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Limits of ideomotor action–outcome acquisition

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ABSTRACT

Ideomotor theory proposes that goal-directed action emerges from the implicit, incidental acquisition of bi-directional associations between actions and their outcomes. In line with this idea, a simple two-stage priming paradigm has provided evidence that presentation of outcomes primes previously associated actions. In the current study we compare the standard priming paradigm with two actions and two unique outcomes (Experiment 1) with two more complex, but otherwise identical versions (Experiment 2: two vs. four actions with four outcomes). Our results show stronger evidence of action–outcome learning in the simple compared to the more complex versions. We suggest that, when using the classic two-stage paradigm, action–outcome acquisition is limited to just a few action–outcome associations that can be concurrently learned—at least if learning is not supported by discriminative stimuli and outcomes are not salient or motivationally relevant.

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1. Introduction

A defining characteristic of goal-directed actions is that behavior is driven by anticipated outcomes (Adams and Dickinson, 1981; Balleine and Dickinson, 1998; Greenwald, 1970; Harless, 1861; James, 1950; Lotze, 1852; Pavlov, 1927). Ideomotor theories of action control propose that the anticipation of action goals emerges from the acquisition of bidirectional action–outcome associations (Hommel et al., 2001; Hommel, 2009; see for review Shin et al., 2010). For instance, accidentally touching a light switch and turning on the light would create an association between the representation of the light being on and the motor pattern of touching the switch (and the perceptual experiences accompanying this event). Once created, this association can be used to intentionally switch on the light by imagining the switched-

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on light, which will reactivate the light-related representation that will spread activation to the associated motor pattern. According to this view, the ability to carry out goal-directed action emerges from the incidental, implicit acquisition of action–outcome associations.

Supporting evidence for spontaneous ideomotor learning generally comes from a simple priming paradigm demonstrating that after the acquisition of action–outcome relationships, presenting the outcome as a stimulus facilitates the action that previously led to that outcome. If instructed to make a response that is incongruent to previously learnt associations, participants are slower and more error prone (Beckers et al., 2002; Elsner and Hommel, 2001; Herwig and Waszak, 2009; Hommel et al., 2003; Kunde et al., 2002; Wolfensteller and Ruge, 2011).

Although the majority of studies to date have examined purely sensory outcomes that have no motivational significance, some studies have shown evidence of a priming effect with motivationally relevant outcomes (Beckers et al., 2002; Eder et al., in press; Muhle-Karbe and Krebs, 2012). In addition, EEG studies have shown that random presentation of irrelevant outcomes generates a similar EEG signal to task-relevant feedback (Band et al., 2009) and that deviant auditory events in place of expected outcomes cause an orienting response (Waszak and Herwig, 2007). fMRI studies have shown that presentation of outcomes activates brain regions involved in attention and motor preparation (Hughes and Waszak, 2011; Melcher et al., 2008), and that action preparation is accompanied by the activation of brain areas that are coding for perceptual action outcomes (Kühn et al., 2011, 2010). Overall these studies show considerable evidence for the ideomotor mechanism and suggest that anticipation of outcomes is an important feature of goal-directed behavior, drawing on attentional resources and facilitating responding.

Previous studies have explored different parameters of the outcome-response priming effect. Wolfensteller and Ruge (2011) systematically examined how many acquisition trials are required before a priming effect is observed. Others have studied the temporal dynamics by varying the time between actions and outcomes either during the acquisition phase, or during test (Desantis et al., 2014; Elsner and Hommel, 2004; Ziessler and Nattkemper, 2011). A number of studies have examined how task instructions and intention during acquisition modulate the acquisition and expression of action–outcome learning (Herwig and Waszak, 2009; Zwosta et al., 2013). Overall these studies show that under simple conditions, the priming effect is robust and associations between actions and outcomes are quickly acquired. This fits with the ideomotor assumption that action–outcome acquisition is spontaneous, implicit, and incidental, and thus not dependent on any intention to learn (Elsner and Hommel, 2001). However, research on the characteristics of implicit versus explicit learning has provided strong evidence that implicit learning is restricted to simple, transparent relationships between the to-be-associated events. For instance, while few, unique stimulus–response relationships or event sequences can be learnt implicitly and incidentally, more complex relationships seem to require the presence of explicit processes (e.g., Alonso et al., 2006; Nissen and Bullemer, 1987; Tubau et al., 2007; for a review, see Keele et al., 2003). If thus ideomotor learning is aptly characterized as implicit and incidental, it would seem plausible that there are limits with respect to the complexity and number of ideomotor associations that can be acquired at one time.

On the one hand, there is clear evidence that the acquisition of ideomotor associations is not restricted to one action–outcome pairing: Elsner and Hommel (2001) demonstrated acquisition for two action–outcome relations and other studies have demonstrated successful acquisition for four relations (e.g., Band et al., 2009; Elsner and Hommel, 2004). And yet, the substantial diversity of experimental designs makes it difficult to assess whether and to which degree the number of simultaneously available actions and action–outcome relations might affect action–outcome acquisition. That it may play a role was suggested to us by two informal observations. In piloting for a study on action–outcome acquisition in infants, Verschoor et al. (2010; see Section 1) observed that an infant-friendly version of the Elsner and Hommel two-choice paradigm was too difficult for the investigated infants. In addition, pilot studies on adults in our lab suggest that replicating the original effects with more extended choice tasks can sometimes be difficult. The present study aimed at providing a formal test of these informal observations. In Experiment 1, we thus tried to replicate Elsner and Hommel's (2001) original observation. In Experiment 2 we tested whether this effect could also be demonstrated in two more complex versions of the otherwise identical paradigm.

