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Acquisition and generalization of action effects

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Three experiments studied the acquisition of action-contingent events (action effects). In a first, acquisition phase participants performed free-choice reactions with each keypress leading to the presentation of either a particular category word (e.g., *animal* or *furniture*) or an exemplar word (e.g., *dog* or *chair*). In the test phase, choice responses were made to category or exemplar words by using a word–key mapping that was either compatible or incompatible with the key–word mapping during acquisition. Compatible mapping produced better performance than incompatible mapping if the words in the practice and the test phase were the same (e.g., *animal→animal*), if they had a subordinate–superordinate relationship (e.g., *dog→animal*), belonged to the same category (e.g., *dog→cat*), or referred to visually related concepts (e.g., *orange→circle*). The findings support the assumption that action effects are acquired and integrated with the accompanying action automatically, so that perceiving the effect leads to the priming of the associated response. And, most importantly, they demonstrate that effect acquisition generalizes to other, feature-overlapping events.

Humans perform actions to attain intended goals, that is, they produce events they would like to happen. However, actively attaining a goal is only possible if the actor knows which event can be produced by what action, which means that voluntary action relies on, and presupposes knowledge about relations between actions and their effects (Hommel, 1997, 1998). Logically, this implies a sequence of two phases in the emergence of voluntary action: An acquisition

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phase, in which contingencies between particular actions and their effects are picked up and stored, and the subsequent use of the learned relations in planning and performing an action aimed at producing the previously observed, action-contingent effect (Elsner & Hommel, 2001). The latter phase, in which anticipations of acquired action effects become functional for action control, represents the focus of what has become to be known as the ideomotor theory of voluntary action, developed by James (1890) and Lotze (1852). Indeed, this theory proposes that the control of intentional action is mediated by cognitive representations of the perceived effects the required, to-be-planned movements will produce (for overviews, see Greenwald, 1970; Scheerer, 1984). To become functional in action control, however, action effects first need to be acquired. This might happen ‘‘on request’’, that is, whenever the individual is eager to produce an effect that he or she did not produce before. But more useful would be a more automatic learning mechanism that allows the individual to pick up action effects ‘‘on the fly’’, that is, a mechanism that creates action–effect associations whenever a novel action effect is produced (Elsner & Hommel, 2001; Hommel, 1997). It is this acquisition the present study was concerned with, that is, the learning of relationships between actions and their perceivable consequences.

Initial research on the processing of response-produced events suggested that people may be unable to acquire even the simplest action–effect contingencies, such as between a keypress and a light flash (Jenkins & Ward, 1965; Smedslund, 1963). Yet, more recent, methodologically improved studies revealed that humans can perform such tasks quite accurately (Allan & Jenkins, 1980; Shanks & Dickinson, 1987; Wasserman, 1990). However, even these latter studies do not yet provide evidence as to the two most central expectations from an ideomotor approach to action control: That action effects are acquired *automatically* (i.e., even if they are not relevant to the task at hand and even if their acquisition is not explicitly intended) and that their acquisition leads to a *bidirectional* association between the representations of action and effect. That this is actually the case is suggested by more recent studies. Hommel (1996) had participants press a left or right key, or a single key once or twice, in response to features of a visual stimulus. Although this was irrelevant to the task, one response produced a low tone and the other response a high tone. After some practice, the visual stimulus was accompanied by low or high tones. Even though the pitch of this tone varied randomly (i.e., zero correlation between pitch and the relevant stimulus or response) performance was better if the prime tone matched the tone that was produced by the correct response. This suggests that codes of response-contingent tones (*E* for effect) were spontaneously associated with codes of the corresponding response (*R*–*E*), so that perceiving the tone again primes the associated response ($E \rightarrow R$).

The same conclusion is suggested by the findings of Elsner and Hommel (2001). In their study, participants performed free-choice reactions (single versus double keypresses) to a trigger stimulus, with each response producing a tone of a particular pitch. In one task (Exp. 1) participants received some practice with this task, without being instructed or having any reason to learn the response–tone relationship. Then, they received a second task, which required discriminative responses to tone pitch. In one group of participants the tone–response mapping was compatible with the previous response–tone mapping (e.g., practice with single→low, double→high; test with low→single, high→double) but in another group it was incompatible (e.g., practice with single→high, double→low; test with low→single, high→double). The group with compatible mapping performed much better than the group with incompatible mapping, and this was so even if effects were no longer presented in the second, test phase. This shows that, first, response–effect relationships were picked up automatically and, second, the resulting associations are bidirectional (i.e., *R*↔*E*) in the sense that priming can occur in another direction than acquisition.

Indications of bidirectional stimulus–response associations have attracted some attention as proponents of both associative (see Hall, 1984 for an overview) and cognitive (e.g., Waldmann & Holyoak, 1992) views on learning deny the possibility of this kind of backwards conditioning. However, such indications have been obtained even in animal studies. For instance, Trapold (1970) showed that rats learn to discriminate two given stimuli more quickly if the responses to them are followed by different reinforcers, the so-called ''differential outcomes effect'' (cf. McIlvane, Dube, Kledaras, de Rose, & Stoddard, 1992; Urcuioli & DeMarse, 1996). This effect suggests that representations of what has been experienced to follow a response have an impact on how easily that response can be selected. Brogden (1962) presented cats with a tone every time they showed a cage-turning response. When the tone was presented on a later occasion, the cats showed more tone-induced cage-turning responses than cats in a control group, again suggesting that bidirectional response–effect associations had been acquired. Finally, Meck (1985) conditioned rats to perform discriminative responses that he arranged to be followed by tones of a particular duration. In a subsequent transfer phase, those tones served as stimuli and responding to them was to be learned. If the tone–response mapping heeded the response–tone mapping used in the previous phase the percentage of correct responses was significantly higher than when the mapping was reversed. Apparently, then, experiencing that responses are followed by particular effects leads to a bidirectional association between response and effect representation.

