

# Effect Anticipation and Action Control

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According to the authors' 2-phase model of action control, people first incidentally acquire bidirectional associations between motor patterns and movement-contingent events and then intentionally use these associations for goal-directed action. The authors tested the model in 4 experiments, each comprising an acquisition phase, in which participants experienced co-occurrences between left and right keypresses and low- and high-pitched tones, and a test phase, in which the tones preceded the responses in forced- and free-choice designs. Both reaction time and response frequency in the test phase depended on the learned associations, indicating that presenting a tone activated the associated response. Results are interpreted as evidence for automatic action–outcome integration and automatic response priming through learned action effects. These processes may be basic for the control of voluntary action by the anticipation of action goals.

Actions are performed to attain desired goals, hence, to intentionally produce particular events. Some action goals are simple, such as moving a finger to press a key, whereas others are rather complex, such as driving a car. Yet, there always has to be a representation of the goal that controls the selection and execution of appropriate movement patterns. In fact, James (1890) pointed out many years ago that, in principle, there can be no intentional action without a goal because “if, in voluntary action properly so-called, the act must be foreseen, it follows that no creature not endowed with divinator power can perform an act voluntarily for the first time” (p. 487). According to this logic, intentional action requires, and is actually controlled by, some anticipatory representation of the intended and expected action effects. In the following article, we deal with the issue of how these representations of action effects are acquired and how they are then used to control the selection of voluntary actions. In particular, we present a two-stage model that attributes the emergence of action control to the automatic integration of motor structures and the sensory consequences their activation produces.<sup>1</sup> We report four experiments that successfully tested some predictions derived from this model, and we conclude by discussing some implications of our findings.

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## Acquisition of Voluntary Action Control: A Two-Stage Model

In their introspective analyses of how the control of voluntary action may be acquired, Lotze (1852) and Harless (1861) claimed the existence of two different stages or phases. In the first stage, a movement is carried out in a random fashion, driven by internal needs and external stimulation, and the relationships between this movement and its effects are perceived and registered. In the second stage, once sufficient knowledge about movement-effect contingencies is available, this knowledge can be used to intentionally carry out a particular movement to produce the to-be-expected effect—hence, to perform a voluntary action.

On the one hand, this general picture drawn by Lotze (1852) and Harless (1861) has gained broad acceptance, particularly in the field of cognitive and developmental psychology. For instance, it directly motivated the ideomotor theory of James (1890) and is reflected in how Piaget (1969) conceived of the agent's transition from primary to secondary circular reactions. Moreover, most approaches to movement control agree in that the planning, programming, and execution of voluntary action are strongly influenced by the anticipation of action goals (Jeannerod, 1994; Prinz, 1997; Rosenbaum & Krist, 1996).

On the other hand, little is known about exactly how knowledge on movement-effect relations is acquired or about whether and how it is used to perform voluntary actions. To change this situation, we tried to transpose the considerations of Lotze (1852), Harless (1861), and followers into a working model that, although admittedly very simple and preliminary, is transparent and open to empirical testing. In a sense, this model combines Greenwald's (1970b) learning-theoretical interpretation of James's ideomotor principle with Prinz's (1990, 1997) idea of perceptual and action codes being represented within a common representational me-

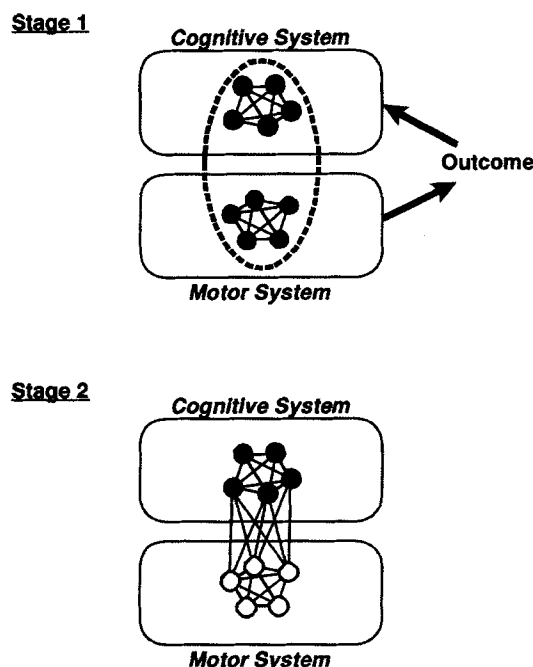
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<sup>1</sup> We use the term *automatic* in this context to imply that no explicit intention or allocation of attention is needed to (a) acquire response–effect associations or (b) activate a response through activating its associated effect representation.

dium, and it has already been fruitfully applied to issues in stimulus–response (S–R) compatibility (for an overview, see Hommel, 1997).