2. Experiment 1

Experiment 1 was modeled after the original study of Elsner and Hommel (2001). It included the acquisition phase, in which participants carried out free binary-choice responses, followed by unique but task-irrelevant visual outcomes (blue shapes), and a test phase, in which the blue shapes now served as response-signaling stimuli. As in the original study, one group of participants was instructed to respond to each blue shape by performing the response that had triggered that outcome in the acquisition phase (the congruent mapping group). The other group of participants received incongruent mapping instructions in the test phase – they were instructed to perform the response that had not triggered the blue-shape outcome in the acquisition phase. The expectation was that performance should be better in the congruent than the incongruent group, which would indicate spontaneous action–outcome acquisition in the acquisition phase.

2.1. *Methods*

2.1.1. *Participants*

Forty participants (mean age: 22.4 years, SD 4.2 years; 68% female) were recruited from the University of Amsterdam. Participants were rewarded either with €3.50 or half a participation credit. The Psychology Ethics Committee of the University of Amsterdam approved the study.

2.1.2. *Stimuli and materials*

A computerized task similar to that described by Elsner and Hommel (2001) was used. The task was programmed in Inquisit and presented to participants on a Dell monitor.

Participants responded by pressing the 'z' and 'm' keys on a standard QWERTY keyboard. Each experiment consisted of an acquisition phase and a test phase. In the acquisition phase participants saw a 'go' stimulus – a white double-headed arrow and each participant saw two from a set of four possible outcome stimuli. These stimuli were all blue shapes of 5 × 5 cm – a square, a rectangle, a star or a circle. The participant saw the same two blue shapes as cue stimuli during the test phase (see Fig. 1).

2.1.3. *Procedure*

Participants were randomly assigned to either the 'congruent' or 'incongruent' groups. All instructions were given verbally. During the acquisition phase participants were instructed to push on either the left or the right key every time that they saw a white, double-headed arrow appear on the screen. They were told that it did not matter which key they pressed, but that they should try and push the left and right keys about equally often during the task, in a non-systematic manner. In addition, participants were told that every time they pressed a key a blue shape would appear but that these were not important and could be ignored. The blue shapes were counterbalanced across response keys and across participants.

Each acquisition trial began with the presentation of a white fixation cross that was presented for a random length of time between 1000 and 1500 ms. The cue was then presented for 200 ms and the computer waited for up to 1000 ms after the end of the cue presentation for a response (see Fig. 1). If a response was made, the participant saw the outcome (blue shape) for 500 ms. One blue shape was consistently paired with one response button and if no response was made the message "too late" was shown for 500 ms. Trials for which no response was recorded were considered invalid trials and were repeated before the end of the acquisition phase. Participants received 8 practice trials and 80 valid acquisition trials. After 30 valid trials and again after 60 valid trials a 'pause screen' was presented telling participants how often they had pushed the left and right keys and reminding them to try and push them about equally often. Participants could push the spacebar to continue at their own pace.

After the acquisition phase participants were instructed that during the second phase they would be presented with blue shapes and that they must push a specific key in response to each shape. During this test phase, the same two blue shapes that had been used in the acquisition phase as outcomes were now used as stimuli. For half of the participants (congruent group), the mapping instructions were congruent with the mapping during the acquisition phase. For the other half of the participants (incongruent group), the mapping instructions were incongruent such that the shape that had previously appeared following a right key press, was now the stimuli that required a left key press (see Fig. 1).

The test phase began with an instruction screen showing both shapes with the words 'left' and 'right' indicating what the correct response for each shape was (see Fig. 1). This was followed by 8 practice trials and then the mapping instruction screen was presented again. Each test trial began with the presentation of a white fixation cross that was presented for a random length of time between 1000 and 1500 ms. The shape cue was then shown for 200 ms and response window was open 50 ms after the end of cue presentation and closed 2000 ms after the end of cue presentation. Stimuli were shown in blocks of 8 (no pause between blocks), with the two stimuli presented four times randomly within each block. Response omissions were repeated before the end of the block. Each participant completed 32 valid test trials. After the task had finished, participants filled in the demographic questionnaire.

2.2. Results

Three participants were excluded for having error rates in excess of 25% (one participant from the congruent group and two participants from the incongruent group).

2.2.1. *Acquisition phase*

After exclusion of response omissions (3.9% of all trials), the response ratios for left and right key presses were calculated. Participants pushed the two keys equally often during the training (mean: 50% right key presses, SD 3%). Mean RT was not significantly different when comparing the congruent group (mean: 235 ms, SD: 51 ms) to the incongruent group (mean: 240 ms, SD: 46 ms; $t<1$, $p=0.72$).