More recent studies in humans have provided further support for the assumption that response–effect relations are acquired spontaneously. Estévez, Fuentes, and colleagues were able to demonstrate the ''differential outcomes effect'' in healthy young children (Estévez & Fuentes, 2003; Estévez, Fuentes, Mari-Beffa, González, & Alvarez, 2001) and in children and adults suffering from Down syndrome (Estévez, Fuentes, Overmier, & González, 2003) by using a complex symbolic-discrimination task. Subjects learned the conditional discrimination faster and showed a higher terminal accuracy when each response was followed by a different rather than the same outcome (reinforcer). Ziessler and colleagues (Ziessler, 1998; Ziessler & Nattkemper, 2001) observed that implicit learning of stimulus–response sequences critically depends on constant, predictable response–stimulus transitions, suggesting the existence of a learning mechanism specialized in the integration of responses and their effects. Likewise, both Hazeltine (2002) and Hoffmann, Sebald, and Stoecker (2001) found better acquisition and transfer performance for sequences in which each response was followed by a particular (nominally irrelevant) tone. By using a response-precuing paradigm, Kunde, Hoffmann, and Zellmann (2002) showed that switching from a precued to another response is easier if both responses have been learned to produce the same tone, hence, share an action effect. Finally, Kunde (2001) demonstrated that performance in choice-reaction time tasks is strongly affected by the compatibility between the responses and the (actually irrelevant) stimuli they are experienced to produce.

Taken altogether, there is substantial evidence that response–effect relationships are acquired more or less independent of any intention to learn them, and that the acquired associations affect performance in various ways, response selection in particular. Such findings are in line with the ideomotor theory proposed by James (1890) and Lotze (1852) and the hypothesis that action control makes use of previously learned action–effect associations (Elsner & Hommel, 2001; Hommel, 1997). However, there are two limitations most or all of these studies share, and it is these limitations the present study was aimed to overcome.

First, most studies have used tone pitch or tone location as action effects.[1] This has obvious methodological advantages over other, especially visual action effects: If visual action effects are task-irrelevant, participants may not only fail to attend but overtly avoid them by looking away or closing their eyes, which is not an option with auditory effects. Moreover, visual stimuli have been argued to lack the potency of auditory events to attract attention in an automatic, bottom-up fashion (Posner, Nissen, & Klein, 1976), which makes auditory effect stimuli

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[1] There are a few exceptions. One is the study of Hommel (1993), where responses were coupled with light flashes in different locations. However, participants were urged to consider these effects in planning their action, so that this study cannot be taken to demonstrate spontaneous acquisition of action effects. Moreover, the lights were flashed in almost complete darkness, which must have rendered them as salient as a tone. Another exception are the studies of Ziessler (1998) and Ziessler and Nattkemper (2001), who obtained evidence that manual responses became associated with subsequent visual letters. However, here learning these transitions was highly functional and the ‘‘effects’’ of one trial were, at the same time, targets for the next trial. A final exception are Estévez and colleagues' studies on differential outcomes effect with humans. Responses were associated with tokens of different colours that children knew they could change for either food or toys at the end of the experiment. This highly motivational feature of the visual outcomes (the tokens) was likely to render them exceptionally salient effects.

an even more convenient choice. However, these modality differences also raise the question whether findings on auditory action effects extend to visual effects. This question is the more pressing as, in an investigation of trial-to-trial binding of actions and effects, Dutzi and Hommel (2003) found the integration of visual effects to be much more dependent on attentional factors than the integration of auditory effects. As in daily life visual action effects are commonly more frequent and more relevant than auditory effects, it was important to see whether the spontaneous acquisition of bidirectional response–effect associations can also be demonstrated with visual action effects.

Second, in previous studies the acquired action-contingent event (i.e., the E in the $R \rightarrow E$ practice phase) and the stimulus used to prime the presumably associated response (i.e., the E in the $E \rightarrow R$ test phase) were physically identical. However, outside the lab it is rather unlikely that a given action produces always exactly the same effect; rather, it will produce effects of a particular sort or category, effects that share some but not all features of the acquired effect. Accordingly, an action–effect integration mechanism would only be useful if it allows the generalization from action effects encountered in a particular situation to other, similar effects. In the context of stimulus–stimulus learning, evidence for such generalization has in fact been observed. Alonso and Fuentes (2000) presented category labels as primes and exemplars of different categories as targets, resulting in relationships of the form $A \rightarrow b_i$ (A = category label; $\mathrm{b_i}$ = exemplars of category B). In the acquisition phase, participants were presented with either the labels *BODY* or *PLANT* as prime stimuli, followed always by exemplars of animal or furniture, respectively. Participants were told to categorize the target as being an animal or a furniture, without explicit instructions about the prime–target relations. In the test phase, the category labels of the targets in the first phase were used now as primes, and exemplars of the prime labels in the first phase were now used as targets. Participants were told to perform lexical decisions on targets. Prime words were followed by an equal number of trials by compatible targets (e.g., *ANIMAL* followed by exemplars of body parts, and *FURNITURE* followed by exemplars of plant), or by incompatible targets (e.g., ANIMAL followed by exemplars of plant, and FURNITURE followed by exemplars of body).

