# Reward Strengthens Action-Effect Binding

Andreas B. Eder

University of Würzburg, Germany

Thorsten M. Erle

University of Cologne, Germany

Wilfried Kunde

University of Würzburg, Germany

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Correspondence concerning this article should be addressed to AE, Department of Psychology, University of Würzburg, Röntgenring 10, 97070 Würzburg, Germany. Email: andreas.eder@uni-wuerzburg.de

# Abstract

According to ideomotor theory, anticipatory representations of action consequences are the basis for voluntary action control. A previous study suggested that rewards strengthen the acquisition of action effect links, and hence ideomotor learning. Participants in our experiments (total *N*=231) first learned to associate four manual actions with unique sound effects. Two sound effects were additionally predictive of a monetary reward. In a subsequent test phase, the former sound effects were presented as response primes in a speeded reaction time task. Response times were higher when the primes preceded a response other than the one to which they were linked in the preceding learning phase, an index of response-effect learning. Importantly, response priming was stronger for previously rewarded actions. Critically, this effect was not observed in a control condition with previously punished actions that produced a monetary loss. Overall, the results suggest that relations to rewarding consequences enhance associations between actions and sensory effects, a process that may facilitate reinforcement learning.

*Keywords*: ideomotor theory; action-effect binding; reward; reinforcement learning

# Reward Strengthens Action-Effect Binding

According to modern ideomotor theory, bi-directional relations between actions and their perceptual consequences enable voluntary action (Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001). Supportive of this claim, numerous studies showed that body movements become associated to the perceptual effects they produce, and that codes of these sensory effects are retrieved during the selection, initiation, and execution of the action (for reviews see Nattkemper, Ziessler, & Frensch, 2010; Shin, Proctor, & Capaldi, 2010). The influence of motivational action consequences, such as rewards and punishments, on action-effect binding is however less clear.

A recent study suggested that reward strengthens action-effect learning (Muhle-Karbe & Krebs, 2012). As shown in Figure 1, the experiment had two phases. Participants first learned in an *acquisition phase* to associate particular actions (actions: A1 to A4) with unique visual effects (effects: E1 to E4). Importantly, two out of the four action effects were additionally paired with a monetary reward (rewarded A-E associations), while the other two effects were not rewarded (unrewarded A-E associations). In a subsequent *test phase*, the color effects of the acquisition phase served as task-irrelevant response primes in a speeded reaction time task. The color of the response cue could be compatible or incompatible with the action-effect relation learned in the previous acquisition phase. As shown in Figure 1, this task design resulted in combinations of previously (un-)rewarded actions with compatible primes (cP), incompatible rewarded primes (iRP), and incompatible unrewarded primes (iNP).

--Figure 1 about here—

Results showed that participants responded slower when a formerly unrewarded action (NA) was primed by iRP relative to iNP or cP. For previously rewarded actions (RA), no significant differences were observed. Based on this result, the authors concluded that rewarded effects were bound stronger to their actions during the acquisition phase, producing more interference in incongruent trials relative to non-rewarded primes.

However, this interpretation is questionable. Firstly, based on ideomotor theory one would in general expect faster reactions with congruent relative to incongruent primes. This response-priming effect, however, was not observed. Hence, it is unclear whether the task procedures were appropriate to study ideomotor learning (for a discussion of action-effect acquisition in stimulus-response tasks see Herwig, Prinz, & Waszak, 2007; Pfister, Kiesel, & Hoffmann, 2011). Secondly, it is unexplained why there was no ideomotor priming effect for RA. If reward has strengthened action-effect binding, as the authors concluded, effects bound to RA should have been retrieved more quickly from memory during the test phase, facilitating responses in congruent relative to incongruent trials. Thus, ideomotor theory would have predicted the largest effect for previously rewarded actions. In contrast to this, there was a significant response priming effect for NA but not for RA. Thirdly, the results can alternatively be explained by differences in the saliency of RA and NA, which could have facilitated action-effect binding during the learning phase (see e.g., Dutzi & Hommel, 2009). If saliency was the critical factor, an analogous effect could be expected for salient punishing effects (see Eder, Dignath, Erle, & Wiemer, 2017). Finally, it should be noted that the authors' conclusions rested on a single experiment with *N* =26 participants. Therefore, more research is needed to corroborate this conclusion.

