The interaction between response effects during the acquisition of response priming

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The first author, Rüdiger Flach, died in June 2005 at the age of 33. As his colleagues and co-authors, we publish this paper as a mark of our affection for Rudi and our respect for the quality of his research and scholarship. We hope that others will pursue the project on which he embarked, forging links between research on action control and associative learning.

Abstract

In three experiments we investigated the role of associative learning in the acquisition of response priming by effect stimuli, by examining their interaction during response–effect learning. Having replicated the ability of visual effect stimuli to prime their associated responses, we paired a response with a compound consisting of visual and auditory effects before assessing the ability of the auditory effect stimulus to prime the response. This priming was reduced if the visual stimulus had been pretrained as an effect of the response. By contrast, priming by the visual effect stimulus was potentiated when the auditory effect had been pretrained. We interpret these interactions in terms of contemporary associative learning theory derived from studies of conditioning.
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1. Introduction

Human behaviour can be analyzed as a function of external stimuli or as a function of internal goals. Whereas we often adopt the former framework in an experimental setting, goal-directed behaviour also plays a significant role in our everyday lives. One reason for the relative neglect of goal-directed action is the difficulty of bringing goals under experimental control. However, an approach to the analysis of goal-directed action can be derived from ideomotor theory (James, 1890; Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001; see Stock & Stock, 2004, for a historical review). The core assumption of this theory is that actions are represented in terms of their effects. Crucially, these effect representations not only inform us about the consequences of our actions, but also function as cues for action selection and/or initiation. James (1890), for instance, contended that "every representation of a movement awakens in some degree the actual movement which is its object" (p. 526).

James (1890) clearly thought that voluntary actions must be learned when he argued that "if, in voluntary action properly so-called, the act must be foreseen, it follows that no creature not endowed with divinatory power can perform an act voluntarily for the first time" (p. 487). Assuming that we represent our actions in terms of their effects, the question arises of how we acquire these representations in the first place. One solution is that randomly generated or stimulus-elicited movements cause perceivable effects in the environment that, due to the temporal overlap of the resulting sensory and motor activity, become associated with the movement. Anticipation of these effect representations then serves as the basis for voluntary action selection because their activation tends to elicit the corresponding movement.

It should be noted that the hypothesized sensory–motor associations are assumed to be bidirectional in nature. Thus, the response activates the representation of its effects, and the effects are assumed to activate the response (see also Greenwald, 1970). A similar bidirectional associative account for instrumental action was developed by Pavlov (1932) and his students (e.g., Asratyan, 1974). According to Pavlovian bidirectional theory, the pairing of responses and effects (which, in the case of instrumental conditioning, are motivationally significant 'reinforcers') establishes associations from responses to effects so that activation of an effect representation in turn excites its associated response. In fact, this Pavlovian analysis (see Gormezano & Tait, 1976, for a review) assumes that a response–effect contingency establishes independent response-to-effect (response ⇒ effect) and effect-to-response (effect ⇒ response) associations rather than a unitary bidirectional association. Although we adopt this analysis, none of our interpretations depend critically upon this assumption.

1.1. Response–effect learning

Evidence for effect ⇒ response associations comes from two sources: animal discrimination learning and human response priming. Meck (1985) arranged that presses on one lever by rats produced a brief auditory effect stimulus and on another lever a brief visual effect stimulus, before teaching his rats a biconditional discrimination using these effects as discriminative stimuli. Meck found that the rats learned a congruent discrimination, in which the effect of a response signalled that the same response would be reinforced, more rapidly than an incongruent discrimination, in which the effect signalled that the other response would be reinforced. This finding is a straightforward prediction of bidirectional theory.

The first stage of training should have established, for example, a sound ⇒ right press association and a light ⇒ left press association, which should have then transferred directly to the control of responding in the congruent discrimination. In contrast, effect ⇒ response associations would have had to be reversed in the incongruent discrimination in order for these effects to acquire control over the reinforced response.

Elsner and Hommel (2001) used a similar design to demonstrate the operation of effect ⇒ response associations in human response priming. During training, participants pressed one of two keys in response to a trigger stimulus. Each response was contingently followed by a distinct tone. Elsner and Hommel then used these tones as imperative stimuli for the two responses in a subsequent test phase, while varying the stimulus–response mapping. In accord with Meck's findings, response times were faster if the stimulus–response mapping in the test phase was congruent, rather than incongruent, with the response–effect mapping used in the training phase.

Subsequent studies then elaborated on the fact that the effect ⇒ response associations are retrieved in an automatic fashion. To note just a subset of these studies, Elsner et al. (2002) observed an activation of neural motor structures during the passive monitoring of effect stimuli, whereas Kunde (2004) showed that effect–response priming occurs irrespective of the (conscious) identification of the response effects. For this purpose, he used visual effect stimuli, which he masked during the priming of the response. The generality of these findings was also demonstrated by Beckers, De Houwer, and Eelen (2002) Hommel, Alonso, and Fuentes (2003), who showed that response priming can generalize to emotionally and semantically related stimuli. Finally, Eenshuistra, Weidema, and Hommel (2004) reported that younger children are more prone to response effect priming than older children, as indicated by the fact that they commit more errors in the incongruent test phase.