Stage 1 of the model is, as in Lotze (1852) and Harless's (1861) original approach, concerned with the acquisition of contingencies between movements and effects. Imagine a newborn infant, who is confronted with a world full of action opportunities. In the beginning, there is no logical way of how the infant could perform a voluntary action: If voluntary action is defined as performing a movement to attain a particular effect, the effect needs to be anticipated and, hence, known before the movement begins. Therefore, voluntary action requires knowledge about action effects.

The upper panel of Figure 1 provides a diagram of how we conceive of this knowledge acquisition: First, some randomly generated motor pattern ( $r$ ; represented by the network of activated codes in the motor system) is set up and a movement is carried out, which leads to a particular effect, that is, a specific, perceivable change in the relationship between the infant and its environment. Second, this change is perceived and registered, leading to a pattern of activation in the cognitive system ( $e$ ; represented by the upper network of activated codes). Third, given the temporal overlap of the activation of the motor and the sensory pattern, the corresponding codes are integrated (i.e., linked with each other) so that activating one pattern on a later occasion will lead to activating the other one, too. Because the temporal overlap of the codes' activations is sufficient for their integration, the learning in Stage 1 is automatic in the sense that it does not depend on attention being focused on the response–effect (R–E) relationship or on an explicit intention to learn about it.



**Figure 1.** The two-stage model of the emergence of action control. At Stage 1, the motor pattern producing a particular effect is automatically integrated with the cognitive codes representing this effect. At Stage 2, the motor pattern is intentionally executed by activating the cognitive codes that represent its expected effect.

Stage 2 of the model refers to the selection of goal-directed movements. Voluntary action does not only require the specification of a goal but also the recruitment of appropriate movements that are functional in reaching the goal. However, how does the cognitive system “know” which movements are appropriate? According to our model, movements are recruited by activating the perceptual codes that represent the desired goal. Given that past co-occurrences of movements and their consequences have led to associations between the underlying motor patterns and the codes of their perceivable effects (see lower panel of Figure 1), activating such an effect code will tend to activate its associated motor pattern to a certain degree. This activation allows the effect-oriented selection of motor patterns. Although this selection may be controlled by additional intentional processes, the spreading of activation from the effect to the response codes happens automatically, that is, independent of the agent's intentions. Thus, movements are selected by anticipating (i.e., activating the codes of) their consequences.

Although the example of a newborn may be particularly useful in understanding the problem of action-control acquisition, the two-stage model has implications that go beyond the first few months in life. Certainly, adults know and can correctly anticipate most of the perceivable effects of their movements and can draw on this knowledge to set up more complex movement patterns to successfully reach their everyday goals. However, when being confronted with a novel sensorimotor task, like trying to operate an unknown electronic apparatus, adults may also find themselves in conditions not too different from those of a newborn child. Here, we argue, learning proceeds as described by the two-stage model, starting with a phase of random, exploratory behavior. Moreover, the model makes the strong claim that action control operates on codes of anticipated action effects, irrespective of the agent's age and expertise and irrespective of the moment at which learning occurred.

For reasons discussed in more detail elsewhere (Hommel, 1997, 1998; Hommel, Muesseler, Aschersleben, & Prinz, in press), our version of the two-stage model makes four further assumptions that go beyond the considerations of Lotze (1852), Harless (1861), and followers. First, it claims that actions are cognitively represented in a distributed fashion, that is, in terms of their features. Under the assumption that integrated feature codes do not lose their identity as representations of single features, action representations are no unitary structures but comprise interconnected bundles of action–feature representations, just as shown in Figure 1. This implies that activating only a few feature codes belonging to an integrated action representation will tend to activate the whole action, including its motor part. That is, one does not need to anticipate all effects of an action to recruit the corresponding movement. However, the more effects—or effect features belonging to an action representation—that are anticipated, the greater is the activation of the motor part, which in turn increases the likelihood of selecting this action.

Second, the model makes the perhaps counterintuitive assumption that there is no qualitative distinction between movement effects from different sensory modalities. Some motor-control and developmental theories assume a special role of one—commonly the proprioceptive–kinesthetic—modality in movement acquisition (e.g., Meltzoff, 1993; Schmidt, 1971). It may well be that the perceiver–actor relies more heavily on information from one mo-

dality than from another when learning or performing a particular action: Kinesthetic and tactile information may be particularly useful in guiding hand movements, visual information may be central for controlling eye movements, and so forth. However, according to our model, it is only the quantity and the quality of information delivered by a sensory channel that counts, not the channel's identity.