## The present research

The present research investigated effects of rewards on action-effect learning using improved task procedures that should produce clear evidence of ideomotor learning. Previous research showed that responses are linked to their effects rapidly in free-choice action tasks.

Specifically, Wolfensteller & Ruge (2011, 2014) observed that ideomotor effects (i.e., response priming by previously learned action effects) stabilize after only twelve learning trials. Here, we adapted their procedures of multiple brief acquisition and test phases. In each acquisition phase, participants associated four manual button presses with unique sound effects. Two sound effects additionally signaled a monetary reward. Acquisition of the action-effect relations was immediately probed in a subsequent test phase in which participants responded to the former action effects with keypresses that could be consistent or inconsistent with the action-effect relations in the previous learning phase. This task procedure allowed us to investigate a modulation of ideomotor learning by rewards like Muhle-Karbe & Krebs (2012).

In a pilot study (*N*=38), we obtained a robust response priming effect by former action effects; however, this effect was not influenced by reward associations (see the supplement for a report). In this pilot study, however, the rewarded keypresses produced, in addition to a unique sound effect, a visual icon of the monetary reward on the computer screen. This multimodal display could have produced selective attention effects (see Flach, Osman, Dickinson, & Heyes, 2006). Furthermore, instructions stated that all buttons should be pressed with about the same frequencies during the acquisition phase. While this instruction should promote sufficient learning trials for each action-effect pair, it may have reduced the relevance of the rewards.

As a consequence, we improved the task procedures to increase the relevance of reward associations. Participants in the experiments below were informed about the identity of rewarded tones prior to each acquisition phase. Task instructions stated that they should find out which keypresses generate these tones; a contingency test probed this knowledge at the end of each learning phase and the reward was only earned if participants indicated the correct keypresses. With this procedure, sounds were the only action effects, of which two were particularly relevant due to their relation to monetary rewards. Experiment 1A used this procedure to examine a modulation of ideomotor learning by reward associations. Experiment 1B used the identical task protocol but this time with associations to monetary losses (i.e., punishing response effects). Experiment 2 was a pre-registered direct replication experiment that included both, a reward and a loss condition. We hypothesized that associations to monetary rewards (but not to monetary losses) should strengthen action-effect binding. That means, effects of compatible and incompatible primes on the speed of response initiation in the test phase should be larger for previously rewarded keypresses in comparison to previously unrewarded or punished keypresses.

# Method

## Design and participants

The experiments had a 2 (RA vs. NA) x 3 (cP vs. iNP vs. iRP) within-subjects design. Reward and loss conditions were varied in groups (Study 2) or across experiments (Experiment 1A: reward; Experiment 1B: loss). A total of $N$=231 volunteers ($n$=172 female, $M_{\text{age}}$=26.96, $SD_{\text{age}}$=8.4) were recruited. Sample sizes for Experiment 1A/1B were $n$=49 and $n$=60. For Experiment 2, we calculated a sample size of $n$=130 to replicate the three-way interaction effect ($\eta_p^2$=.037) obtained in Experiments 1A and 1B with a power of 1-β=.80. This sample size was nearly reached with $n$=122. The study protocols were approved by a local ethics review board (Reference no. 2014-10). The study plan and the data-analytic approach for Experiment 2 were preregistered (https://osf.io/2j86q/.)

## Apparatus and material

Participants were seated in front of a 24-inch computer screen. Responses were entered via a mechanical computer keyboard with illuminated response keys. Acoustic effects were randomly drawn from a pool of 96 unique sounds (e.g., bird chirp, rattle sound, etc.; cf. Wolfensteller &

Ruge, 2011). A German version of the Behavioral-Inhibition and Behavioral-Activation Scales (Strobel, Beauducel, Debener, & Brocke, 2001) was completed in Experiment 2 for exploratory analyses (cf. Muhle-Karbe & Krebs, 2012).

## Procedure

Participants worked through 24 blocks, each consisting of an action-effect acquisition phase and a test phase.

***Acquisition phase.*** Participants pressed four buttons (A, S, K, and L) that triggered unique sound effects. They were informed that two of the four sounds would signal a monetary reward (or a monetary loss depending on the experiment condition); their task was to find out which keypresses produced these sounds. Participants heard the two rewarded tones before the learning task started and were informed that they would receive the reward (or punishment) only if they passed the contingency test.