To summarize, discrimination learning and response priming provide empirical evidence for a central tenet of bidirectional and ideomotor theories, specifically that responses can be activated via effect ⇒ response associations. What is less clear, however, is the nature of the learning processes by which effect ⇒ response associations are acquired, and it is this issue that is the focus of our studies.

1.2. Associative learning and stimulus interactions

Most theoretical and empirical analyses of associative learning have focused on the acquisition of associations from a representation of an antecedent event to that of a consequent event within animal conditioning and human causal and predictive learning paradigms, rather than consequent-to-antecedent learning, such as the acquisition of effect ⇒ response associations. However, Elsner and Hommel (2004) recently investigated whether response–effect learning is sensitive to parameters that modulate associative learning in these other paradigms. Based on the well-established finding that delaying the outcome reduces learning in both animal conditioning (see Mackintosh, 1974; Tarpy & Sawabini, 1974) and human causal learning (e.g., Shanks, Pearson, & Dickinson, 1989), Elsner and Hommel found that an analogous delay between response and effect also reduced response priming by the effect stimuli. They also reported that response priming, like animal conditioning (e.g., Hammond, 1980) and human causal learning (e.g., Dickinson, Shanks, & Evenden, 1984), is sensitive to a reduction in response–effect contingencies produced by increasing the probability of effects that are unpaired with the response. These

results encourage the view that the response–effect learning that mediates response priming may be governed by the same processes as other, more standard forms of associative learning.

The purpose of the present experiments was to extend this analysis by investigating whether response priming is also sensitive to the stimulus interactions observed in standard associative paradigms. Such interactions have been the touchstone for the development of associative theories of both conditioning and human causal learning, with the most influential form of cue interaction being overshadowing. Pavlov (1927) reported that when a target cue is conditioned in compound with another stimulus, responding to the target cue alone is reduced relative to a control condition in which the target cue is conditioned in isolation. This reduction is attributed to overshadowing of learning about the target cue by the presence of the other stimulus. Two factors are known to affect the magnitude of overshadowing. The first is the salience of the target and overshadowing cues. The lower the salience of the target cue, the more susceptible it is to overshadowing, and the greater the salience of the overshadowing cue the more its presence reduces learning about the target cue (e.g. Mackinosh, 1976).

The other factor affecting the magnitude of overshadowing is the associative status of the overshadowing cue. If the overshadowing cue is pretrained as a predictor of the outcome, before being presented in compound with the target cue, the amount learned about the target cue during compound training is reduced. Pretraining enhances the ability of a cue to overshadow and therefore to block learning about the target cue during the compound training. Such blocking has been reliably demonstrated in both animal conditioning (e.g. Kamin, 1969) and human causal learning (e.g. Dickinson et al., 1984).

Overshadowing and blocking are theoretically important because they demonstrate that the simple contiguous pairing of two events, the target cue and the outcome, during compound training, is not sufficient to establish an association between their representations. Instead, it appears that learning is modulated by the presence of other cues. This simple conclusion has spawned a variety of associative learning theories of animal conditioning (e.g. Mackintosh, 1975; Miller & Matzel, 1988; Pearce & Hall, 1980; Rescorla & Wagner, 1972; Wagner, 1981) and human learning (e.g. Aitken & Dickinson, 2005; Van Hamme & Wasserman, 1994).

Although almost all overshadowing and blocking studies have used a forward procedure in which the target cue precedes the associated event, typically a reinforcer, Esmoriz-Arranz, Miller, and Matute (1997, Experiment 1) have reported that blocking may occur between consequent events in animal conditioning. They used a sensory preconditioning procedure in which rats were presented with an antecedent stimulus, S, followed by a simultaneous compound of two consequent events, S_X and S_A (S–$S_X S_A$ training). Following this training, they found that less was learned about the backward $S_A \Rightarrow S$ association if S_X had been previously paired with S (S–S_X training). In other words, pretraining with S_X blocked subsequent learning about S_A.

To complicate matters, we should note that overshadowing and blocking are not ubiquitous consequences of compound conditioning. Under certain circumstances, training the target cue in compound with another stimulus can enhance or potentiate, rather than overshadow, responding to the target cue. Indeed, the magnitude of the enhancement can be increased by pretraining the potentiating cue (e.g., Holland, 1980; Rescorla, 1981; Speers, Gillan, & Rescorla, 1980). The factors that determined whether overshadowing or potentiation is observed during compound conditioning will be addressed in Section 5.

1.3. The present studies

The present studies sought to determine whether overshadowing and/or potentiation occurs in the response–effect priming paradigm. Our purpose in doing this was to investigate whether the associative processes mediating effect–response learning are similar to those mediating standard animal conditioning and human associative learning.