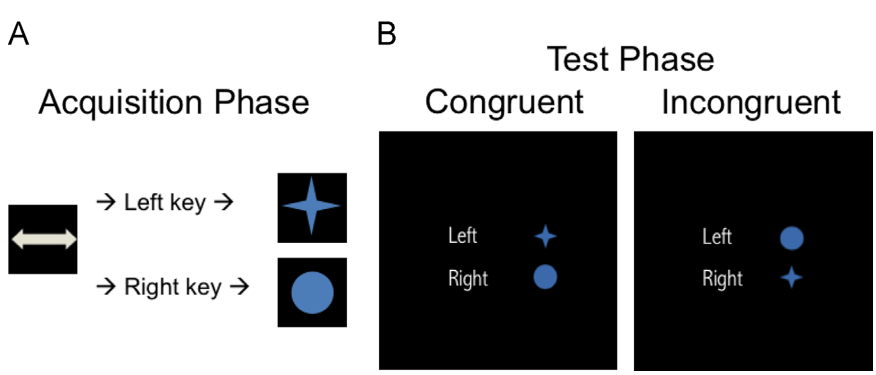

Fig. 1 – Experimental procedure in Experiment 1. (A) During acquisition phase a particular key press was always followed by a particular shape. (B) Instruction screens for the two different groups at test. For half of the participants (incongruent group), the action – outcome mapping was reversed.

2.2.2. Test phase: reaction time

Trials with response omissions were excluded from the test phase dataset (1.5% of all trials) and repeated measures ANOVA was used to assess RT as a function of congruence group assignment, across the four blocks. As expected, and as can be seen in Fig. 2a, a congruence effect was observed such that participants in the congruent condition were faster to respond. Mean RT for this group was 286 ms (SD 24 ms) compared to 321 ms (SD=43 ms) for the incongruent group (main effect of group; F (1, 35)=9.99, p=0.003). Participants' reaction times decreased across the four blocks (main effect of block F (3, 105)=4.28, p=0.015). There was no interaction between these two factors ($F<1$, p=0.65).

2.2.3. Test phase: accuracy

Repeated Measures ANOVA was used to assess accuracy as a function of congruence group assignment, across the four blocks. Error rates were not different between the two groups (incongruent/congruent) as evidenced by a non-significant main effect of group F (1, 35)=1.53, p=0.22 (see Fig. 2b). There was a marginally significant effect of block, F (3, 105)=2.7, p=0.05 (accuracy improved across blocks), but no interaction between these two factors ($F<1$, p=0.53).

2.3. Discussion

During the test phase of Experiment 1, participants were instructed to respond to stimuli that had previously functioned as outcomes during an acquisition phase. We replicated previous demonstrations of a congruence effect by showing that after acquisition of action–outcome relationships, participants in the incongruent group (who were instructed during the test phase to make responses incongruent to previously learnt associations) were slower to respond. This is presumably due to interference from the previously acquired action–outcome associations. In Experiment 2 we attempted to extend these results to more complex situations involving more than two response and outcome options.

3. Experiment 2

Experiment 2 extended the number of outcomes from two to four. Different variations of the task examined (a) four outcomes paired with two response keys and (b) four outcomes paired with four response keys.

3.1. Methods

3.1.1. Participants

Subject recruitment and testing took place at two locations (Leiden University & University of Amsterdam). 77 participants took part and were rewarded either with €3.50 or half a participation credit. Participants were assigned to one of two versions of the task: 39 participants to the '*Four outcomes & Two responses*' version (mean age: 21.1 years, SD 3.1 years; 66% female) and 38 participants to the '*Four outcomes & Four responses*' version. Due to experimenter error, age and gender data was missing for 20 participants in the latter condition. Of the remaining 18 participants, the mean age was 22.6 years (SD: 4.7 years) and 77% were female. It should be noted that advertisements specified that participants should be aged between 18 and 40 and gender differences have not previously been reported in studies making use of this two-stage priming paradigm.

3.1.2. Materials and procedure

Two different versions of the priming task described in Experiment 1 were used, consisting of an acquisition phase followed by a test phase. The same four outcome stimuli used in Experiment 1 were also used in both versions of the task and were counterbalanced across response keys and across participants. Any differences in the task from that described previously are outlined below.

3.1.3. 2 responses & 4 outcomes (2R4O) task

In this version of the task, participants received the same verbal instructions during the acquisition phase as Experiment 1 and saw the same 'go' stimulus. For each key

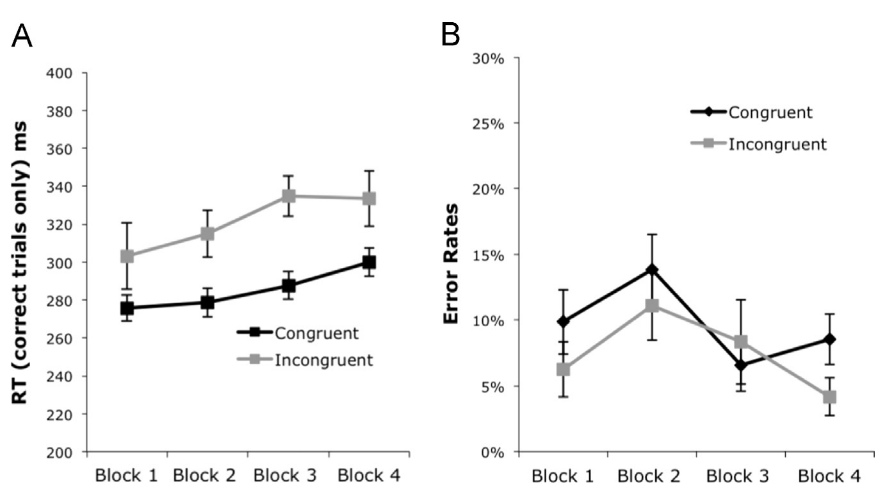

Fig. 2 – (A) RT data for experiment 1 across 4 blocks. Participants in the incongruent group were overall significantly slower (p=0.003). (B) Error rates. Error bars represent standard error of the mean.