Third, the model does not distinguish between movement effects that differ in their degree of remoteness, such as proximal sensations (e.g., feeling the arm moving toward the light switch) and distal consequences (e.g., experiencing the light going on). Again, it may well be that some movement-effect relationships are more difficult to discover than others. However, from the internal perspective that the cognitive system necessarily adopts, there is no qualitative difference between a body sensation and an external event (Wolff, 1987). Therefore, whatever the source, actions are cognitively represented by codes that provide information about the sensory effects a given motor program is likely to produce. The resulting integrated structures of perceptual and motor-related information, which Hommel (1997) referred to as *action concepts*, are the building blocks of voluntary action control.

Fourth, the model assumes that the effect representation mediates both the anticipation and the perception of the features of action consequences. Thus, the same effect code will be activated when the agent forms an intention to produce a certain action effect (endogenous activation) and when he or she perceives an event that resembles a known action effect (exogenous activation; for a broader discussion of this issue, see Hommel, 1997; Hommel et al., in press).

### Previous Studies

A first experimental step to investigate the issue of anticipatory action control was undertaken in 1970 by Greenwald (1970a, 1970b). Following James (1890), Greenwald stated that the anticipatory control of voluntary action is based on R-E learning, and he

conducted several experiments to investigate this assumption (Greenwald, 1970a, 1970b). These studies provide evidence that stimuli resembling well-known action effects prime the actions that typically produce them (i.e., verbal responses are faster to auditory stimuli than to visual stimuli because speaking produces auditory, but not visual, effects), an observation that is consistent with the assumptions regarding the second stage of our model.

To also include a test of assumptions regarding the first, acquisition-related stage, a further step was taken by Hommel (1996). Each of his six experiments was divided into two phases. In the first phase—the acquisition phase—participants performed a speeded two-choice response task, such as responding to the appearance of the letter *O* (Stimulus 1;  $S_1$ ) by pressing a left key (Response 1;  $R_1$ ) and responding to the appearance of the letter *X* (Stimulus 2;  $S_2$ ) by pressing a right key (Response 2;  $R_2$ ). After each response, a certain tone was presented, such as a low tone (response-contingent action effect,  $E_1$ ) after the left keypress and a high tone (response-contingent action effect,  $E_2$ ) after the right keypress (see the “Acquisition” column of Figure 2A). According to our two-stage model, the experience of several co-occurrences of a response ( $R_1$ ) and a tone ( $E_1$ ) should lead to the formation of an association between the motor pattern underlying the keypress ( $r_1$ ) and the cognitive representation of the action effect ( $e_1$ ), as indicated in Figure 1 ( $r_1 \leftrightarrow e_1$ ). If so, presenting one of the tones (e.g.,  $E_1$ ) should prime the associated response ( $R_1$ ): Hearing the tone should activate the codes representing its features ( $e_1$ ), and this activation should spread to the motor pattern with which these codes are linked ( $r_1$ ).

This assumption was tested in the second phase of the experiments—the test phase. Participants performed the same task, but now one of the “effect tones” was randomly chosen to appear together with the stimulus letter (see Figure 2A, far right column). Thus, while selecting a response, participants heard a tone that was either response compatible (i.e., expected to be produced by the response that the stimulus letter called for, such as with  $S_1 + E_1 \rightarrow$

	Acquisition	Test	
<b>A</b> Hommel, 1996	<b>Forced Choice</b>	<b>Forced Choice</b>	
	$S_1 - R_1 - E_1$ $S_2 - R_2 - E_2$	Compatible Trials	$S_1 + E_1 - R_1 - E_1$ $S_2 + E_2 - R_2 - E_2$
		Incompatible Trials	$S_1 + E_2 - R_1 - E_1$ $S_2 + E_1 - R_2 - E_2$
<b>B</b> Exp. 1A, 1B	<b>Free Choice</b>	<b>Forced Choice</b>	
	$S < \begin{matrix} R_1 - E_1 \\ R_2 - E_2 \end{matrix}$	Nonreversal Group	$E_1 - R_1 - (E_1)$ $E_2 - R_2 - (E_2)$
		Reversal Group	$E_2 - R_1 - (E_1)$ $E_1 - R_2 - (E_2)$
<b>C</b> Exp. 2A, 2B, 3A, 3B, 4A, 4B	<b>Free Choice</b>	<b>Free Choice</b>	
	$S < \begin{matrix} R_1 - E_1 \\ R_2 - E_2 \end{matrix}$	Acquisition-consistent Choices	$E_1 - R_1 - (E_1)$ $E_2 - R_2 - (E_2)$
		Acquisition-inconsistent Choices	$E_2 - R_1 - (E_1)$ $E_1 - R_2 - (E_2)$