Our general paradigm is based on that of Elsner and Hommel (2001). Our initial experiment sought to demonstrate that we could replicate response–effect priming using our visual stimuli. The remaining two experiments then investigated the interaction between auditory and visual response effects on response priming. The participants first performed a response R that was consistently followed by a single effect stimulus S_X during pretraining, but by a compound effect stimulus consisting of S_A and S_X during the subsequent training stage. Finally, we assessed the ability of S_A to prime R. In Experiment 2, the pretrained effect stimulus S_X was visual and the target effect stimulus S_A auditory. In Experiment 3, the modalities of the two stimuli were reversed. If the presence of S_X overshadowed learning about S_A, the ability of S_A to prime R should have been reduced. In contrast, if the presence of S_X potentiated learning about S_A, the ability of S_A to prime R should have been enhanced.

2. Experiment 1

The first experiment attempted to replicate Elsner and Hommel's (2001) demonstration of response–effect priming, but using visual rather than auditory effect stimuli. In the first training phase, the participants performed a free-choice reaction time (RT) task in which each of the two responses was followed by a brief, visual effect. Following training, the test phase was a forced-choice RT task. On each trial, one of the two visual effects was presented and participants were asked to perform the assigned response as fast as possible. For the congruent group, the stimulus–response mapping was the same in free-choice training and the forced-choice RT test stages, whereas this mapping was reversed across the two stages for the incongruent group. With this design, response–effect priming is indicated by faster and/or more accurate responding during the test by the congruent group relative to the incongruent group. The visual effect stimuli were large, unicoloured lights that were presented at the centre of the participant's visual field in an almost dark room in order to make them simple, salient, and non-spatially biased.

2.1. Method

2.1.1. Participants

The participants were 9 men and 15 women with ages ranging from 20 to 41 years ($M = 25.5$ years). All, but one participant was right-handed. They were randomly assigned in equal numbers to the congruent and incongruent groups.

2.1.2. Apparatus and stimuli

The visual stimuli were presented on a 40.5-cm (diagonal) screen (refresh rate: 70 Hz). Viewing was unrestrained at a distance of about 100 cm from the screen. Apart from the visual stimuli, only a very faint light filled the experimental room. In the training phase,

the participants responded to a 600-Hz tone, which was presented for 200 ms at a comfortable volume [~60 dB (A)] through headphones. The responses consisted of pressing either the 'c' key of a standard computer keyboard with the left index finger or the 'n' key with the right index finger. Effect stimuli consisted of a change of screen colour from black to one of two colours, which differed only in their saturation. The hue was red and the saturation was set to 50% for one stimulus, which gave the impression of pink (saturation: 50%) and 100% for the other stimulus, which was perceived as red.

2.1.3. Procedure

The experiment consisted of two phases. The first, training phase was a free-choice reaction time (RT) task, in which the two responses were followed by either the red or pink colour. The participants were asked to perform one of the two responses as rapidly as possible following the onset of the auditory trigger stimulus, which was terminated by the response. The instructions pointed out that the participant was free to choose which response to perform on each trial but emphasized that they should choose each response equally frequently in no systematic order. The instructions did not mention the presentation of the visual effects. After an initial or intertrial interval of 1500 ms, the auditory trigger stimulus was presented for a maximum of 200 ms. Responses within 1000 ms of the onset of the trigger stimulus were followed after 50 ms by one of the two visual effects for 200 ms with the response–effect assignment counterbalanced across participants within each group. If no response occurred within 1000 ms or if the response latency was shorter than 100 ms, no effects were presented and the participant received error feedback (i.e., the message "Error: Too fast..." or "Error: Too slow..." appeared for 1000 ms at the centre of the screen). The training phase consisted of four 50-correct trial blocks. Error trials were repeated at a random position in the block, and participants received feedback about their performance at the end of each block. They were informed about their average reaction time, about the frequencies of their key presses, and about the randomness of the sequence of key presses they had generated.

The second phase was a forced-choice RT test, in which the two visual effects were used as stimuli. The participants were asked to press a specific key in response to a specific colour. For example, they were asked to press the left key in response to the pink colour and the right key in response to the red colour. The instructions stressed speed of response and error avoidance to the same degree. Each trial started with an initial or intertrial interval of 1500 ms, after which one of the two colour stimuli was presented for 200 ms. After stimulus onset, the program waited for 1000 ms for a response. Response onset terminated the stimulus presentation. If the correct response did not occur, if no response occurred, or if the response latency was shorter than 100 ms, error feedback was displayed for 1000 ms at the centre of the screen (e.g., "Error: Wrong key..."). Testing consisted of two 50-correct trial blocks within each of which trials with the red and pink stimuli were equally likely. An error trial was repeated at a random position in a block.