Alonso and Fuentes (2000) found that performance in the compatible condition produced shorter reaction times than in the incompatible condition (i.e., there was a priming effect), supporting the hypothesis of bidirectional stimulus–stimulus associations.[2] This effect replicated when exemplars instead of category labels were used as prime stimuli in both phases. Importantly, priming effects generalized when different but related primes and targets to those used in

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[2] Further evidence for the acquisition of bilateral stimulus–stimulus associations without generalization comes from Gerolin and Matute (1999), Matzel, Held, and Miller (1988), and Murdock (1958).

the acquisition phase were used in the test phase. It is true that there are several, potentially important differences between stimulus–stimulus learning as investigated by Alonso and Fuentes and action–effect integration as focused on here. Nevertheless, given that generalization can be argued to serve a crucial role in both types of learning, we wanted to test whether generalization can also be demonstrated in the acquisition of action effects.

EXPERIMENT 1

Experiment 1 had two goals. First, we wanted to see whether visual action effects are acquired at all and, in particular, whether bidirectional associations emerge between responses and the (codes of) visual effects they produce. Second, we wanted to test whether such associations generalize to other, novel effects as Alonso and Fuentes (2000) had observed for stimulus–stimulus relations. To attain these goals we conducted an experiment with two phases: An acquisition phase, where participants were presented with task-irrelevant, response-contingent words, and a test phase, where the spontaneous acquisition of response–word relations was diagnosed along the lines of Elsner and Hommel (2001).

In the acquisition phase, participants carried out freely chosen keypress responses (*R1* and *R2*), with the only restriction that the two response keys should be used about equally often. The major advantage of such a free-choice design is that no discriminative stimulus is required, so that stimulus–response learning or transfer can be ruled out as a possible factor in the test phase. In one condition of Experiment 1, the response effects (i.e., the response-contingent words, *E1* and *E2*) consisted of the same two category labels (animal and furniture) that were also used in the test phase, hence the E in the $R \rightarrow E$ practice phase was physically and semantically identical with the stimulus of the $E \rightarrow R$ test phase (the *category group*). In another condition of Experiment 1, however, the response effects consisted of two exemplars (dog and chair) of the categories labelled by the stimulus words of the test phase, hence the E in the $R \rightarrow E$ practice phase was only semantically related to the stimulus of the $E \rightarrow R$ test phase (the *exemplar group*).

In the test phase, all participants were to respond to the category words (animal and furniture) by pressing a particular key. For half of the participants the word–key assignment was *compatible* with the key–word relationship in their acquisition phase while for the other half it was *incompatible*. If compatibility played a role at all, this would show that visual action effects are actually acquired and integrated with the responses they have been experienced to follow. With regard to our second question, we were interested in whether a possible compatibility effect would interact with type of practice (category versus exemplar), that is, depend on whether action effects in practice and stimuli in test are identical.

Method

Participants

In total, 195 students from the University of Almería participated in single sessions of about 30 min for course credit. From these, 12 were excluded from analyses because they failed to perform each of the two responses at least 80 times—which according to pilot studies appears to represent a minimum to acquire stable response–effect associations. Moreover, the observation of bimodal distributions in reaction times and errors, as well as excessive error rates of up to 20%, suggested that a considerable number of participants had used a rather lenient accuracy criterion. As this was particularly true for groups with compatible mappings, such a tendency is likely to distort the outcome of analyses by mimicking a compatibility effect in RTs. To rule out this possibility we decided to apply a very strict error criterion of 5%, which left 63 and 77 participants in the category and exemplar groups, respectively (see Table 1 for detailed distribution of participants across conditions). Note that this provision works *against* the hypothesized compatibility effect and, thus, allows for a rather conservative test.

Stimuli and apparatus

The display and timing was controlled by a standard PC. Two adjacent white asterisks (**) on black background, presented at the screen centre, served as fixation mark. In acquisition trials, the visual reaction stimulus consisted of the green uppercase word VAMOS (Spanish for ‘‘go’’) also appearing at screen centre. The action effects (*E1*, *E2*), which appeared in green and one line below the centre, consisted of either the uppercase category words *ANIMAL* (animal) and *MUEBLE* (furniture) or the lowercase exemplar words *perro* (dog) and *silla* (chair), while in catch trials, the uppercase word *FRUTA* (fruit) was presented

TABLE 1
Reaction times (RT, in ms) and percentages of error (PE, in %) in test phase (*SD* in parentheses), and number of participants (*N*) as a function of type of action effects in acquisition phase and practice-compatibility of stimulus–response mapping

Practice	*Mapping*	*RT*	*PE*	*N*
Category	Compatible	431 (52)	2.5 (1.5)	30
	Incompatible	447 (57)	2.4 (1.7)	33
	Δ	16		
Exemplar	Compatible	429 (42)	2.4 (1.7)	30
	Incompatible	447 (63)	2.0 (1.5)	47
	Δ	18		

instead. In test trials, the stimulus to be responded to always consisted of the green uppercase category words *ANIMAL* and *MUEBLE*. From a viewing distance of about 60 cm, each character measured about 0.3° in width and 0.4° in height. Participants responded by pressing the left or right shift key of a standard computer keyboard with the corresponding index finger (*R1*, *R2*).

Procedure

The experiment was divided into an acquisition phase and a test phase (see Figure 1).

Acquisition phase. Each trial began with the presentation of the fixation mark for 500 ms, followed by a blank interval with randomly determined length of 200–400 ms. Then the go stimulus (the word *VAMOS*) was presented for 200 ms and participants were to press the left or right key as quickly as possible within 1000 ms. They were verbally instructed to choose freely which key to press, but to use the keys in a random order and about equally often.

Each keypress triggered the presentation of a word for 500 ms (*R1*→*E1*, *R2*→*E2*). In the category group the words were the same category words that served as stimuli in the test phase (animal and furniture). In the exemplar group the words consisted of two exemplars of the same categories (dog and chair). Within groups the mapping of response keys to words was balanced across participants. Participants were not informed about the response–effect mapping and were told that the response-triggered words were irrelevant for the task and should therefore be ignored. However, some processing of the action effects was enforced by presenting a catch word (fruit) in 10–11 randomly chosen trials, which was to be responded to by pressing the space bar within 2000 ms after having performed the left or right keypress. Note that even if this procedure arguably introduced some indirect task relevance of effect words, it by no means made the response–word *relationship* relevant or salient, or even suggested learning that relationship.