Participants were to press each button 8 times before the experiment proceeded to the test phase. The order of the keypresses was free; however, each response button should be pressed about equally often. If any button was pressed more than 8 times, a message appeared (instead of a tone) instructing the participant to stop using this button. The inter-trial interval (ITI) ranged between 250-500 ms.

After sufficient keypresses, a contingency test asked the participant to press the two buttons that produced the rewarded (or punished) tones of this block. The money was added to (or subtracted from) the participant's account only if the responses were correct. In the case of an incorrect response, an error feedback appeared and the money was not added (or subtracted).

Participants received small plastic discs that represented a particular amount of money, and were asked to drop two plastic coins into a nearby box after each correct contingency test. In the reward condition, the coins in the box represented their earning that was converted into Euros at the end of the study (max. 8 Euros). In the loss condition, the participant received an initial endowment of 12 Euro from which money was subtracted (by depositing plastic coins in the box). Participants knew that they could save most of the endowed money (max. 8 Euros). To prevent participants from strategically providing incorrect responses in the contingency tests (in order to save money), participants were explicitly warned after the fourth failure that they run risk of losing the endowed money, and the endowment was lost after the sixth failure. In this case, study participation was aborted and compensated with 4 Euros.

***Test Phase.*** The sounds presented as action effects during the previous phase were now presented as stimuli for keypresses that were either congruent or incongruent with the response-tone relations learned in the previous phase. The test phase had a 2 (response: RA vs. NA) x 3 (prime: cP vs. iNP vs. iRP) within-subjects design, with half of the trials in a block being congruent and the other half being incongruent.

In the first 12 trials of a test block, an additional response cue (the letters A, S, K or L) was presented to instruct the sound-response mapping rules for this block (3 repetitions of each of the 4 sound-response mappings). The letter cue was removed for the next 12 trials (3 repetitions of each sound-response mapping). The ITI ranged between 1,000-1,500 ms and participants received error feedback after incorrect and slow responses (RTs>3,000 ms). Although Wolfensteller & Ruge (2014) did not find a difference in the magnitude of response priming for cued and uncued trials, we included this factor in our analyses.

## Mega-analysis

The data of the experiments were pooled in a mega-analysis (valid $N$=230) to increase the sensitivity of the statistical test. More precisely, we conducted an analysis of variance (ANOVA) of the reaction times (RT) in the test phase with the within-subjects factors *prime* (cP, iRP, iNP), *action-outcome relation* (yes, no), and *cueing* (present, absent), and the between-subjects factors *outcome* (reward, loss) and *study* (1, 2). Degrees of freedom were corrected with Greenhouse-Geisser for a violation of sphericity. Follow-up comparisons of RTs after compatible and incompatible primes were one-tailed and Bonferroni-corrected. Error analyses, single-study analyses, and exploratory analyses of the performance in the acquisition phases are reported in the supplement.

The same exclusion criteria were applied to each experiment (see the supplement). After exclusions, there were $n$=49 in Study 1A (reward); $n$=60 in Study 1B (loss); $n$=65 in the reward and $n$=56 in the loss condition of Study 2.

## Results

Descriptive statistics are reported in the supplement. In the omnibus ANOVA, the main effect of cueing was significant, $F(1,226)=362.66, p<.001, \eta^2_p=.616$. Responses were much slower in the first 12 trials with response cues than in the subsequent trials without response cues. The main effect of action-outcome relation was also significant, $F(1,226)=7.68$, $p=.006$, $\eta^2_p=.033$. Previously rewarded or punished button presses were on average 6 ms slower. The main effect of prime was significant, $F(1.89,427.54)=34.91$, $p<.001$, $\eta^2_p=.134$, indicating faster responses following compatible relative to incompatible primes. The interaction between study and prime reached significance, $F(1.89,427.54)=3.10$, $p=.049$, $\eta^2_p=.014$, with larger congruency effects in Study 1 than Study 2. Most important, the three-way interaction between prime, action-outcome relation, and outcome was significant, $F(1.88,425.54)=3.47$, $p=.035$, $\eta^2_p=.015$. This interaction was analyzed separately for each outcome in the analyses presented below. All other effects in the omnibus analysis were not significant (all $p$s>.05).