Figure 2. Overview of the designs used in the Hommel (1996) study (Panel A), in Experiment 1 (Panel B), and in Experiments 2–4 (Panel C). The symbols  $S$ ,  $R$ , and  $E$  refer to stimuli, responses, and response-contingent action effects, respectively. The symbol  $(E)$  denotes that postresponse effects are provided in Experiments 1A, 2A, 3A, and 4A but not in Experiments 1B, 2B, 3B, and 4B. Exp = Experiment.

$R_1 \rightarrow E_1$ ) or response incompatible (i.e., expected to be produced by the alternative response, such as with  $S_1 + E_2 \rightarrow R_1 \rightarrow E_1$ ). As predicted, response-compatible tones allowed for faster responses than response-incompatible tones. In line with our two-stage model, this suggests (a) that response-tone associations are actually formed, (b) that these associations are bidirectional so that activating one associate tends to activate the other, and (c) that these associations have an impact on, and thus are likely to mediate, response selection.

It is interesting to note that support for the two-stage model can also be found in research on animal learning. Indeed, the assumption that the mere experience of movement-effect co-occurrences leads to the formation of integrated action concepts bears similarity to Tolman's (1932) theory of sign learning and to related approaches (e.g., Rescorla, 1992). Recently, several authors have advocated the hypothesis that the effects of instrumental responses are represented themselves and that instrumental learning results in the acquisition of associations between the stimulus, the response, and the effect (S-R-E associations). For example, Trapold's (1970) studies on the differential outcome effect revealed that rats learned to discriminate between stimuli more quickly when they were reinforced with a food pellet after a correct response to Stimulus A and with sucrose after a correct response to Stimulus B, as compared with a condition in which both responses were followed by the same reinforcement (either food or sucrose). In a further investigation on pigeons, Urcuioli and DeMarse (1996) reported evidence suggesting that the differential outcome effect is based on bidirectional associations between responses and their effects.

Indications for a spontaneous emergence of bidirectional R-E associations have also been observed in cats by Brogden (1962). He presented a tone every time the animal showed a cage-turning response. After acquisition, the tone was presented when the cat had not been moving for a while. As expected, the trained cats showed more tone-induced cage-turning responses than cats in a control group, which had not received response-contingent tones during training.

A study of Meck (1985) was based on similar logic: In a training phase, rats were conditioned to discriminate between stimuli by pressing a left versus a right lever. Every correct left response was reinforced and followed by a noise signal of a short duration, and every correct right response was reinforced and followed by a noise signal of a longer duration. After extended training, the rats faced a transfer phase, in which one of the signals preceded the opportunity to select a left or a right response. Half of the rats were reinforced for realizing the same relation between signal duration and response as in the previous training (nonreversal group), that is, when they responded to the short signal with a left response and to the long signal with a right response. The remaining rats were reinforced for realizing the reversed relation between signals and responses (reversal group). As expected, the percentage of correct responses was significantly higher in the nonreversal than in the reversal group. As Meck points out, the rats processed the post-reinforcement signals and acquired bidirectional response-signal associations so that presenting the signal led to an activation of the corresponding response—just as the two-stage model predicts.

In sum, postresponse events have been shown to become associated with the responses they follow, suggesting a spontaneous integration of the codes representing responses and response-

contingent effects, respectively. Evidence of this kind of integration has been found in the reaction time (RT) patterns of human participants and in the learning rates and response frequencies of rats and cats as well.

### Purpose of the Present Study

The evidence available from studies on humans and other animals is consistent with the central assumptions of the two-stage model of the emergence of action control. Nonetheless, there is still reason to doubt that this evidence is fully convincing.

First, even if the observations from animal studies suggest an integration of response and effect codes, one may doubt whether this has anything to do with the control of voluntary action in humans. However, we think that the automatic acquisition of R-E associations (that is, Stage 1 of the proposed model) and the automatic response activation by the perception of a known action effect (Stage 2) occur in both humans and animals and do so for the same reason. If so, the phenomena demonstrated in animals should be applicable to humans as well; one purpose of the present study was to demonstrate this.