Trials with latencies exceeding 1000 ms were counted as missing and responses faster than 100 ms were considered to be anticipation errors. Response omissions and anticipations were fed back to the participants by a 2000 ms presentation of a warning message on the screen and the corresponding trial was repeated. The intertrial interval was 2000 ms. Participants worked through 200 valid acquisition trials. In 10–11 of these trials the response was followed by the catch word (calling for an additional spacebar response) and in the remaining 189–190 trials the two responses produced their assigned action–effect word.

Test phase. After having completed the acquisition trials, participants received a message on the screen informing them about the stimulus–response mapping for the choice-reaction task in the test phase. For half of the

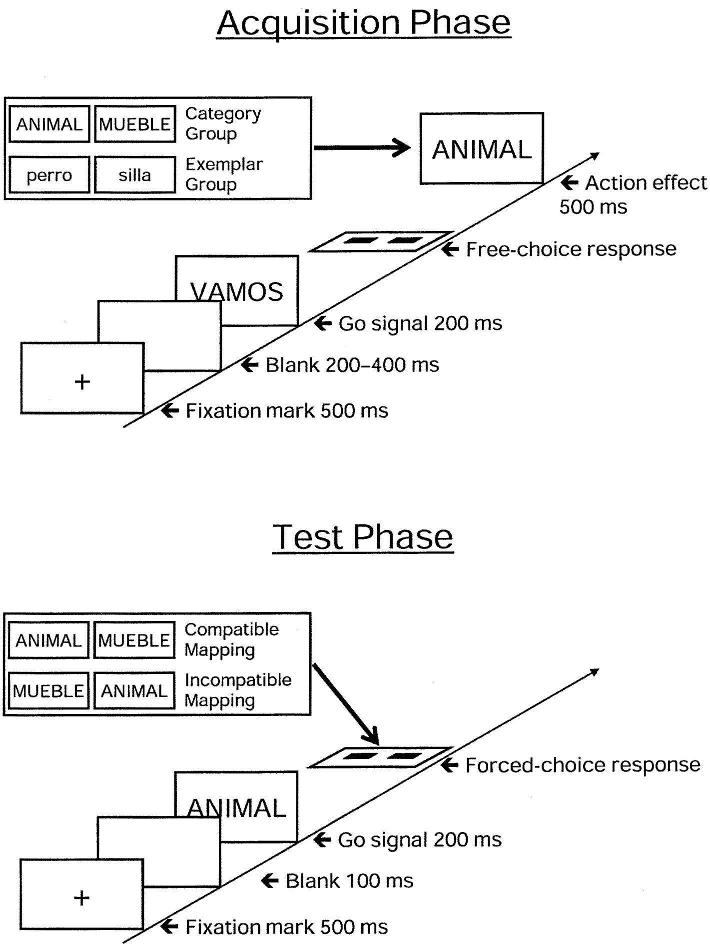

Figure 1. Overview of the sequence of events in the two experimental phases of Experiment 1. In the acquisition phase, the same go signal (''VAMOS'' = go) signalled a free-choice response that produced either an uppercase category word or a lowercase exemplar word. E.g., pressing a left key might have produced the word ''ANIMAL'' (=animal) in the category group but the word ''perro'' (=dog) in the exemplar group, and pressing a right key the word ''MUEBLE'' (=furniture) in the category group but the word ''silla'' (=chair) in the exemplar group. In the test phase, left and right responses were carried out to the words ''ANIMAL'' and ''MUEBLE'' (=furniture), with a stimulus–response mapping that was either compatible with the response–effect relation in the acquisition phase (e.g., ''ANIMAL''→left and ''MUEBLE''→right after having produced ''ANIMAL'' or ''perro'' with the left key and ''MUEBLE'' or ''silla'' with the right key) or incompatible with that relation (e.g., ''ANIMAL''→left and ''MUEBLE''→right after having produced ''ANIMAL'' or ''perro'' with the right key and ''MUEBLE'' or ''silla'' with the left key).

participants this mapping was compatible with their response–effect mapping in the acquisition phase (*E1*→*R1*, *E2*→*R2*; e.g., *ANIMAL*→left key, *MUEBLE*→right key, after practice with either left key→*ANIMAL*, right key→*MUEBLE* or, in the exemplar group, with left key→*perro*, right key→*silla*) and for the other half it was incompatible (*E2*→*R1*, *E1*→*R2*; e.g., *ANIMAL*→left key, *MUEBLE*→right key, after practice with either left key→*MUEBLE*, right key→*ANIMAL* or, in the exemplar group, with left key→*silla*, right key→*perro*).

Again, each trial began with the presentation of the fixation mark for 500 ms, followed by a blank interval of 100 ms. Then the stimulus word (*ANIMAL* or *MUEBLE*) appeared for 200 ms and participants were to press the left or right key according to the instructed word–key mapping. This time, keypressing did not trigger the presentation of any stimulus and there were no catch trials. Response omissions and anticipations were fed back as in the acquisition phase, and the corresponding trials were stored and repeated later. Participants worked through 80 valid test trials comprising 40 repetitions of each of the two stimuli. The trials were randomly mixed, except that no more than three repetitions of the same stimulus were allowed.