For the congruent group, the stimulus–response mappings during the forced-choice test were the same as the response–effect mapping in the free-choice training, whereas these mappings were reversed for the incongruent group. For example, when participants in the congruent group had seen a pink screen background as an effect of a left key press and a red screen background as an effect of a right key press in the training, they responded with a left key press to the pink screen background and with the right key press to the red screen background in the test.
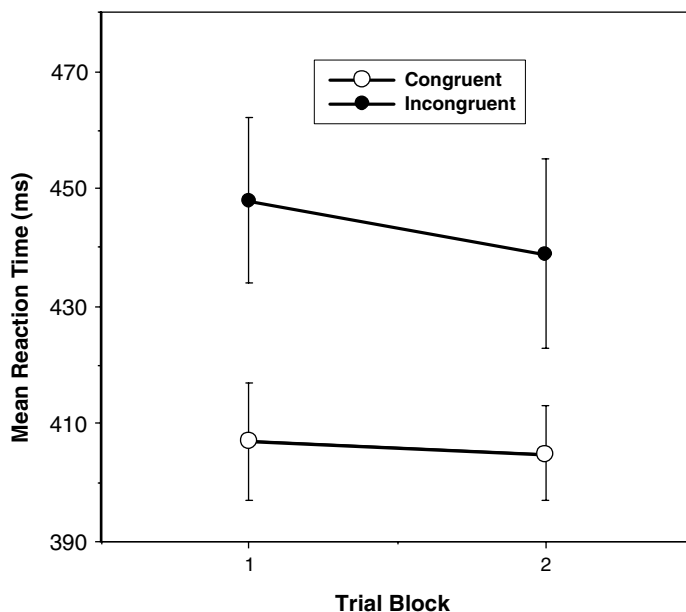
Fig. 1. Mean reaction times (ms ± sem) of the congruent and incongruent groups to the effect stimuli during the two trial blocks of the test stage of Experiment 1.

2.2. Results and discussion

The RTs and error rates were evaluated by analyses of variance against a Type 1 error rate of 0.05. Standard errors of the mean are reported in parentheses.

During training the participants distributed their responses equally between the two responses with a mean percentage right response of 50 (0.1) for both groups. The mean RT was 259 (17) ms for the congruent group and 251 (11) ms for the incongruent group ($F < 1$).

Fig. 1 shows that responding during the test replicated the priming effect reported by Elsner and Hommel (2001) for auditory stimuli in that the mean RT for correct responses of the congruent group [406 (9) ms] was significantly shorter than that of the incongruent group [443 (15) ms], $F(1,22) = 5.18$; $p = 0.03$; $\eta^2 = 0.19$. Like Elsner and Hommel (2001), we did not find any sign that the RT difference between the groups diminished in the course of testing; the F ratio for the interaction between group and trial block was less than one. Finally, there was no evidence for a speed–accuracy tradeoff. The mean percentage of errors was 8.6 (1.5) for both groups ($F < 1$).

This demonstration of response priming by visual effects enabled us to use these stimuli to study the interaction between response effects in the next experiment.

3. Experiment 2

The design of Experiment 2 is illustrated in Table 1. During pretraining, the participants had a free choice between the two responses with one response, R_1, being followed by one visual effect, S_X, and the other response, R_2, being followed by another visual effect, S_Z. On the basis of Experiment 1, we expected that this pretraining would establish an

Table 1
Design of Experiments 2 and 3

Pretraining	Compound training	Test	Posttest	
			Congruent	Incongruent
R_1–S_X	R_1–S_X & S_A	S_A–R_1	S_X–R_1	S_Z–R_1
R_2–S_Z	R_2–S_Y & S_B	S_B–R_2	S_Z–R_2	S_X–R_2

Note. R_1 and R_2 refer to left and right key press responses. S_X and S_Z were red and pink screen backgrounds in Experiment 2 and high and low tones in Experiment 3. S_Y was a white screen background in Experiment 2 and a white noise in Experiment 3. S_A and S_B were high and low tones in Experiment 2 and red and pink screen backgrounds in Experiment 3. The assignment of the tones and colours to S_X and S_Z and to S_A and S_B and of the two responses to R_1 and R_2 was counterbalanced across participants.

$S_X \Rightarrow R_1$ (and an $S_Z \Rightarrow R_2$) association. At issue is whether or not this $S_X \Rightarrow R_1$ learning would affect the acquisition of an association between R_1 and an auditory effect, S_A, when each R_1 was followed by a compound of the visual and auditory effect stimuli, S_X and S_A, during subsequent compound training. The strength of the $S_A \Rightarrow R_1$ association was then assessed by measuring the forced-choice RT for performing R_1 to S_A in the test.

The effect of pretraining was assessed against the priming of a control response, R_2, by another auditory effect stimulus, S_B. The only difference between the relationship of S_A and S_B to their respective responses was that S_B was trained in compound with a non-pre-trained visual effect stimulus, S_Y, whereas S_A was compounded with the pretrained effect stimulus, S_X. Consequently, if the pretrained S_X overshadowed the target S_A during compound conditioning relative to the control S_B, the correct RTs to S_A should have been slower than those to S_B. By contrast, if the pretrained S_X potentiated S_A, the correct RTs to S_A should have been faster than those to S_B.