***Reward condition.*** The interaction between prime and action-outcome relation was significant, $F(2,224)=3.50$, $p=.032$, $\eta^2_p=.030$. As shown in Figure 2 (left panel), former RA were faster following cP relative to iRP, $t(113)=4.08$, $p<.001$, $dz=0.38$, and iNP, $t(113)=6.49$, $p<.001$, $dz=0.61$. Former NA were also faster after cP compared to iRP, $t(113)=2.06$, $p=.02$, $dz=0.19$; and iNP, $t(113)=2.33$, $p=.010$, $dz=0.22$. However, the former difference was not significant after Bonferroni correction ($\alpha/4 =.0125$). To sum up, response priming by compatible and incompatible sound effects was stronger for previously rewarded actions.

***Loss condition.*** There was no interaction between prime and action in this condition, $F < 1$, $\eta^2_p = .005$. As shown in Figure 2 (right panel), previously punished keypresses were facilitated by cP relative to iNP sounds, $t(115)=3.85$, $p<.001$, $dz=0.36$. The difference to iRP was however not significant ($t<1$), $dz=0.09$. In contrast, former NA were faster after cP relative to iRP, $t(115)=4.34$, $p<.001$, $dz=0.40$; and iNP, $t(115)=4.24$, $p<.001$, $dz=0.39$. In short: Response priming was in tendency weaker for previously punished actions.

—Figure 2 about here—

## Discussion

Two studies ($N=231$) examined the effect of rewards on the acquisition and automatic retrieval of action effects during action selection. Keypresses were initiated faster after presentations of compatible relative to incompatible sound effects. This priming effect is in line with the ideomotor hypothesis that a voluntary action is selected, initiated, and controlled by representations of action effects (Shin et al., 2010). Most importantly, response priming by compatible and incompatible sound effects was stronger for previously rewarded actions relative to unrewarded or punished actions. This pattern of results suggests that reward has strengthened action-effect binding during learning, which resulted in larger interference effects in the subsequent test phase.

Importantly, the modulation by reward cannot be explained with differences in the saliency of action effects because, in this case, punishing action effects should have produced the same pattern. Furthermore, response priming in the test phases was not generally larger for reward-associated primes (iRP) compared to neutral sounds (iNP) but, rather, depended on the reward history of the action (RA, NA). Differences in the attention to rewarded action effects hence cannot plausibly explain the present results.

It should be also noted that the present results are inconsistent with that of a previous study of reward and action-effect learning (Muhle-Karbe & Krebs, 2012). In this study, response priming was larger with iRP relative to iNP but only for actions without reward history (NA) and not for rewarded ones (RA). In contrast, the present study observed an effect of reward on RA and not on NA. We have no explanation for this discrepancy, except differences in the study procedures. As we have noted in the introduction, Muhle-Karbe and Krebs did not observe a basic response priming effect, and their inference of strengthened action-effect binding by reward is questionable. Accordingly, we believe that the present study was better suited to examine this question.

The present research also has limitations. One limitation is that the task procedure directed the participants' attention at the contingencies between actions and rewards. Hence, it is unclear whether a similar reward influence is observed in the absence of explicit contingency knowledge. A second limitation is that the receipt of the reward was made contingent upon knowledge of the action-effect contingencies. This procedure may have caused uncertainty about the receipt of reward during learning, which is known to affect reward learning (see e.g., Fiorillo, Tobler, & Schultz, 2003). In fact, in a pilot study we observed no modulation with perfectly predictable rewards. A third limitation concerns the loss condition that was introduced in the present study as a control condition for differences in saliency. Participants in this condition were asked to intentionally generate a small loss in order to prevent an even larger loss. It is unclear whether the representation of the small loss in this condition was a loss from the initial endowment (= a negative outcome) or a saving in comparison to a total loss (= a positive value). A representation as a negative outcome is indirectly suggested by the magnitudes of response priming in the reward and loss conditions. If the production of a small loss was a negative outcome, the production of no loss in this condition should have been a positive outcome (Eder & Dignath, 2014). In line with this reasoning, response priming effects were largest with the intentional production of a reward; second largest with the intentional production of no loss; and smallest with the voluntary production of losses and no rewards (see the effect sizes in Fig. 2). Clearly, more research is needed on the effects of negative outcomes and punishments on ideomotor learning. Finally, we should note that the present conclusions rest on a mega-analysis of several experiments that was not planned a-priori. In fact, a direct replication experiment was planned after comparison of Experiments 1A and 1B, and the main finding of a three-way interaction between priming, action-outcome relation, and outcome was not replicated (see the supplement for single-study analyses). Thus, more research is warranted on the robustness of the effect.