Results

Acquisition phase. A significance criterion of $\alpha = .05$ was adopted for all statistical tests. On average, the included 140 participants pressed the response key too early (RT < 100 ms) or too late (RT > 100 ms) on 2.2% and 2.0% trials, respectively. In the remaining 200 valid trials per participant, responses were given in 359 ms, and the left and right key were used equally often (99.8 vs. 100.2). To see whether response choice covaried with experimental conditions we calculated individual response biases (number of left responses) divided by number of right responses), which ranged from 0.67 to 1.50, and ran an ANOVA with the between-participants factors practice (category vs. exemplar) and mapping (S–R mapping in test phase compatible vs. incompatible with R–E mapping in acquisition phase). However, no effect even approached significance (*p*s > .26). The same was true for a corresponding analysis of the RTs. Responses to the catch word were almost perfect, the error rate was below 1%.

Test phase. Trials with anticipations (0.3%) or response omissions (0.3%) were excluded, and mean RTs and percentages of error (PEs) were calculated and analysed as a function of practice and mapping. The group means are presented in Table 1. In the RT analysis the mean RT from the acquisition phase was used as a covariate, so to reduce noise due to interindividual differences. The RT analysis yielded only one significant effect, which indicated faster responses when the S–R mapping was compatible with the practised R–E mapping than when it was not, $F(1, 135) = 8.93$. Separate analyses confirmed that the mapping effect was reliable after both category practice, $F(1, 60) = 4.50$, and exemplar practice, $F(1, 74) = 4.51$. The analysis of PEs did not reveal any reliable effect.

Discussion

Experiment 1 was guided by two questions which the present findings allow us to answer tentatively. First, reliable mapping-compatibility effects were obtained with words as response effects in acquisition and as stimuli in the test. This demonstrates that the integration of actions and their consequences is not restricted to the auditory effects used in previous studies but also takes place with visual effects. We hasten to add that the size of the compatibility effect was smaller than in Elsner and Hommel's (2001, Exp. 1) similar experiment with auditory effects, though. This might indicate that the salience of action effects does play a role for the degree or likelihood of acquisition, at least when the effects are irrelevant and, thus, acquisition occurs spontaneously. However, a conclusive answer as to this issue requires a more systematic variation of salience independent from stimulus modality and stimulus material.

Second, the compatibility effect was not modified by the type of practice, hence, by whether practised effects and test stimuli were physically identical or only semantically related. Numerically, the effect was even larger in the exemplar group, demonstrating that action effects generalize to other, related stimuli, especially if they refer to the same category. This means that actions are not only integrated with codes representing their immediate, perceivable consequences but also with those codes that get indirectly activated in the course of coding the consequences—such as representations of the category the consequences belong to.

EXPERIMENT 2

The choice of stimuli in Experiment 1 was motivated by the study of Alonso and Fuentes (2000), who presented evidence for both *generalization* from category stimuli to only episodically related exemplar stimuli (and vice versa) and *bidirectionality* of the underlying associations. Evidence for generalization is provided by the observation that learning the sequence of a category label and an exemplar word of another category (e.g., *BODY→dog*) transfers to sequences of the category label of the previous exemplar and an exemplar of the previous category (e.g., *ANIMAL→hand*). This implies that the associations a category label becomes engaged in are inherited by the exemplars of this category, and vice versa. Indeed, this conclusion is supported by the present Experiment 1, where associations emerging between an action and a category label apparently also connected the action to the exemplars of this category. Evidence for the bidirectionality of category-exemplar associations in the Alonso and Fuentes study is provided by the fact that the benefits from the acquisition of word–word relations survived the reversal of the domain order: *ANIMAL* primed *hand* after participants had learned that *BODY* is followed by *dog*. Again, this conclusion is consistent with our present observation that words primed responses after participants having learned that responses predict words.

Although our findings are in nice agreement with the results of Alonso and Fuentes (2000) they refer to a rather special kind of transfer from superordinate to subordinate of a hierarchically structured category, or vice versa. However, if the learning mechanism underlying action–effect acquisition is really as general as the studies discussed in the introduction suggest, other types of generalization may often be more helpful. In particular, one would expect *similarity* and *feature overlap* to play a central role, so that learning that an action produces a particular effect would allow the cognitive system to generalize to other, similar and/or feature-sharing effects. For instance, learning that pressing a particular key on a computer keyboard produces a visible *m* on the screen should facilitate learning that combining this action with a press of the shift key produces the letter *M*.

Experiments 2 and 3 were carried out to explore whether such feature-based generalization of action–effect learning can be demonstrated. In Experiment 2 we asked whether associations between actions and linguistic effects transfer to other members of the same category. Accordingly, we first had participants to press keys that produced the words *dog* and *chair*, just like in the exemplar condition of Experiment 1. Then we asked them to carry out choice reactions to other words from these two categories, *cat* and *table*. If within-category generalization of action–effect associations would exist, the mapping of stimuli to responses in the test phase should matter. Thus, if *R1* produces *dog* and *R2* produces *chair*, one would expect performance to be better with a compatible mapping (*cat*→*R1*, *table*→*R2*) than with an incompatible mapping (*table*→*R1*, *cat*→*R2*).

Method

Fifty-two students from the University of Almería participated for course credit. The method was as in the exemplar condition of Experiment 1, i.e., *perro* (dog) and *silla* (chair) served as action effects and *FRUTA* (fruit) as catch word during practice. However, in the test phase the stimulus words were *GATO* (cat) and *MESA* (table), implying a transfer from one exemplar from each of the categories animals and furniture to two other exemplars from the same categories. Analogously to Experiment 1 this transfer was practice-compatible for one half of the participants (*R*→*dog*, *R2*→*chair* in practice phase and *cat*→*R1*, *table*→*R2* in test phase) and incompatible for the other half (*R1*→*chair*, *R2*→*dog* in practice phase and *cat*→*R1*, *table*→*R2* in test phase).