3.1. Method

3.1.1. Participants, apparatus and stimuli

Six men and 10 women with ages ranging from 18 to 35 years ($M = 22.2$ years) participated. All were right-handed. The apparatus, responses, and stimuli were the same as in Experiment 1 with the following exceptions. The auditory trigger signal was replaced by a visual trigger signal, consisting of a white rectangle (height: 29 mm; width: 21 mm) appearing at the centre of the screen. In the compound training phase, the new visual effect consisted in the screen background turning from black to white, whereas the auditory effects consisted in 400-Hz (low) and 800-Hz (high) tones [∼60 dB (A)].

3.1.2. Procedure

The procedure during pretraining was identical to that during training in Experiment 1. The participants therefore received free-choice training in which performing R_1 was followed by S_X and performing R_2 by S_Z. The assignments of the left and right responses to the roles of R_1 and R_2, and of the red and pink screens to the roles of S_X and S_Z, were counterbalanced with respect to each other across the participants.

Compound training continued the free-choice RT procedure used during pretraining in terms of inter-trial interval, feedback, correction trials, and trial structure. The only difference was that each response was now followed by a compound of a visual and an auditory effect. R_1 was followed by the $S_X S_A$ compound and R_2 by the $S_Y S_B$ compound. S_X was the

same visual effect as that paired with R_1 during pretraining, whereas S_Y consisted of the black screen background turning white. S_A and S_B were the high and the low tones. The assignment of the auditory effects was counterbalanced across the response-visual effect pairings established during pretraining. As in pretraining, compound training consisted of four 50-correct trial blocks under the instructions to produce equal numbers of R_1 and R_2.

The final two stages employed the same forced-choice RT procedure as Experiment 1. To assess learning about S_A and S_B during compound training, the participants were asked to perform R_1 in response to S_A and R_2 in response to S_B during the test. The final posttest was designed to assess whether the effect $\Rightarrow$ response associations established during pretraining survived through compound training and the test. For this purpose, the posttest replicated the test procedure of Experiment 1. Depending on the pretraining response–effect assignment, participants were divided into equal congruent and incongruent groups in the posttest, while counterbalancing the colour effect–response assignments. That is, the congruent group was asked to respond with R_1 as fast as possible to S_X and with R_2 as fast as possible to S_Z, an instruction which accords with the response–effect assignment in force during pretraining. In contrast, the incongruent group was asked to perform the reverse stimulus–response assignments, which were the opposite of the pretraining contingencies.

3.2. Results and discussion

The participants distributed choices equally between the two responses during pre- and compound training with a mean percentage choice of the right response of 50 (0.75) and 51 (0.72), respectively, and mean RTs of 235 (6) ms and 240 (9) ms, respectively. More importantly, as Fig. 2 illustrates, performance during the test revealed a small but reliable effect of
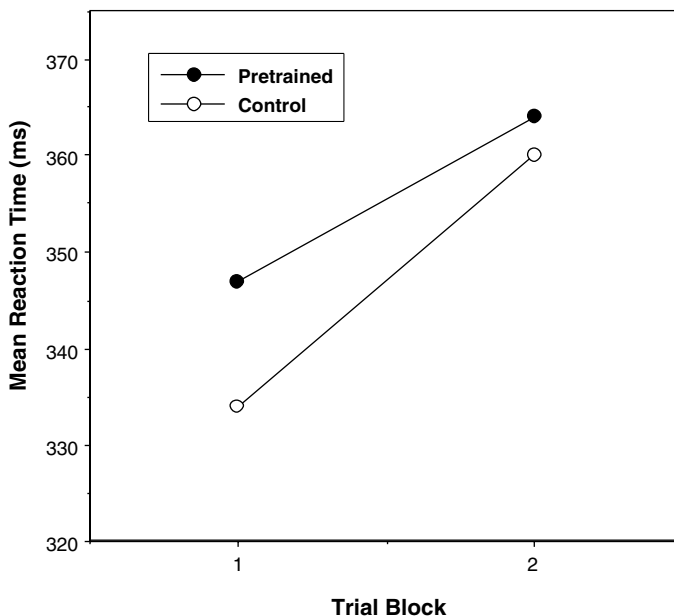

Fig. 2. Mean reaction times (ms) to effect stimuli trained in compound with either the pretrained or control effect stimulus during the two trial blocks of the test stage of Experiment 2.

pretraining; the mean RT for R_2 to S_B [345 (13) ms] was significantly shorter than that for R_1 to S_A [355 (15) ms], $F(1, 15) = 4.56$; $p < 0.05$; $\eta^2 = 0.23$. Although Fig. 2 suggests that the magnitude of the pretraining effect decreased with testing, the Pretraining X Trial Block interaction was not significant, $(F(1, 15) = 1.51; p = 0.24; \eta^2 = 0.09)$. Finally, the interpretation of this RT difference was not compromised by a speed–accuracy tradeoff. The mean percentage of response errors to S_A [4.4 (1.4)] and S_B [5.3 (1.0)] did not differ reliably, $F < 1$.

