account on how anticipations of effects (the idea of them) are transformed into appropriate motor commands (cf. also Hoffmann & Lenhard, 2004), at least not inasmuch as anticipations of distal effects are concerned.

This failure of the ideomotor approach to provide an account for movement control has already been bewailed by Greenwald (1970b) when he wrote: “The problem of explaining

response execution . . . has been set aside temporarily until a more precise formulation of the ideomotor linkage is available" (p. 96). This is now 39 years ago, and with respect to the control of movement execution we still do not have a more precise formulation of the ideomotor linkage. Thus, the integration of the ideomotor principle with other contemporary accounts of motor control (e.g., Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Wolpert & Kawato, 1998) remains to be done (cf. also Butz et al., 2007; Herbort, Butz, & Hoffmann, 2005a, 2005b, for further discussions).

The present findings suggest a functional distinction of proximal and distal effects. Apart from exceptions, distal effects are weakly associated with motor patterns so that movements can rarely be determined by them. In contrast, proximal effects are always highly correlated with the corresponding motor patterns so that they are always able to specify the movements that typically brought them about. Thus, ideomotor linkages are probably to be dissected in at least two relations: first, relations between distal and proximal action effects and, second, relations between proximal effects and corresponding movements. Distal effects on their own are likely to specify only the target of an action whereas the movement itself is specified by transforming distal into proximal effects. This transformation may be conceptualized as a cascade of "inverse models" and feedback-loops (see Butz et al., 2007; Hoffmann, in press; Hoffmann et al., 2007).

However, this topic goes far beyond the scope of the present experiments, which mainly aimed at clarifying to what extent distal action effects are associated with contingent movements or contingent targets. The data clearly indicate a contribution of both movement-effect and key-effect associations under the present conditions.

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