however, there were now two associated outcomes (blue shapes; see Fig. 4). For every eight presses on a particular key, the two shapes assigned to that key were presented four times each in random order. All timings were exactly as described previously, although participants now had 160 valid acquisition trials with the pause screen after 50 and again after 130 valid trials. The test phase was exactly the same as described previously except that the instruction screen now had all four outcomes and the words 'left' and 'right' were used twice (see Fig. 3a). There were 64 valid test trials and within each block of 8 trials, each of the four outcomes was presented twice at random.

3.1.4. *4 responses & 4 outcomes (4R4O) task*

In this version of the task, participants were assigned four response keys (the 'c' and '.' keys in addition to the 'z' and 'm' keys). They were instructed to use the middle and index fingers from both hands. During the acquisition phase participants were instructed to push on all four keys about equally often, but all other verbal instructions were the same as Experiment 1. All timings were exactly as described previously, although participants now had 160 valid acquisition trials with the pause screen presented after 50 and again after 130 valid trials. The test phase was exactly the same except that the instruction screen now had mapping instructions for all four outcomes with the words 'middle finger – left' ' ring finger right' etc., across the four keys (see Fig. 3b). The test phase proceeded in exactly the same manner as described previously except that there were 64 valid test trials and each of the four outcomes was presented randomly twice within each block of 8 trials.

3.2. Results

Participants were excluded for having response omissions and/or error rates in excess of 50% during the test phase. This criterion (rather than the 25% used in Experiment 1) was chosen because the task was comparably more difficult, with twice the number of action–outcome relationships to be learnt. This resulted in 10 exclusions; two participants (both incongruent) were excluded from the 2R4O task and eight participants (four incongruent) excluded from the 4R4O task.

3.2.1. *Acquisition phase*

After exclusion of response omissions (2.7% of all trials), response ratios were calculated. Participants pushed the two keys equally often for the *2R4O task* (mean: 50% right key presses, SD 2%) and mean RTs were not significantly different when comparing the congruent group (mean: 222 ms, SD: 26 ms) to the incongruent group (mean: 225 ms, SD 25 ms; $t<1$, $p=0.75$. In order to ensure that responses were spread evenly across the four keys for the *4R4O task*, we compared response rates on three of the keys using a repeated-measures ANOVA, $F<1$, $p=0.53$). Mean RTs were not significantly different when comparing the congruent group (mean: 251 ms, SD: 56 ms) to the incongruent group (mean: 253 ms, SD: 34 ms; $t<1$, $p=0.89$.

3.2.2. *Test phase: reaction time*

Trials with response omissions were excluded (1.3% of all trials). Repeated measures ANOVA was used to assess RT as a function of task version (2 levels) and congruence group assignment (2 levels), across the four blocks.

As can be seen in Fig. 4, there was a main effect of task version F (1, 63)=53.2 $p<0.0001$). Participants were, unsurprisingly, slower to respond when there were more actions available in the four-choice task (4R4O task) compared to the two-choice task (2R4O task). There was also a task and block interaction F (3, 189)=9.6, $p<0.0001$). There was no main effect of, nor interaction with, congruence group assignment (all $ps>0.50$).

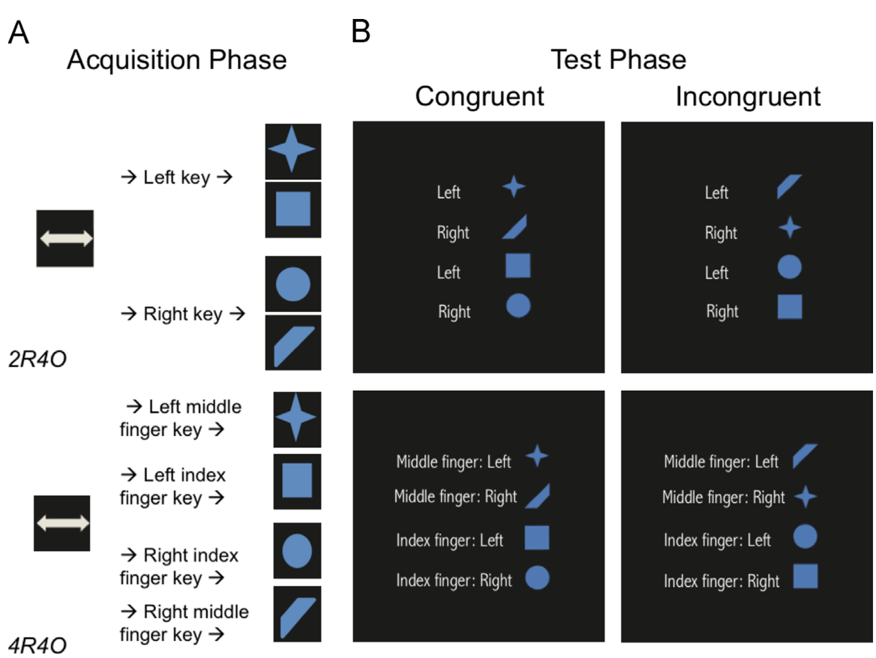

Fig. 3 – Set up of experimental procedure in Experiment 2 for the '2 *responses* & 4 *outcomes*' version (upper row) and '4 *responses* & 4 *outcomes*' (lower row). (A) Acquisition phase mappings. (B) Instruction screens seen by participants during the test phase.