These results suggest that the pretrained S_X overshadowed learning of the $S_A \Rightarrow R_1$ association more than the control S_Y overshadowed learning of $S_B \Rightarrow R_2$ association. This overshadowing occurred in spite of the fact that the response–effect associations established during pretraining failed to survive through the training and testing to the posttest. The posttest mean RT and percentage errors for the congruent group [398 (15) ms, and 11.1 (4.0), respectively] did not differ significantly from those for the incongruent group [381 (18) ms and 12.8 (3.5), respectively], $Fs < 1$. The failure of the pretrained associations to survive through to the posttest is not surprising given the evidence that establishing a cue–outcome association can retroactively interfere with previously trained associations to the same cue (e.g. Matute, Vegas, & De Marez, 2002).

In summary, the observed overshadowing effect demonstrates that response-generated effects interact during the learning of response–effect associations.

4. Experiment 3

The purpose of the third experiment was to determine the generality of the interaction between response effects by reversing the roles of the visual and auditory effect stimuli. The design was exactly the same as that used in Experiment 2 except for the fact that the auditory effects were pretrained, and therefore acted as S_X and S_Z, whereas the colour effects were added during compound training to take the roles of S_A and S_B.

4.1. Method

4.1.1. Participants, apparatus, and stimuli

Eight men and 8 women with ages ranging from 19 to 29 years ($M = 22.1$ years) participated. One participant was left-handed. The apparatus and stimuli were the same as those used in Experiment 2, except for the auditory effect S_Y, first introduced in the compound training, which consisted in white noise [$\sim$60 dB (A)].

4.1.2. Procedure

The procedure was the same as that employed in Experiment 2 (see Table 1) except that the roles of the auditory and colour effects were reversed. To recapitulate, during pretraining, the participants freely chose between performing two responses with one producing the high tone as an effect and the other the low tone. Then, during training, one response, R_1, continued to produce the same auditory effect, S_X, as during pretraining, whereas the other response, R_2, was followed by a novel auditory effect, S_Y, consisting of white noise. Each auditory stimulus was presented in compound with a colour effect, either red or pink, with the assignment of the colour and auditory effects to responses being counterbalanced with respect to one another across participants.

There followed a forced-choice test to assess the interaction between the auditory and colour effects during compound training. In this test, R_1 was required in response to S_A

and R_2 to S_B. Finally, the forced-choice posttest assessed the persistence of the pretraining associations. The congruent group was required to perform responses consistent with pretraining, i.e. R_1 to S_X and R_2 to S_Z, whereas the incongruent group performed responses that were inconsistent with pretraining, i.e. R_1 to S_Z and R_2 to S_X.

4.2. Results and discussion

As in Experiment 2, the participants distributed choices equally between the two responses during pre- and compound training with the mean percentage choice of the right response being 50 (0.56) and 50 (0.55), respectively, and mean RTs being 242 (6) ms and 256 (6) ms, respectively. At variance with the results of Experiment 2, however, potentiation rather than overshadowing was observed during test responding. As Fig. 3 illustrates, the mean RT of R_1 to the stimulus S_A [410 (12)] was significantly shorter than that of R2 to the control stimulus S_B [420 (12) ms], $F(1, 15) = 6.56$; $p = 0.02$; $\eta^2 = 0.30$. Although Fig. 3 suggests that the magnitude of this potentiation effect increased across testing, there was in fact no significant interaction between pretraining and trial block [$F(1, 15) = 1.37$; $p = 0.26$; $\eta^2 = 0.08$]. Moreover, the interpretation of the RT difference was not compromised by the error rate in that the mean percentage errors to S_A [3.3 (0.7)] and S_B [3.9 (0.7)] were not reliably different ($F < 1$).

Nor could the occurrence of potentiation rather than overshadowing be attributed to a failure of the pretraining to establish strong effect $\Rightarrow$ response associations. The mean RT for correct responses in the posttest by the congruent group [347 (11) ms] was significantly shorter than that for the incongruent group [391 (18) ms], $F(1, 14) = 4.92$; $p = 0.04$; $\eta^2 = 0.26$, demonstrating that the associations established during pretraining
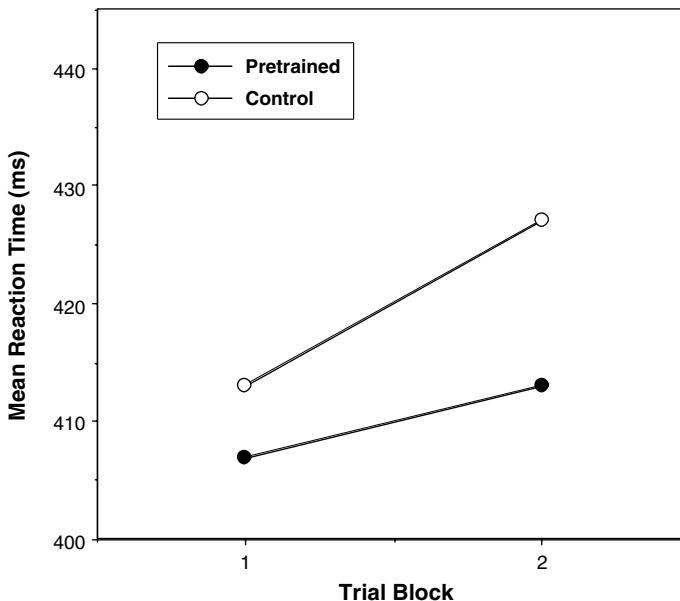