Another reason to doubt the sufficiency of the available evidence has to do with the particular design of Hommel's (1996) study. The fact that the same stimuli were used in the acquisition and the test phase possibly led to a confounding: The critical associations could have been formed between the representations of the effect tones and the responses (e.g.,  $r_1 \leftrightarrow e_1$ ) or between the representations of the effect tones and the preceding stimuli (e.g.,  $s_j \leftrightarrow e_i$ ). In the latter case, the tone may not have activated the associated response but may rather have primed, and thus enhanced the processing of, the associated stimulus. Because the findings of Hommel (1996) do not allow one to rule out this interpretation, a second purpose of the present study was to provide further evidence for the assumed central role of R-E associations in action control.

To fulfill the two purposes of this study, we combined the approaches of Hommel (1996) and those used to investigate response-outcome learning in the animal literature. In Experiment 1, we transformed the design of Meck (1985) into a forced-choice RT task. In the acquisition phase, participants made free-choice left or right keypressing responses, and each keypress was contingently followed by a low or a high tone (see Figure 2B). In the test phase, the tones were used as imperative stimuli requiring a left or a right keypress, and two groups of participants were compared: A nonreversal group, in which the tone-key mapping in the test phase was consistent with that in the acquisition phase, and a reversal group, in which the tone-key mapping in the test phase was inconsistent with that in the acquisition phase. As we explain later in the article, the RT patterns exhibited by human participants are very similar to the learning rates Meck obtained with rats. As our task did not use a discriminative stimulus in the acquisition phase, it precludes differential stimulus-effect learning. Thus, any observed impact of effect-response compatibility can be taken as an indicator for R-E associations.

Experiments 2–4 extended our approach to include a further dependent variable. In animals, indications of R-E associations have been found in learning rates and response frequencies. These measures may represent different processes than RTs, such as in the measure we focused on in Experiment 1: RTs indicate the ease

of response selection; response rates and frequencies stand for its outcome. To test whether this makes a difference, we transformed the design of Brogden (1962) into a free-choice task with response frequencies as a dependent measure. The acquisition phase was exactly the same as in Experiment 1, and in the test phase, the effect tones were again used as stimuli. However, response choice was free in either phase (see Figure 2C). Accordingly in the test phase, the primary issue was not how quickly participants would respond to a tone but whether they would select the response that had formerly preceded this tone (i.e., the *acquisition-consistent* response) more often than the alternative response (i.e., the *acquisition-inconsistent* response).

### Experiment 1

Like Meck's (1985) and Hommel's (1996) experiments, Experiment 1 was divided into two phases (see Figure 2B). In the acquisition phase, human adults experienced several co-occurrences of left-right keypressing responses and response-contingent tones of low or high pitch ( $R_1 \rightarrow E_1$ ,  $R_2 \rightarrow E_2$ ). Although the tones were completely irrelevant to the task—which was pointed out to the participants—we assumed that experiencing those co-occurrences would result in the formation of bidirectional associations between the representations of the keypresses and of the tones ( $r_1 \leftrightarrow e_1$ ,  $r_2 \leftrightarrow e_2$ ) so that activating the tone code would activate the response.

At the end of the acquisition phase, participants were randomly assigned to one of two test groups: The nonreversal group was to respond to the tone by pressing the key that preceded this tone in the acquisition phase ( $E_1 \rightarrow R_1$ ,  $E_2 \rightarrow R_2$ ), whereas the reversal group was to respond by pressing the alternative key ( $E_1 \rightarrow R_2$ ,  $E_2 \rightarrow R_1$ ). If participants had not learned the (irrelevant) relationship between keypresses and tone pitches, or if they had not formed bidirectional key-tone (code) associations, performance in the nonreversal and the reversal group should not differ. However, if those associations were formed, the tones would prime the correct responses in the nonreversal group, but the wrong responses in the reversal group, so that performance should be better in the former than the latter.

In Experiment 1A, pressing a key triggered the corresponding tone in both the acquisition and the test phase. This manipulation meant that participants in the nonreversal group always heard the same two tones in each test trial (e.g., a low tone as a stimulus and as a response-contingent effect), whereas members of the reversal group always heard two different tones (e.g., a low tone as stimulus and a high tone as effect). Unfortunately, this introduces a possible confounding factor: The participants in the reversal group may exhibit worse performance than those in the nonreversal group merely because they have to deal with two mismatching tones in each trial and not because they have to struggle with misleading R-E associations.