3.2.3. Test phase: accuracy

Repeated measures ANOVA was used to assess error rates as a function of task version (2 levels) and congruence group assignment (2 levels), across the four blocks. Error rates did not differ between the task versions F (1, 63)=2.3, p=0.13. There was, however, an interaction between block and congruence F (3, 189)=407, p=0.006. As can be seen in Fig. 5, error rates during Block 1 were marginally higher at 22% for participants in the incongruent groups compared to the congruent groups (15%) across both task versions, $t(65)=1.9$, p=0.06, whereas this disadvantage had disappeared by block 2 ($t<1$, p=0.37).

3.2.4. Further analyses

It could be argued that the congruence effect was not observed in Experiment 2 due to a lack of power. In order to address this we used the G*power 3 software (Faul et al., 2007) to calculate the sample size required to observe a main effect of incongruence in reaction times (using a t-test) between two equal size groups. We used the effect size obtained in Experiment 1 ($M_1-M_2/\sigma_{\text{pooled}}=1.01$). This power analysis suggested that for a two-tailed effect size of 1, with error probability of 0.05 and power of 0.9 a total sample size of 46 (23 in each group) should be sufficient. However, we further used ANOVA to examine the complete data set (experiments 1 and 2 combined). Mean RT during the test phase was entered as dependent variable with congruence group assignment (incongruent/congruent) and experiment (1 vs. 2) entered as independent variables. This analysis did not reveal a significant interaction between incongruence group and experiment F (1, 100)=1.7, p=0.195 making interpretation of the null effect found in experiment 2 difficult.

4. General discussion

Using a simple paradigm with two action–outcome relationships we were able to replicate previous demonstrations of slower responding in a group of participants instructed to produce responses that were incongruent with what had been previously learnt. However, we did not observe this congruence effect in Experiment 2 when we increased the number of outcomes to four and had either two or four response keys. In this latter case there was a marginal difference in error rates between the two groups, but this trend did not persist past the first block. Although given the lack of interaction between congruence group and experiment these data should be interpreted with caution, this study does suggest that there may be limitations with respect to the number of action–outcome associations that can be created concurrently. As pointed out in the introduction, this is to be expected when the mechanism responsible operates automatically, implicitly, and without any explicit intention to learn (Keele et al., 2003; Nissen and Bullemer, 1987; Tubau et al., 2007).

It could be argued that participants in Experiment 2 did not sufficiently learn the action–outcome mappings and that this is the reason we did not observe interference from previously learned mappings in the incongruent groups' RTs. Wolfensteller and Ruge (2011), however, showed that 12 acquisition trials are sufficient for participants to learn the relationships between two responses and two outcomes. In the current study we replicated the learning phase of Elsner and Hommel (2001) by having 80 valid acquisition trials in the simple condition (Experiment 1). We then doubled this (160 trials) for the more complex conditions of Experiment 2. Although we cannot rule out the possibility that participants were not able to learn the action–outcome mappings, this seems unlikely. An alternative explanation, in regards to the 2R40 condition, is that associating two outcomes with one response key causes overshadowing to occur – associative learning of action–outcome relationships is reduced because of competition between the outcomes for associative strength with the response that produces them. Accordingly, this reduced associative strength leads to reduced interference during test (and eliminates the congruence effect; Flach et al., 2006).

This overshadowing explanation highlights the role that discriminative stimuli play in supporting learning of multiple action–outcome relationships. De Wit et al. (2013) for example, assigned four outcomes to one response key and, con-

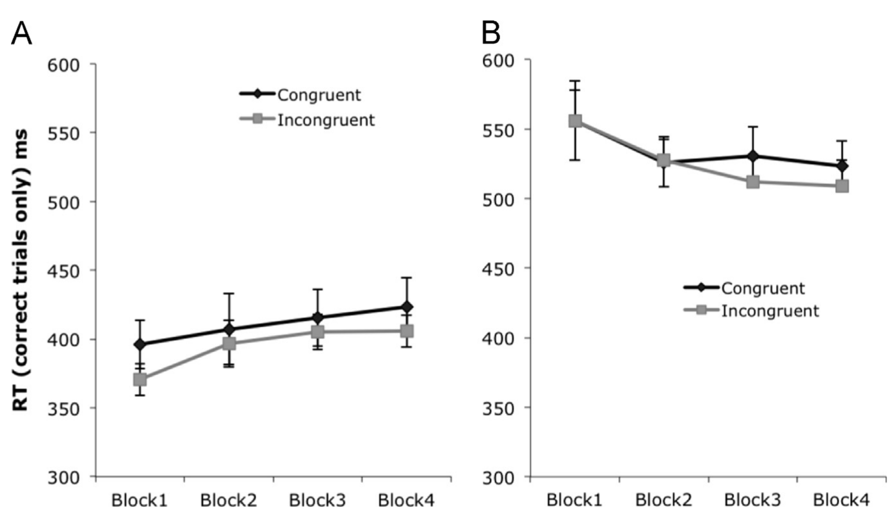

Fig. 4 – RT data for Experiment 2. (A) '2 *responses* & 4 *outcomes*' version. (B) '4 *responses* & 4 *outcomes*' version. There was no effect of incongruent mappings. Error bars represent standard error of the mean.