Fig. 3. Mean reaction times (ms) to effect stimuli trained in compound with either the pretrained or control effect stimulus during the two trial blocks of the test stage of Experiment 3.

persisted through the compound training and testing. Not only were the congruent participants responding faster during the posttest than those in the incongruent groups, they were, if anything, more accurate, although the difference failed to meet the conventional level of significance, $F(1, 14) = 3.53$; $p = 0.08$; $\eta^2 = 0.20$. The mean percentage errors by the congruent and incongruent groups were 2.8 (0.8) and 5.4 (1.2), respectively.

The present experiment produced the opposite pattern of performance to that observed in Experiment 2 in two important respects. Although an interaction was observed between response effects during compound training, it took the form of potentiation rather than overshadowing. In other words, training a colour effect in compound with a pretrained auditory effect enhanced the subsequent ability of the colour stimulus to prime its associated response. Second, unlike the visual pretraining in Experiment 2, the auditory pretraining in the present study persisted through the compound training and testing to influence performance in the posttest. Possible reasons for the discrepancies between the results of the two experiments are considered in Section 5.

5. General discussion

The first experiment replicated the response priming by effect stimuli previously reported by Elsner and Hommel (2001) and extended this priming to our visual stimuli. More importantly, Experiments 2 and 3 demonstrated that response effects interact when trained in compound. The pretrained visual effect overshadowed learning of an auditory effect ⇒ response association during compound training in Experiment 2. In contrast, in Experiment 3, training of a visual effect in compound with a pretrained auditory effect potentiated the ability of the visual stimulus to prime its associated response.

We anticipated overshadowing on the basis of the cue interactions observed during sensory preconditioning in animal conditioning procedures (Esmoriz-Arranz et al., 1997) and, at the very least, this finding supports the claim that the learning of effect ⇒ response associations are governed by the same processes as those operating within more standard conditioning procedures. We should note, however, that with our present design we cannot be certain that the overshadowing was due to the pretraining of S_X or, in other words, that S_X blocked learning about S_A during compound training. The pretrained overshadowing and control stimuli, S_X and S_Y, respectively, differed not only in their pretraining history but also in their sensory properties. Therefore, it is possible that the pretrained stimulus was a more effective overshadowing stimulus than the control stimulus because it was more salient rather than because it was pretrained.

Whatever the source of the overshadowing, at issue is whether the associative theories developed for cue interactions within standard animal conditioning and human associative learning paradigms can explain the interaction between effect stimuli. The problem is that all these theories were designed to explain the interaction between antecedent cues that stand in a predictive relationship to the outcome.

The overshadowing of effects would seem to lie outside the scope of attentional or associability theories (Mackintosh, 1975; Pearce & Hall, 1980). By one process or another, these theories assume that overshadowing occurs because the target cue is a redundant predictor of the outcome when trained in compound with the pretrained cue. As a consequence, the target cue fails to command the processing required to associate it with the

outcome. Because response effects do not stand in a predictive relationship to their associated responses, these attentional/associability theories are not obviously applicable to the present paradigm.

Whether or not the present form of overshadowing can be explained by the error-correcting learning algorithm proposed by Rescorla and Wagner (1972) is less clear. The basic idea is that an associated event, the response in the present case, can only support a limited associative strength. The overshadowing S_X, either through its pretraining or salience, absorbs much of this associative strength so there is little capacity left to establish an $S_A \Rightarrow$ response association during compound training. Although the algorithm was intended to explain predictive learning, in the absence of a process theory sensitive to temporal parameters, whether the Rescorla–Wagner learning rule can be applied to response–effect learning is unclear.

A real-time process account is offered by Wagner's (1981) SOP model. In SOP, stimuli (and, by extension, responses) are represented by nodes in an associative memory, each composed of a number of elements. Wagner proposed that these elements could have three different activation states: an inactive state, I, and two active states, A1 and A2. Unpredicted presentation of a stimulus activates a proportion of the elements in the corresponding node from I into A1. Over time, the A1 state of these elements decays into A2, and then back into I. Importantly, activating a node by an associative connection bypasses A1 and leads to a direct transition from I to A2. This property of the model is critical because it allows SOP to explain cue competition, such as overshadowing and blocking.