Results

Acquisition phase. Data were analysed analogously to Experiment 1. On average, participants pressed the response key too early on 2.5% and too late on 2.7% of the trials. In-time responses were given in 337 ms. Two participants (who both happened to be preassigned to the incompatible test group) failed to press each key for at least 80 times and were therefore excluded from further analyses. The remaining participants pressed the left and right key equally often on average (99.8 vs. 100.2), each key 82 times at minimum. Responses to the catch word were incorrect in 2.2% of the trials.

Test phase. Trials with anticipations (0.5%) or response omissions (0.2%) were excluded, and mean RTs and PEs were analysed as a function of mapping. Means are presented in Table 2. The mapping effect was reliable in RTs, $F(1,47) = 5.87$, but not in PEs.

Discussion

The outcome is clear in showing generalization from one set of exemplars to other exemplars of the same category. Thus, action–effect acquisition is not restricted to either identical action effects, as in the category group of Experiment 1, or category labels, as in the exemplar group of Experiment 1, but transfers to other category members.

EXPERIMENT 3

One reason why the action–effect learning transferred to other category members in Experiment 2 might be that exemplars of a category tend to share features (Rosch, 1973). If we think of word stimuli being associated with representations of their referent objects, and of these objects to be represented in terms of their features (e.g., Barsalou, 1999), we can come up with the following scenario (which we discuss in more depth in the Conclusion): Perceiving a word might, among other things, activate the representation of its referent object. Accordingly, the feature codes representing the object get activated and this activation overlaps in time with the activation of the codes representing the action pattern. Under the assumption that temporal overlap of codes is sufficient for the creation and strengthening of associations between them (the classical

TABLE 2
Reaction times (RT, in ms) and percentages of error (PE, in %) in test phase (*SD* in parentheses), and number of participants (*N*) as a function of type of practice-compatibility of stimulus–response mapping

Mapping	*RT*	*PE*	*N*
Compatible	393 (43)	2.5 (1.5)	26
Incompatible	417 (52)	2.4 (1.7)	24
Δ	24		

notion of *trace conditioning*; see Elsner & Hommel, 2001; Hommel, 1998), we would expect action codes to become associated with codes of the features of the word referent. If so, presenting a word should prime all those responses that have become associated with features that the referent of the word possesses as well. In other words, words prime responses that are known to produce words with feature-overlapping referents—as can be expected of exemplars of the same category.

If this scenario is realistic, we would expect transfer between any words with feature-overlapping referents, not just between members of the same (semantic) category. Indeed, words have been shown to prime other, categorially unrelated words with perceptually (e.g., shape-) related referents, such as *pizza* and *coin* (Schreuder, Flores d'Arcais, & Glazenborg, 1984), even though this effect seems to vary with the particular task (Pecher, Zeelenberg, & Raaijmakers, 1998). This suggests that having referents that share features does link word representations, so that activation can spread from one word to the other. Applied to action–effect learning this would lead us to expect that acquiring an association between an action and a word transfers to words of a different category, if they only refer to a perceptual feature that the original word's referent possesses.

In Experiment 3 we tested this expectation. Participants were to press keys that produced the words *orange* and *blackboard*, before performing choice reactions to the nouns *circle* and *rectangle*—words describing the shape of an orange and a blackboard, respectively. If perceptually based generalization of action–effect associations existed, we again would expect a mapping effect. Thus, if *R1* produces *orange* and *R2* produces *blackboard*, performance should be better with a compatible mapping (*circle→R1*, *rectangle→R2*) than with an incompatible mapping (*rectangle→R1*, *circle→R2*).

Method

Sixty students from the University of Almería participated for course credit. The method was as in Experiment 2, except for the word stimuli. During practice, the two responses triggered the presentation of the words *naranja* (orange) and *pizarra* (blackboard), respectively. The stimulus words in the test phase were *CIRCULO* (circle) and *RECTANGULO* (rectangle), implying a transfer between words referring to round and rectangular objects, respectively. To compensate for the difference in word length—which may motivate participants to respond to visual word size—the two words were extended to 11-symbol strings by filling in double crosses (''#RECTANGULO'' and ''##CIRCULO##''). Again, transfer was practice-compatible for one half of the participants (*R1→orange*, *R2→blackboard* in practice phase and *circle→R1*, *rectangle→R2* in test phase) and incompatible for the other half (*R1→blackboard*, *R2→orange* in practice phase and *circle→R1*, *rectangle→R2* in test phase).

Results

Acquisition phase. Data were analysed analogously to Experiment 1. On average, participants pressed the response key too early on 0.4% and too late on 1.9% of the trials. In-time responses were given in 348 ms. Four participants failed to press each key for at least 80 times and were therefore excluded from further analyses. The remaining participants pressed the left and right key equally often on average (100.7 vs. 99.3), each key 80 times at minimum. Responses to the catch word were incorrect in 1.3% of the trials.

Test phase. Trials with anticipations (0.4%) or response omissions (0.4%) were excluded, and mean RTs and PEs were analysed as a function of mapping. Means are presented in Table 3. The mapping effect was significant in RTs, $F(1, 53) = 8.20$, but not in PEs.

Discussion

Again, the outcome is clear in demonstrating generalization from one set of words to other words referring to a common perceptual attribute. Thus, the transfer of action–effect associations is not limited to members of the same category but apparently can be mediated by perceptual features as well.