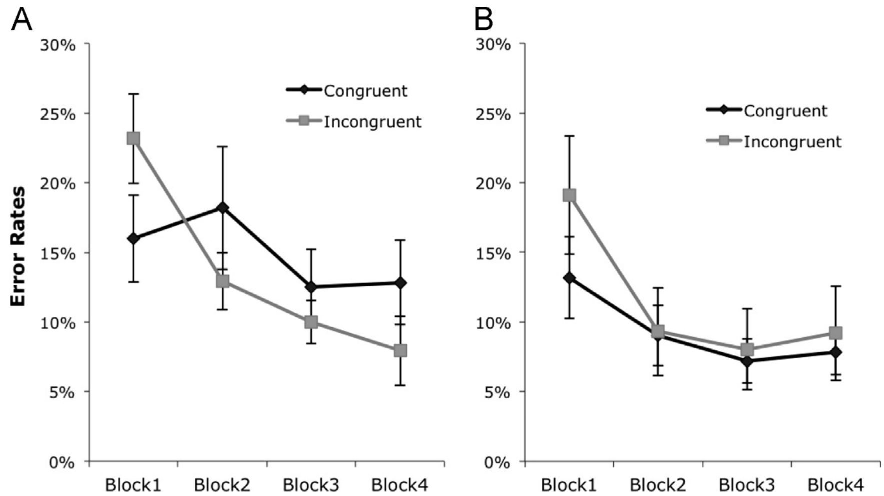

Fig. 5 – Accuracy data for Experiment 2. (A) '*2 responses & 4 outcomes*' version. (B) '*4 responses & 4 outcomes*' version. Error bars represent standard error of the mean.

trary to the current experiments, showed evidence of outcome-response priming after limited training. Although the paradigm differed in many respects, one crucial difference was that discriminative stimuli were used in the training phase, signaling which outcome was available and which response was therefore required (see also Elsner and Hommel, 2004). This presumably facilitates learning of multiple action–outcome relationships by providing a unique context in which the association is to be learnt and reduces the likelihood of overshadowing.

Some studies have actually reported that discriminative stimuli impair the learning of response–outcome relationships (Herwig et al., 2007; Herwig and Waszak, 2009) although others have shown acquisition of these relationships in forced-choice learning phases (Elsner and Hommel, 2004; Pfister et al., 2011; Wolfensteller and Ruge, 2011; Ziessler and Nattkemper, 2011), including demonstrations in rats (e.g. Adams and Dickinson, 1981). The expression of this learning (i.e. the activation of responses via outcome representations) may, however, be modified by task demands and instructions to participants (Pfister et al., 2010; Zwosta et al., 2013). In these latter studies participants were instructed to either produce outcomes (effect-based mode) or to respond on a certain response key (stimulus-based mode) in the presence of different stimuli. The placement of outcomes was then spatially compatible or incompatible to the response. Importantly the relationships between stimuli, responses and outcomes were held constant and only the instructions changed. Both studies observed an incompatibility effect in the effect-based mode only, leading to suggestions that the mere experience of outcomes is not enough to trigger associated responses, but that intention to act is required. While relating the results of these studies back to those of the classic two-stage paradigm is difficult, they relate to a broader theme of understanding whether ideomotor learning is sufficient or necessary for goal-directed action (Marien et al., 2013; Ziessler and Nattkemper, 2011; Ziessler et al., 2012). Indeed the current results suggest that the ideomotor priming effect is a simple mechanism that may not scale up to more complex situations, as would be expected if this were an important component of goal-directed action control.

It should be clear that while we consider our present findings to point to a limit of spontaneous action–outcome acquisition, our test was very conservative and the apparent limitation is relative rather than absolute. In addition, while the sample size should have been sufficient to detect a congruence effect in Experiment 2, interpretation of this null effect is difficult. The outcomes we used were not particularly salient and had no motivational relevance whatsoever in contrast to other designs that have made use of reinforcement learning tasks (Band et al., 2009) or encouraged participants to collect points for accuracy and speed during the acquisition phase (De Wit et al., 2007, 2013). There is evidence that more salient outcomes are more likely to be acquired (Dutzi and Hommel, 2009) and it seems reasonable to consider that outcomes with more motivational significance (for example monetary outcomes) might be learned more easily. A related paradigm, the Pavlovian-to-instrumental-transfer (PIT) task, has generally used motivationally relevant outcomes to demonstrate outcome-response priming (Colwill and Rescorla, 1988; Estes, 1948; Hogarth and Chase, 2011; Watson et al., 2014). The majority of these studies have also used simple one-to-one mappings of actions and outcomes and generally only examined two response keys (although see De Wit et al., 2013 for a more complex design).