To control for this possibility, we ran Experiment 1B, which was identical to Experiment 1A except that in the test phase, keypressing no longer triggered effect tones. If the performance of the two groups differed even under those conditions, this could only be traced back to what participants had experienced in the acquisition phase. A favorable side effect of having included Experiment 1B is that comparing its outcome to that of Experiment 1A allows us to evaluate the effect of extinction conditions on acquired action concepts. It would surely not be surprising to find

that those conditions reduce the impact of R-E associations. Nevertheless, knowledge of action effects is quite important for the setting of future goals so that one can expect that, once acquired, action concepts are rather permanent. If so, some impact of R-E associations should show up even in Experiment 1B.

### Method

#### Participants

Twenty-four adults (14 female, 10 male) and another 24 adults (15 female, 9 male) were paid to participate in Experiments 1A and 1B, respectively. Either experiment consisted of a single session of about 25 min. The participants reported having normal or corrected-to-normal vision and audition and were naive as to the purpose of the experiment.

#### Stimuli and Apparatus

The display and timing was controlled by a Hewlett Packard Vectra QS/20 computer, interfaced to an Eizo Flexscan monitor. The visual stimulus was a central, white rectangle displayed on a black background. Measured from a viewing distance of about 60 cm, the rectangle subtended a visual angle of 2.0° in width and 2.8° in height. Participants responded by pressing the left or right Shift key of a standard computer keyboard with the corresponding index finger. Auditory stimuli were 400-Hz (low-pitch) and 800-Hz (high-pitch) sinusoidal tones of 60 dB, presented simultaneously through the left and right speaker of a set of headphones.

#### Procedure

Each experiment was divided into an acquisition phase and a test phase.

**Acquisition phase.** Participants had to press the left or right key as quickly as possible on appearance of the white rectangle. They were verbally instructed to choose freely which key to press but were instructed to use the keys in a random order and about equally often. Each keypress triggered a tone. For one half of the participants, the left key triggered a low tone and a right key triggered a high tone (Response-Effect Mapping A), whereas the other half of the participants received the opposite key-tone mapping (Response-Effect Mapping B). Participants were not informed about the R-E mapping but were told that the tones were completely irrelevant for the task and should therefore be ignored.

Each acquisition trial started after an intertrial interval of 1,500 ms with a 200-ms presentation of the white rectangle. Then, the program waited up to 1,000 ms for a response. If a response was made, the corresponding tone was presented for 200 ms, starting 50 ms after the onset of the keypress. Trials with latencies exceeding 1,000 ms were counted as missing, and responses faster than 100 ms were considered to be anticipated. Response omissions and anticipations were fed back to the participants by a 1,000-ms presentation of a warning message on the screen. Both kinds of trials were recorded and then repeated at a random position during the remaining trials of the block. Participants could interrupt the experiment by pressing the *Escape* key and could continue by pressing the space bar. They worked through 8 practice trials and 200 valid acquisition trials. After each 50 valid trials, feedback was presented on the screen, informing the participant about the response ratio he or she had produced so far.

**Test phase.** After 200 valid acquisition trials, the participants were verbally instructed about the test phase. In each test trial, one of the two effect tones was presented as an imperative stimulus. The participants were told to respond to this stimulus as quickly and as correctly as possible according to a fixed S-R mapping. They were randomly assigned to two groups of 12 participants each. In each test group, one half of the participants had experienced Response-Effect Mapping A; the other half had experienced Response-Effect Mapping B.

For the nonreversal group, S-R mapping was consistent with the mapping of response and effect in the acquisition phase. For instance, participants who had acquired R-E Mapping A (left key → low tone, right key → high tone) were now to respond to the low tone by pressing the left key and to the high tone by pressing the right key. For the reversal group, the S-R mapping was inconsistent with the R-E mapping in the acquisition phase. Thus, the participants who practiced under R-E Mapping A were now to respond to the low tone by pressing the right key and to the high tone by pressing the left key.

The test trials in Experiments 1A and 1B differed only as to the presentation of the response-contingent tones. In Experiment 1A, each keypress triggered the same tone as in the acquisition phase, whereas in Experiment 1B, no tone appeared after the response.

Each test trial started after an intertrial interval of 1,500 ms with a 200-ms presentation of the white rectangle, this time accompanied by a randomly chosen low or high tone. Then the program waited up to 1,000 ms for a response. In Experiment 1A, each keypress triggered the corresponding tone, which appeared for 200 ms, starting 50 ms after keypress onset. Response omissions and anticipations were treated as in the acquisition phase. In addition, wrong keypresses were counted as errors, signaled by a warning message and repeated at a random position during the remainder of the block. Participants worked through 8 practice trials and 100 valid test trials. They were again able to interrupt and to continue the experiment on their own.