An interesting theoretical discussion is whether the reward functioned as an amplifier of action-identity associations during learning or whether it became an integrated feature of the outcome representation that biased action selection after learning. The amplification hypothesis would be in line with research suggesting that positive affect enhances episodic binding between stimuli and responses (Colzato, van Wouwe, & Hommel, 2007; Giesen, Scherdin, & Rothermund, 2017; Waszak & Pholulamdeth, 2009) and, perhaps, also between actions and sensory effects

(Moeller, Pfister, Kunde, & Frings, 2016). According to this account, reward has strengthened action-effect binding during learning while the reward itself was not included in the binding. An alternative possibility is that the reward was integrated into the cognitive representation of the producing action. Reward integration is suggested by behavioral studies showing that affective stimuli prime actions producing a matching affective outcome (Beckers, De Houwer, & Eelen, 2002; Eder, Rothermund, De Houwer, & Hommel, 2015; Strohmaier & Veling, 2018). Anticipation of a memorized reward during action choice is also suggested by operant learning studies with animals (e.g., Colwill & Rescorla, 1985) and by brain imaging studies with humans (e.g., Breiter, Aharon, Kahneman, Dale, & Shizgal, 2001). The reward signal could bias action preparation in favor of the previously rewarded action (Damasio, 1996). Hence, both hypotheses are in line with the present results, and more research is needed.

To conclude, the present research suggests that reward strengthens action-effect binding, which in turn should facilitate the selection, initiation, and execution of a previously rewarded action, as suggested by the ideomotor principle (Hommel et al., 2001). By increasing the probability of a previously rewarded behavior, enhanced action-effect binding by reward could be a cognitive micro-process that underlies reinforcement learning.

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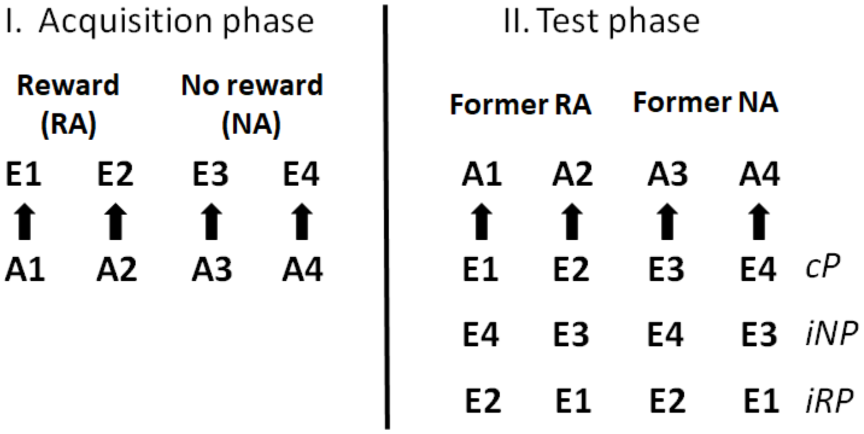

*Figure 1.* Study design of the present research and of Muhle-Karbe & Krebs (2012). During acquisition, two actions were rewarded (RA) and two other actions were not rewarded (NA). Each action (A1 to A4) produced a distinct effect (E1 to E4) that were presented as response primes in a subsequent test phase. The task-irrelevant primes could be either compatible (cP) or incompatible with the instructed action. Due to the reward manipulation in the acquisition phase, incompatible primes could be associated with a reward (iRP) or with no reward (iNP) and they could be paired with a formerly rewarded action or formerly unrewarded action. No rewards were given during the test phase.

*Figure 2.* Reaction times (in ms) in the test phase as a function of prime, action-outcome relation, and outcome. The eta-squared statistics indicates the magnitude of the response priming effect (cP vs. iRP vs iNP) in each condition. cP = compatible prime; iRP = incompatible prime associated with an outcome; iNP = incompatible prime associated with no outcome. R→O = Button press associated with an outcome (i.e., reward or loss); R→¬O = Button press associated with no outcome (i.e., no reward or loss).