It is also important to consider that the present test was conservative by using a forced-choice paradigm, which might reduce the impact of action–outcome anticipation on action control. Strong action-priming effects have been reported in free-choice tests where participants are freely able to respond on each test trial (see for example Eder et al., in press; Hogarth and Chase, 2011; Watson et al., 2014). Presumably, as there is no relevant, discriminative stimulus signaling the correct response during a free-choice test, action selection via outcome anticipation has more space in which to operate. One reason for the strong priming effects observed in PIT tasks might be that they often endogenously cue outcome representations by simply reminding participants of outcomes during the test phase, rather than presenting them (Colwill and Rescorla, 1988; Estes, 1948; Watson et al., 2014). This is a strategy that may also increase the priming effect although to date the two types of outcome cuing (direct and indirect) have not been compared in the same experiment.

Taken altogether, our findings suggest that successful action–outcome acquisition is less likely as the number of possible responses and response-related outcomes increases. This raises the question whether and to what degree other factors can enhance action–outcome acquisition, and we have suggested saliency and motivational relevance of outcomes as possible candidates.

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REFERENCES

Adams, C.D., Dickinson, A., 1981. Instrumental responding following reinforcer devaluation. Q. J. Exp. Psychol.: Sect. B 33 (2), 109–121, http://dx.doi.org/10.1080/14640748108400816.

Alonso, D., Fuentes, L.J., Hommel, B., 2006. Unconscious symmetrical inferences: a role of consciousness in event integration. Conscious. Cogn. 15, 386–396.

Balleine, B.W., Dickinson, A., 1998. Goal-directed instrumental action: contingency and incentive learning and their cortical substrates. Neuropharmacology 37 (4–5), 407–419, http://dx.doi.org/10.1016/S0028-3908(98)00033-1.

Band, G.P.H., van Steenbergen, H., Ridderinkhof, K.R., Falkenstein, M., Hommel, B., 2009. Action-effect negativity: irrelevant action effects are monitored like relevant feedback. Biol. Psychol. 82 (3), 211–218, http://dx.doi.org/10.1016/j.biopsycho.2009.06.011.

Beckers, T., De Houwer, J., Eelen, P., 2002. Automatic integration of non-perceptual action effect features: the case of the associative affective Simon effect. Psychol. Res. 66 (3), 166–173, http://dx.doi.org/10.1007/s00426-002-0090-9.

Colwill, R.M., Rescorla, R.A., 1988. Associations between the discriminative stimulus and the reinforcer in instrumental learning. J. Exp. Psychol.: Anim. Behav. Process. 14 (2), 155.

Desantis, A., Roussel, C., Waszak, F., 2014. The temporal dynamics of the perceptual consequences of action-effect prediction. Cognition 132 (3), 243–250.

De Wit, S., Niry, D., Wariyar, R., Aitken, M.R.F., Dickinson, A., 2007. Stimulus–outcome interactions during instrumental discrimination learning by rats and humans. J. Exp. Psychol.: Anim. Behav. Process. 33 (1), 1–11.

De Wit, S., Ridderinkhof, K.R., Fletcher, P.C., Dickinson, A., 2013. Resolution of outcome-induced response conflict by humans after extended training. Psychol. Res. 77 (6), 780–793.

Dutzi, I.B., Hommel, B., 2009. The microgenesis of action-effect binding. Psychol. Res. 73, 425–435.

Eder, A., Rothermund, K., De Houwer, J., Hommel, B., 2015. Directive and incentive functions of affective action consequences: An ideomotor approach. Psychol. Res. http://dxdoi.org/10.1007/s00426-014-0590-4 in press.

Elsner, B., Hommel, B., 2001. Effect anticipation and action control. J. Exp. Psychol. Hum. Percept. Perform. 27 (1), 229–240.

Elsner, B., Hommel, B., 2004. Contiguity and contingency in action-effect learning. Psychol. Res. 68 (2–3), 138–154, http://dx.doi.org/10.1007/s00426-003-0151-8.

Estes, W.K., 1948. Discriminative conditioning. II. Effects of a Pavlovian conditioned stimulus upon a subsequently established operant response. J. Exp. Psychol. 38 (2), 173–177, http://dx.doi.org/10.1037/h0057525.

Faul, F., Erdfelder, E., Lang, A.-G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39 (2), 175–191.

Flach, R., Osman, M., Dickinson, A., Heyes, C., 2006. The interaction between response effects during the acquisition of response priming. Acta Psychol. 122 (1), 11–26.

Greenwald, A.G., 1970. Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. Psychol. Rev. 77 (2), 73–99.

Harless, E., 1861. Der Apparat des Willens. Zeitschrift fuer Philosophie und philosophische Kritik, 38; 50–73.

Herwig, A., Prinz, W., Waszak, F., 2007. Two modes of sensorimotor integration in intention-based and stimulus-based actions. Q. J. Exp. Psychol. (2006) 60 (11), 1540–1554, http://dx.doi.org/10.1080/17470210601119134.

Herwig, A., Waszak, F., 2009. Intention and attention in ideomotor learning. Q. J. Exp. Psychol. (2006) 62 (2), 219–227, http://dx.doi.org/10.1080/17470210802373290.

Hogarth, L., Chase, H.W., 2011. Parallel goal-directed and habitual control of human drug-seeking: Implications for dependence vulnerability. J. Exp. Psychol.: Anim. Behav. Process. 37 (3), 261–276, http://dx.doi.org/10.1037/a0022913.

Hommel, B., 2009. Action control according to TEC (theory of event coding). Psychol. Res. 73 (4), 512–526, http://dx.doi.org/10.1007/s00426-009-0234-2.