## Results

### Acquisition Phase

The significance criterion was set to  $p < .05$  for all analyses (one-tailed for single contrasts). After excluding trials with response omissions (Experiment 1A, 1.3%; Experiment 1B, 0.8%) or anticipations (Experiment 1A, 1.5%; 1B, 1.4%), response proportions (left vs. right keypresses) were calculated for each group and experiment. As revealed by  $t$  tests, the mean response ratios did not deviate from 50%—Experiment 1A, 49.9% versus 50.1%,  $SE = 0.4$ ,  $t(23) = 0.30$ ; Experiment 1B, 50.3% versus 49.7%,

$SE = 0.5$ ,  $t(23) = 0.69$ —confirming that the participants experienced the two R-E couplings about equally often.

### Test Phase

Because anticipations did not occur, only the trials with response omissions (Experiment 1A, 0.3%; Experiment 1B, 0.3%) were excluded. Then, mean RTs and percentages of error were calculated and analyzed as a function of experiment, group, and block (20 valid trials each).

As shown in Figure 3, the nonreversal group responded more quickly than the reversal group in both experiments but more so in Experiment 1A. There were four significant effects in RTs: a main effect of group,  $F(1, 44) = 19.21$ ,  $MSE = 27,501.0$ , and a main effect of experiment,  $F(1, 44) = 5.04$ ,  $MSE = 27,501.0$ , which was modified by an interaction with block,  $F(4, 176) = 6.24$ ,  $MSE = 1,406.4$ . This interaction was further modified by an interaction with group,  $F(4, 176) = 2.89$ ,  $MSE = 1,406.4$ . Because the three-way interaction including block was significant, we further tested the group effect separately for each block by using one-tailed  $t$  tests. All contrasts were significant; that is, reliable reversal effects were obtained in either experiment.

Response errors were rare (Experiment 1A, 2.8% in both groups; Experiment 1B, 2.5% and 2.6% in the nonreversal and the reversal group, respectively), and an analysis of variance (ANOVA) of error rates did not produce any effect.

### Discussion

Experiment 1 yielded two important outcomes. First, as expected, the nonreversal group responded more quickly than the reversal group in both Experiments 1A and 1B. Apparently, the mere experience of an R-E contingency in the acquisition phase led to the formation of bidirectional associations between response

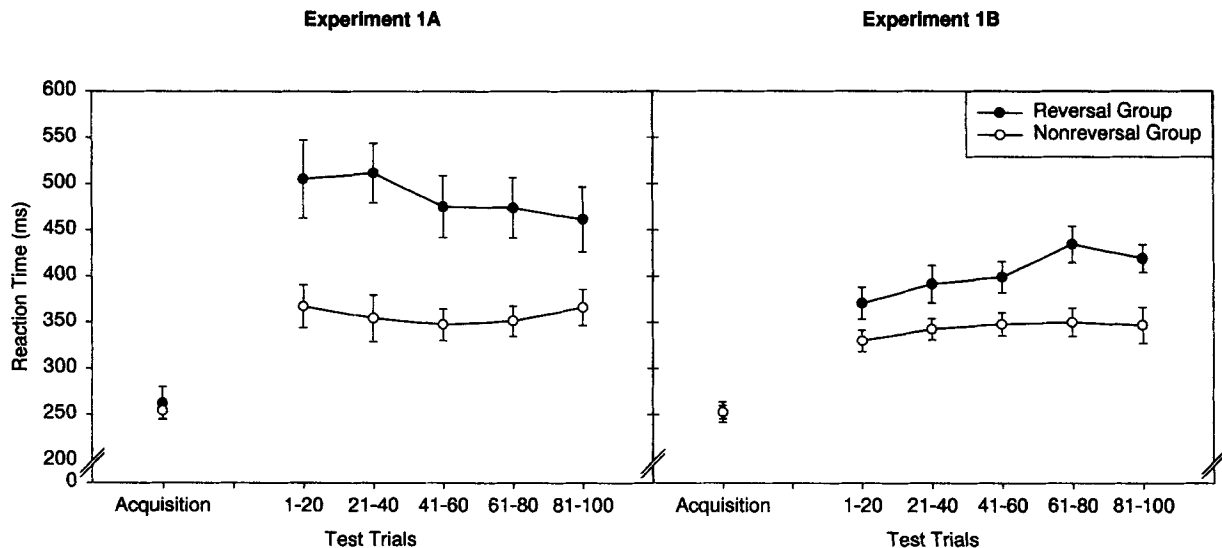


Figure 3. Mean reaction times of the test groups in Experiments 1A and 1B for the acquisition and the test phase (the latter as a function of 20-trial blocks). In the test phase of Experiment 1A, effect tones were still presented, but in Experiment 1B, effect tones were no longer presented. Error bars represent standard errors.