CONCLUSIONS

The goal of this study was to address two questions about the acquisition of action–effect associations. First, we asked whether task-irrelevant visual stimuli—i.e., stimuli of less salience than the commonly used tones—also become integrated with the action they follow. The answer is clearly positive, we found reliable evidence for such integration in all three experiments and all four experimental groups. On the one hand, this confirms Elsner and Hommel's (2001) suggestion that the acquisition of action effects is automatic in the sense that the creation of associations between a given action and the perceptual

TABLE 3

Reaction times (RT, in ms) and percentages of error (PE, in %) in test phase (*SD* in parentheses), and number of participants (*N*) as a function of type of practice-compatibility of stimulus–response mapping

Mapping	*RT*	*PE*	*N*
Compatible	453 (48)	5.2 (5.1)	28
Incompatible	480 (56)	4.9 (4.6)	28
Δ	27		

consequences it is experienced to yield does not presuppose that the individual intends to learn this association or that he or she attends the relationship or contingency between action and effects. In other words, carrying out an action is not only a means to reach an intended goal, it also represents a way to learn more about the goals that this action *could also* achieve. On the other hand, however, we hasten to add that our findings do not prove that action–effect acquisition proceeds entirely independent of the current action goal and attentional set. As briefly mentioned above, Dutzi and Hommel (2003) observed that trial-to-trial bindings between actions and effects affect performance in the following trial. For instance, having a left keypress being followed by a high tone (*left key→high tone*), say, biased subjects towards choosing a left- over a right-hand keypress in a subsequent free-response-choice trial if that decision was primed by an irrelevant, high tone (*high tone→left key*; implying a bidirectional binding: *high tone↔left key*). The same effect was obtained with visual colour effect stimuli but only if attending the visual modality was enforced by including visual go–nogo stimuli. Thus, visual action effects may be integrated only if a sufficient amount of attention is allocated to the visual modality. Although there are reasons to believe that Dutzi and Hommel's binding effect is not identical with the learning effect investigated in the present study, it may well be that our subjects acquired action-produced words only because our use of visual catch words required them to direct their attention to visual stimuli. Hence, we cannot be sure whether visual action effects would also be integrated in an otherwise purely auditory or, say, tactile task. This suspicion is further nurtured by recent findings on the implicit acquisition of event sequences. Results of Jiang and Chun (2001) and Jiménez and Méndez (1999) suggest that learning sequences of stimuli or stimulus–response compounds does not directly draw on or require attentional resources, or the explicit intention to acquire a given sequence, but it does depend on attention being directed to the modality or dimension the to-be-associated events are defined on. That is, only if attention is invested in the processing of individual events the associations between them come for free—a rule that may also apply to the integration of actions and their effects.

Second, we asked whether action–effect learning generalizes to stimuli that are related to, but not identical with the actually learned action effects. Again, we received an affirmative answer: Experiment 1 demonstrated generalization from exemplar words to category labels, Experiment 2 from one exemplar to another exemplar from the same category, and Experiment 3 from one exemplar to an exemplar with a perceptually similar referent from another category. Hence, it seems that the spontaneous integration of actions and their consequences is a rather general phenomenon that can be found across an increasing number of actions and effect types, and that generalizes to other related, but not actually experienced action effects. This is what one would expect from a mechanism that has been claimed to underlie the acquisition of voluntary action

(Elsner & Hommel, 2001; Hommel, 1997, 1998). Indeed, generalization of this sort is of enormous advantage for actors as experience with a single kind of action effects allows them to make inferences regarding similar effects. For instance, once an infant experiences that pressing a key on a piano produces a tone, it would immediately suspect the other keys to produce tones as well—which again is likely to motivate further encounters resulting in the acquisition of more specific action–effect knowledge.

Although our findings strongly suggest that action–effect learning generalizes, they do not allow us to conclusively distinguish between two ways in which generalization may proceed. Figure 2 shows the two possibilities. First consider the acquisition phase of the exemplar group in Experiment 1. In the example shown, a left-hand keypressing response produces the word ‘‘dog’’, while a right-hand response produces the word ‘‘chair’’. As repeatedly producing a response-contingent event should create an association between the respective motor pattern and the cognitive code of the event, the representations of ‘‘dog’’ and ‘‘chair’’ will be associated with the motor pattern responsible for the left and right keypress, respectively. Given the high likelihood that the codes of ‘‘dog’’ and ‘‘chair’’ were pre-experimentally associated with the labels of their category, the word ‘‘animal’’ appearing in the test phase would be able to prime the ‘‘dog’’-producing response indirectly: Seeing the word would activate the code <animal>, which would spread activation to <dog>, which again would spread activation to m_1. This would facilitate performance under a compatible mapping but interfere under an incompatible mapping, as observed in Experiment 1. Alternatively, or in addition to such an indirect link, perceiving the word ‘‘dog’’ in the acquisition phase might spread sufficient activation to the <animal> code to allow for the creation of a direct association between <animal> and m_1. If so, seeing the word ‘‘animal’’ in the test phase would directly prime m_1, which could also have produced the observed mapping effect. One might speculate that indirect response priming should be weaker and, thus, produce a smaller effect than direct priming. Interestingly, the smallest effect size we obtained in this study was in the category condition of Experiment 1, that is, in the only condition where the same stimuli were used as effects in the acquisition phase and as stimuli in the test phase. This does not seem to fit with the idea that generalization works exclusively via indirect associations but, rather, suggests a direct-association account. That is, our findings are consistent with the notion that an action acquires direct associations with all event codes that are active while or briefly after the action is performed—whether their activation is due to a direct effect or only an indirect consequence of the action. However, given the small sizes of the effects we obtained we regard this consideration as no more than an interesting working hypothesis awaiting further corroboration.