Hommel, B., Alonso, D., Fuentes, L., 2003. Acquisition and generalization of action effects. Visual Cogn. 10 (8), 965–986, http://dx.doi.org/10.1080/13506280344000176.

Hommel, B., Müsseler, J., Aschersleben, G., Prinz, W., 2001. The Theory of Event Coding (TEC): a framework for perception and action planning. Behav. Brain Sci. 24 (5), 849–878.

Hughes, G., Waszak, F., 2011. ERP correlates of action effect prediction and visual sensory attenuation in voluntary action. NeuroImage 56 (3), 1632–1640, http://dx.doi.org/10.1016/j.neuroimage.2011.02.057.

James, W., 1950. The Principles of Psychology. Dover Publications, New York.

Keele, S.W., Ivry, R., Mayr, U., Hazeltine, E., Heuer, H., 2003. The cognitive and neural architecture of sequence representation. Psychol. Rev. 110, 316–339.

Kühn, S., Keizer, A., Rombouts, S.A.R.B., Hommel, B., 2011. The functional and neural mechanism of action preparation: roles of EBA and FFA in voluntary action control. J. Cogn. Neurosci. 23, 214–220.

Kühn, S., Seurinck, R., Fias, W., Waszak, F., 2010. The internal anticipation of sensory action effects: when action induces FFA and PPA activity. Front. Hum. Neurosci. 4, 54, http://dx.doi.org/10.3389/fnhum.2010.00054.

Kunde, W., Hoffmann, J., Zellmann, P., 2002. The impact of anticipated action effects on action planning. Acta Psychol. 109 (2), 137–155.

Lotze, R.H., 1852. Medicinische Psychologie oder die Physiologie der Seele. Weidmannsche Buchhandlung, Leipzig.

Marien, H., Aarts, H., Custers, R., 2013. Adaptive control of human action: the role of outcome representations and reward signals. Front. Psychol. 4, 602, http://dx.doi.org/10.3389/fpsyg.2013.00602.

Melcher, T., Weidema, M., Eenshuistra, R.M., Hommel, B., Gruber, O., 2008. The neural substrate of the ideomotor principle: an event-related fMRI analysis. NeuroImage 39 (3), 1274–1288, http://dx.doi.org/10.1016/j.neuroimage.2007.09.049.

Muhle-Karbe, P.S., Krebs, R.M., 2012. On the influence of reward on action-effect binding. Front. Psychol. 3, 450, http://dx.doi.org/10.3389/fpsyg.2012.00450.
Nissen, M.J., Bullemer, P., 1987. Attentional requirements of learning: evidence from performance measures. Cogn. Psychol. 19, 1–32.
Pavlov, I.P., 1927. Conditioned Reflexes. Oxford University Press, London.
Pfister, R., Kiesel, A., Hoffmann, J., 2011. Learning at any rate: action-effect learning for stimulus-based actions. Psychol. Res. 75 (1), 61–65, http://dx.doi.org/10.1007/s00426-010-0288-1.
Pfister, R., Kiesel, A., Melcher, T., 2010. Adaptive control of ideomotor effect anticipations. Acta Psychol. 135 (3), 316–322, http://dx.doi.org/10.1016/j.actpsy.2010.08.006.
Shin, Y.K., Proctor, R.W., Capaldi, E.J., 2010. A review of contemporary ideomotor theory. Psychol. Bull. 136 (6), 943–974, http://dx.doi.org/10.1037/a0020541.
Tubau, E., Hommel, B., López-Moliner, J., 2007. Modes of executive control in sequence learning: from stimulus-based to plan-based control. J. Exp. Psychol.: General 136, 43–63.
Verschoor, S.A., Weidema, M., Biro, S., Hommel, B., 2010. Where do action goals come from? Evidence for spontaneous action-effect binding in infants. Front. Psychol. 1, 201.
Watson, P., Wiers, R.W., Hommel, B., de Wit, S., 2014. Working for food you don't desire. Cues interfere with goal-directed food-seeking. Appetite 79C, 139–148, http://dx.doi.org/10.1016/j.appet.2014.04.005.
Waszak, F., Herwig, A., 2007. Effect anticipation modulates deviance processing in the brain. Brain Res. 1183, 74–82, http://dx.doi.org/10.1016/j.brainres.2007.08.082.
Wolfensteller, U., Ruge, H., 2011. On the timescale of stimulus-based action-effect learning. Q. J. Exp. Psychol. (2006) 64 (7), 1273–1289, http://dx.doi.org/10.1080/17470218.2010.546417.
Ziessler, M., Nattkemper, D., 2011. The temporal dynamics of effect anticipation in course of action planning. Q. J. Exp. Psychol. 64 (7), 1305–1326, http://dx.doi.org/10.1080/17470218.2011.553067.
Ziessler, M., Nattkemper, D., Vogt, S., 2012. The activation of effect codes in response preparation: new evidence from an indirect priming paradigm. Front. Psychol. 3, 585, http://dx.doi.org/10.3389/fpsyg.2012.00585.
Zwosta, K., Ruge, H., Wolfensteller, U., 2013. No anticipation without intention: response-effect compatibility in effect-based and stimulus-based actions. Acta Psychol. 144 (3), 628–634, http://dx.doi.org/10.1016/j.actpsy.2013.09.014.