## Supplemental Information File

### *Exclusion criteria*

Participants with five or more errors in the contingency tests were excluded and immediately replaced with new participants. Blocks with failed contingency tests were removed before analyses (Study 1A: 6.2%; Study 1B: 5.5%; reward condition of Study 2: 3.8%; loss condition of Study 2: 7.9%). One participant in Study 2 responded near chance in the test trials (error rate=44%) and was removed. For RT analyses, trials were removed with incorrect button presses (Study 1: 9.5%, Study 2: 9.5%); with RTs below 100 ms (following the recommendation of Luce, 1986) or with RTs slower than the participant's personal third quartile plus 1.5 interquartiles (following the recommendation of Tukey, 1977) calculated separately for test trials with response cues (Study 1: 5.6%, Study 2: 6.2%) and without response cues (Study 1: 14.4%, Study 2: 14.9%). Table 1 shows the reaction times in each test condition collapsed across both studies.

*Table 1*

Reaction times (in ms) as a function of prime (cP, iRP, iNP), cueing (yes, no), outcome (reward, loss), and action-outcome relation (yes, no). Standard deviation in parentheses.

| | | Reward | | Loss | |
|---|---|---|---|---|---|
| | | yes | no | yes | no |
| cP | cued | 528 (145) | 529 (132) | 522 (143) | 509 (131) |
| | uncued | 397 (111) | 401 (122) | 381 (104) | 377 (99) |
| iRP | cued | 555 (147) | 541 (140) | 530 (151) | 527 (138) |
| | uncued | 424 (143) | 408 (120) | 385 (131) | 386 (102) |
| iNP | cued | 557 (134) | 546 (141) | 538 (135) | 546 (155) |
| | uncued | 422 (128) | 408 (126) | 395 (131) | 386 (126) |

### *Mega-analysis of response accuracy in the test phases*

Table 2 shows the proportion of correct keypresses in each test condition collapsed across both studies. A (Greenhouse-Geisser corrected) ANOVA with the within-subjects factors *prime* (cP, iRP, iNP), *action-outcome relation* (yes vs. no), and *cueing* (present, absent), and the between-subjects factor *outcome* (reward, loss) and *study* (1, 2). The ANOVA produced a significant main effect of cueing, $F(1, 226) = 255.04$, $p < .001$, $\eta^2_p = .530$. Response performance was more accurate in the presence of response cues. The main effect of action-outcome relation was also significant, $F(1, 226) = 5.57$, $p = .019$, $\eta^2_p = .024$. Button presses that were predictive of a monetary outcome in the previous phase were less accurate ($M = 91.1\%$) compared to those that produced no change in the monetary outcome ($M = 91.6\%$). The main effect of prime indicated a congruency effect in line with the effect in the RT measure: keypresses were more accurate after presentations of cP ($M = 91.8\%$) relative to iRP ($M = 89.8\%$) and iNP sounds ($M = 89.6\%$), $F(1.85, 427.54) = 38.01$, $p < .001$, $\eta^2_p = .144$. Keypress performance was also more accurate in the loss condition ($M = 91.1\%$) relative to the reward condition ($M = 89.6\%$); however, this difference was not significant, $F(1, 226) = 3.71$, $p = .055$, $\eta^2_p = .016$. All other effects in this analysis were not significant (*p*s >.05).

*Table 2*

Proportion of correct responses (in %) as a function of prime (cP, iRP, iNP), cueing (yes, no), outcome (reward, loss), and action-outcome relation (yes, no). Standard deviation in parentheses.

| | | Reward | | Loss | |
|---|---|---|---|---|---|
| | | yes | no | yes | no |
| cP | cued | 96.6 (3.0) | 96.9 (2.9) | 97.3 (2.7) | 97.2 (2.5) |
| | uncued | 85.5 (12.2) | 85.9 (11.6) | 87.1 (10.7) | 87.5 (10.0) |
| iRP | cued | 94.1 (7.7) | 95.0 (4.7) | 95.8 (4.8) | 96.5 (3.5) |
| | uncued | 81.9 (15.5) | 83.2 (13.5) | 85.5 (15.8) | 86.0 (12.0) |
| iNP | cued | 94.7 (4.9) | 95.1 (5.9) | 96.0 (3.8) | 95.7 (6.0) |
| | uncued | 81.5 (14.2) | 83.8 (15.5) | 85.0 (10.8) | 84.5 (15.6) |