It is interesting to note that the present findings fit well with Alonso and Fuentes’ (2000) observations on stimulus–stimulus learning, which might

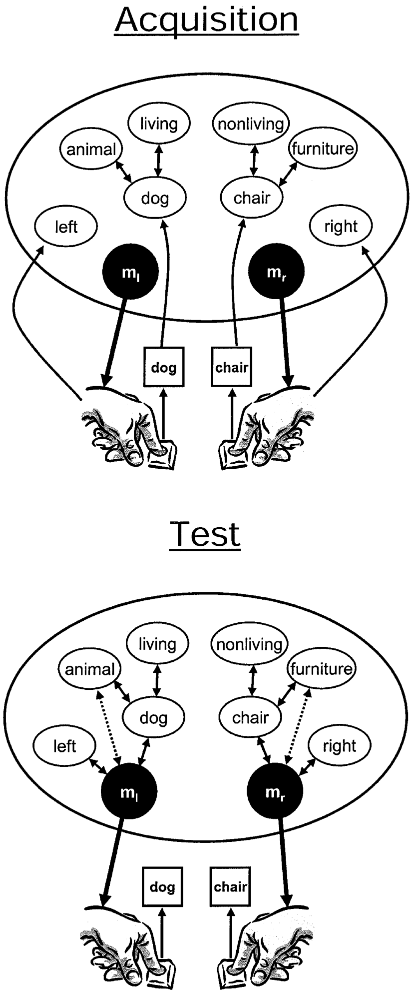

Figure 2. Sketch of the two ways action–effect learning may generalize. The top panel shows the hypothetical flow of activation in the acquisition phase, assuming that pressing a left and right keypress (by executing the motor patterns m_1, respectively) produces the words ‘‘dog’’ and ‘‘chair’’. Performing a left-hand keypress will, among other things, activate the cognitive codes <left> and <dog>, which again will spread activation to other, pre-experimentally associated codes, such as <animal> and <living>, and codes representing perceptual attributes of left events and dogs (not shown). Likewise, performing a right-hand keypress will directly activate the cognitive codes <right> and <chair> and indirectly prime the associated codes <furniture> and <nonliving>, and related perceptual codes. The bottom panel shows the results of this experience as present in the test phase. As indicated, the codes <left> and <dog> have become directly associated with m_1, and the codes <right> and <chair> with m_r, in a bilateral fashion. What is unclear is whether indirectly activating <animal> (or <furniture>) during acquisition creates a direct association between that code and the corresponding motor pattern m_l (or m_r), which would allow the word ‘‘animal’’ (or ‘‘furniture’’) to prime the previously related response directly (via the dotted lines), or whether the associations remain indirect, so that the word ‘‘animal’’ (or ‘‘furniture’’) would prime the corresponding response only via the previous action effect (<dog> and <chair>, respectively).

indicate that related, or even the same learning mechanisms were at work. As Elsner and Hommel (2001) did, for action–effect acquisition, Alonso and Fuentes attributed the acquisition of bidirectional (here: stimulus–stimulus) associations to an automatic processing algorithm that detects covariations among events (cf. Lewicky, 1986). Importantly, this algorithm is assumed to operate on temporally overlapping stimulus traces and, thus, is blind to temporal order within its integration window.[3] Accordingly, it codes the occurrence of event–event contingencies independent of these events' causal or temporal relation, this way fostering the acquisition of bidirectional associations between them.

A final note concerns the issue of backward conditioning. Together with previous observations in humans and other animals, the present results demonstrate that events that have been experienced to follow an action acquire the ability to trigger, or at least prime them upon later appearance. This implies a reversal of the time arrow: R→S learning results in S→R performance. There are several strategies to deal with such observations theoretically. The perhaps most obvious conclusion—and the one suggested here—is to assume that internal integration mechanisms may, within certain limits, not care about external order but simply associate codes with temporally overlapping activation states. Alternatively, one may assume that people learn to anticipate their responses and then acquire associations between the stimuli and response anticipations or between response anticipations and response–effect anticipations (e.g., Bolles, 1972). Along the lines of Trapold and Overmier (1972) one may even attempt to account for the present findings without assuming any direct association between responses and their effects. For instance, people may have created an S–R association between some response cue (e.g., the sight of response keys), that serves as a discriminative stimulus, and the response on the one hand; and an S–S association between this cue and the (expectation of the) effect word on the other. If so, response and effect would not be directly associated by means of a R–S (or R–E) association but mediated by the anticipation of the effect and the response cue.

However, there are some reasons to doubt that such a mediation account represents a viable alternative to the proposed R–E account. One reason is the recent demonstration of Estévez, Overmier, and Fuentes (2003) that S–S associations and R–S associations play different, dissociable roles in the differential outcomes effect, which means that direct response–effect associations are indeed involved. Another reason is that a mediation account represents a real theoretical alternative only from a behaviouristic point of view, while if it comes to the underlying cognitive and neurophysiological mechanisms and structures it is

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[3] Applying the notion of an integration window to action–effect learning implies that increasing the lag between response and response-contingent effect should reduce response–effect integration. Indeed, integration is no longer observed with lags longer than 1 s (Elsner & Hommel, in press).

more or less indistinguishable from an R–S account. What the present findings suggest is that the codes representing an action and the codes representing this action's effects become integrated and, thus, form an associative structure (Elsner & Hommel, 2001; Hommel, Müsseler, Aschersleben, & Prinz, 2001). To some degree this structure seems to act as a unit, so that activating its ''stimulus part'' automatically spreads to its ''response part''—if such a distinction makes functional and neurophysiological sense at all. Indeed, this spreading of activation is what Elsner et al. (2002) observed. They first had participants experience that their manual responses are contingently followed by tones of particular frequencies, just like in Elsner and Hommel's (2001) study. Then they presented them with another task that required the detection of a tone different in type and frequency from the action–effect tones. The second, tone-detection task took place in a PET scanner so that the brain activity of the participants could be measured. It turned out that presenting action–effect tones as nontagets led to marked increases of activation in the supplementary motor area that is known to be involved in sensorimotor learning (Toni, Krams, & Passingham, 1997), and the planning and control of manual actions (Decety et al., 1994). Hence, however one labels the way people learn about novel effects of their actions, they do seem to integrate codes of what they do and codes of what this doing achieves into some common associative structure, a structure that represents the relationship between actions and their effects.

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