Wagner (1981) identified two forms of learning that occur whenever the elements of nodes are concurrently active. First, there is an increment in the strength of an excitatory association between nodes representing these stimuli to the extent that the elements of the nodes are concurrently in A1. Thus, excitatory learning occurs when a novel cue is paired with an unpredicted outcome because at the outset of training the presentation of the cue and outcome excites the elements of their respective nodes conjointly into A1. In the second, inhibitory form of learning, the concurrent activation of cue elements in A1 and outcome elements in A2 leads to the strengthening of an inhibitory association between the cue and outcome nodes.

Application of the SOP model to free-choice compound training assumes that when the response is voluntarily performed, at least some of its elements are in A1. The subsequent presentation of the pretrained S_X should then associatively activate some of the remaining response elements into A_2 and may even hasten the decay of the response elements in A1 into A2. Consequently, the A1 state of S_A generated by its presentation will be paired with mixed A1 and A2 activation of the response elements, resulting in both excitatory and inhibitory learning to S_A. By contrast, the learning for control stimulus S_B will be purely excitatory, at least at the outset of compound training when it is trained in compound with the non-pretrained S_Y. S_Y will be not retrieve any response elements into A2, and therefore there will be no inhibitory learning to S_B. In summary, the SOP model can explain overshadowing between effects in terms of the additional inhibitory learning by S_A due to the presence of a pretrained (or more salient) overshadowing effect, S_X.

Finally, we should note that a different class of theories assumes that overshadowing and blocking do not reflect a failure of learning about a cue but rather a modulation of performance. For example, the comparator theory (Miller & Matzel, 1988) assumes that any two events that are paired in time are automatically associated. Therefore, in addition to learning $S_A \Rightarrow R_1$ and $S_X \Rightarrow R_1$ associations during compound training,

within-compound associations, $S_A \Rightarrow S_X$ and $S_X \Rightarrow S_A$, will also be acquired. Consequently, not only will the presentation of S_A on test, prime the associated response directly, but it will also activate S_X via the $S_A \Rightarrow S_X$ within-compound association. Therefore, the presentation of S_A will activate the response representation by two routes. The first is the direct activation of the response via the $S_A \Rightarrow R_1$ association, whereas the second is indirect activation via the $S_A \Rightarrow S_X \Rightarrow R_1$ associative chain. Comparator theory then assumes that the performance of the response depends upon the comparison of the strength of its direct activation relative to the strength of the indirect activation. Overshadowing results from the fact that a strong $S_X \Rightarrow R_1$ association, whether produced by the salience or pretraining of S_X, enhances the indirect activation of R_1 and thereby reduces the strength to which the response representation is actually primed by S_A.

A problem for the comparator analysis of the response effect priming observed in the present studies is the potentiation that we observed in Experiment 3. The standard associative analysis of this potentiation would appeal to exactly the same associative structures as those invoked by comparator theory, namely the direct $S_A \Rightarrow R_1$ association and the $S_A \Rightarrow S_X \Rightarrow R_1$ associative chain. However, rather than assuming that the activation of the response by the direct association and the associative chain compete, the associative account of potentiation assumes that they summate. Therefore, not only can pretraining S_X reduce priming by S_A by overshadowing the acquisition of the $S_A \Rightarrow R_1$ association, but it can also potentiate priming through $S_A \Rightarrow S_X \Rightarrow R_1$ associative chain.

As it stands, however, this account leaves unexplained why Experiment 2 yielded overshadowing but Experiment 3 yielded potentiation. The answer may well lie with the relative saliences of the visual and auditory effects. In compound conditioning procedures, the strength of within-compound associations, like overshadowing, depends upon the relative saliences of the two stimuli (Bouton, Dunlap, & Swartzentruber, 1987). A generalization of these findings to our response–effect paradigm predicts that the $S_A \Rightarrow S_X$ within-compound association would be strongest when S_X is more salient than S_A. Therefore, we should expect potentiation, like overshadowing, to be dominant when S_X is more salient than S_A. Not only would a salient S_X establish a strong within-compound association but also result in a strong association with the response during pretraining. As a consequence, when S_X has a high salience the $S_A \Rightarrow S_X \Rightarrow R_1$ associative chain would be more likely to control responding and therefore yield potentiation.

Although we do not have a direct comparison of the relative saliences of the visual and auditory effects, the fact that the pretraining of the auditory effects, but not of the colour effects, persisted through compound training and testing to yield priming in the posttest suggests that associations established with the auditory effects during pretraining were stronger than those established with the visual effects. This difference suggests, therefore, that the auditory effects were more salient than the visual ones.

Whatever the merits of this account, the present results demonstrate interactions in response–effect priming that are analogous to those seen in standard conditioning and associative learning procedures. This observation encourages the claim that standard associative processes mediate the learning of effect $\Rightarrow$ response associations. This conclusion has implications for the analysis of action learning beyond simple response priming. For example, Heyes and her colleagues (Heyes, 2001; Heyes, Bird, Johnson, & Haggard, 2005) have suggested that imitation may be based on learned associations between actions and their visual effects. The fact that such learning can be demonstrated in an independent paradigm accords with this analysis.

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