### ***Analyses of reaction times in the acquisition phases***

Log-transformed reaction times of keypresses in the acquisition phases were analyzed in a mixed ANOVA as a function of *outcome* (reward, loss), *action-outcome relation* (yes, no), and *Study* (1, 2). This analysis revealed a significant main effect of Study, $F(1, 226) = 4.08, p = .044, \eta^2_p = .018$; a significant main effect of outcome, $F(1, 226) = 5.89, p = .016, \eta^2_p = .025$; and a significant main effect of action-outcome relation, $F(1, 226) = 10.28, p = .002, \eta^2_p = .044$. The two-way interaction between action-outcome relation and Study, $F(1, 226) = 8.05, p = .005, \eta^2_p = .034$, and the three-way interaction were also significant, $F(1, 226) = 4.45, p = .036, \eta^2_p = .019$. Inspection of the means revealed that button presses producing rewards or losses were initiated faster in Study 1; in Study 2, button presses producing losses were initiated faster, while button presses producing rewards were initiated slower compared to the other button presses. Note that button presses in the acquisition phases were without time limit and that a response key was blocked after eight presses of the key. Therefore, these results should be interpreted with caution.

### *Analyses of Study 1 (n = 109)*

The mixed ANOVA of the reaction times in the test phases of Study 1 with the within-subjects factors *prime* (cP, iRP, iNP), *action-outcome relation* (yes vs. no), *cueing* (present, absent), and the between-subjects factor *outcome* (reward, loss) produced significant main effects of cueing, $F(1, 107)= 183.55, p < .001, \eta^2_p= .632$; outcome, $F(1, 107)= 6.34, p = .013, \eta^2_p= .056$; and prime, $F(1.82, 195.48)= 27.03, p < .001, \eta^2_p= .202$. The interaction between prime and outcome was also significant, $F(1, 107)= 27.03, p < .001, \eta^2_p= .202$. Importantly, his interaction effect was qualified by a significant three-way interaction between prime, action-outcome relation, and outcome, $F(1.95, 209.42)= 4.08, p = .019, \eta^2_p= .037$. All other effects were not significant (*p*s >.05).

### *Analyses of Study 2 (n = 121)*

A corresponding mixed ANOVA of the reaction times in the test phases of Study 2 produced a significant main effect of cueing, $F(1, 119)= 183.37, p < .001, \eta^2_p= .606$; a significant main effect of action-outcome relation, $F(1, 119)= 5.81$, $p = .017$, $\eta^2_p= .047$; and a significant main effect of prime, $F(1.93, 230.26)= 10.76$, $p < .001$, $\eta^2_p= .083$. All other effects were not significant.

### *Analyses of the pilot study (n = 38)*

Thirty-eight volunteers (30 women, $M_{\text{age}} = 27.1$ years, $SD_{\text{age}} = 8.7$) participated in the pilot study. Two participants made an excessive high number of errors in the test phases (> 32%; rest of the sample: $M = 9.4\%$, $SD = 0.6\%$); these data sets were removed. Trials with incorrect responses, anticipatory responses (RTs < 100 ms), and reaction time outliers (identified with Tukey, 1977) were removed before RT analyses. In the repeated-measures ANOVA of the reaction times in the test phases with *prime* (cP, iRP, iNP), *action-outcome relation* (yes vs. no), and *cueing* (present, absent) as factors, only the main effect of prime was significant, indexing a response priming effect ($M_{\text{cP}} = 585$ ms, $M_{\text{iRP}} = 633$ ms; $M_{\text{iNP}} = 628$ ms), $F(1.37, 48.14)= 3.89$, $p = .025$, $\eta^2_p= .10$ (Greenhouse-Geisser correction). All other effects were not significant (largest $F = 1.39$, all $p$s > .25). In a corresponding ANOVA of the proportion of correct responses, the main effect of cueing, $F(1, 35)= 60.02$, $p < .001$, $\eta^2_p= .632$, and the main effect of prime were significant, in line with the response-congruency effect in the RT performance measure, $F(2, 35)= 11.65$, $p < .001$, $\eta^2_p= .250$. All other effects were not significant (with $F$s < 1).

### References

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