and effect codes so that in the test phase, activating the effect code tended to activate the corresponding response. If this response was the correct one, as was the case in the nonreversal group, performance was much better than if the tone activated the incorrect response, as in the reversal group. This effect occurred even though participants knew that response-produced tones were completely irrelevant to the task. This corroborates the assumption that the integration of responses and response-contingent sensory events is automatic, in as much as it does not depend on attention devoted to these events or on the intention to learn the R-E relationship. In this respect, the behavior of our human participants is quite comparable to that of Meck's (1985) rats.

Second, the observation of reliable group differences in Experiment 1B, despite the absence of postresponse tones in the test phase, indicates that R-E associations are rather robust and resistant to extinction—a conclusion also suggested by the fact that the group effect did not diminish during the test phase. This observation parallels recent findings from animal studies implying that the associations underlying response-outcome learning seem to be immune to extinction (Rescorla, 1993, 1995). From an action-control perspective, the stability of R-E associations makes sense. Depending on the situation, a given response may or may not produce a particular effect. For instance, walking in darkness eliminates the visual consequences of the walking movement. Nevertheless, an immediate extinction of the associations between the movement and its visual effects would be dysfunctional because when the situation changes—that is, when the light is turned on—the well-known effects will reappear, and the system would have to relearn the extinguished associations.

Why the group effect in Experiment 1B was nevertheless smaller than in Experiment 1A is difficult to judge from the present data. The difference may indicate that, as already suspected, the occurrence of two mismatching tones in each trial distracted or confused the participants in the reversal group in Experiment 1A, thus artificially increasing the group difference. However, the reliable effects in Experiment 1B clearly show that distraction or related confounding variables cannot account for all of the performance deficits observed in the reversal group.

## Experiment 2

Experiment 1 provided evidence for the impact of acquired R-E associations on the speed of response selection in human participants. Experiment 2 was designed to find out whether these hypothesized associations can also affect the outcome of response selection, that is, the likelihood of performing a particular response. Because response likelihood or frequency is the preferred measure in the relevant animal learning literature, demonstrating a response frequency effect in humans would strengthen our assumption of a close correspondence between R-E integration in humans and other animals.

We used an adaptation of the task Brogden (1962) used in his investigation on cats. The acquisition phase was exactly as in Experiment 1, requiring free-choice responses to a nondiscriminative trigger stimulus. In the test phase, however, we replaced the forced-choice task by another free-choice task: In each test trial, one of the two effect tones was presented, and the participants were to choose freely one of the two possible keypress responses (see Figure 2C). This time our primary interest was not how

quickly this decision was made (RT) but which response was chosen (relative response frequency).

If the experience of particular effects following particular responses really leads to the emergence of bidirectional associations between response and effect codes, presenting a particular effect tone should tend to activate the associated response. Accordingly, we expected that presenting a tone in the test phase would favor choosing the response that preceded this tone in the acquisition phase. In other words, the response consistent with the previous R-E mapping (i.e., the acquisition-consistent response) should be chosen more often than the alternative response (i.e., the acquisition-inconsistent response).

Again, we compared two test phase conditions: In Experiment 2A, postresponse effect tones were still provided during the test phase, whereas in Experiment 2B, the postresponse tones were provided only during the acquisition phase but not during the test phase.

## Method

Because the frequencies of acquisition-consistent and acquisition-inconsistent responses were to be compared intra-individually, we reduced the number of participants to another 12 (7 female, 5 male) and 12 adults (6 female, 6 male), who were paid to participate in Experiments 2A and 2B, respectively. The participants fulfilled the same criteria as in Experiment 1.

Stimuli, apparatus, and procedure were unchanged, with the following exceptions. In the test phase, participants were not instructed to follow a particular tone-key mapping but were free to choose either key to respond to the tone in each trial. Unlike in the acquisition phase, the participants were not to mind a balanced response ratio but to respond as spontaneously as possible. However, it was pointed out that exclusively pressing one key was not acceptable. The RT and frequency differences between acquisition-consistent and acquisition-inconsistent responses were compared within the data of each participant.

In Experiment 2A, each response triggered the same tone as in the acquisition phase so that the R-E mapping in the test trials remained unchanged for each participant. In the test phase of Experiment 2B, the keypresses were no longer followed by a tone.

## Results

### Acquisition Phase

Trials with response omissions (Experiment 2A, 1.0%; Experiment 2B, 0.6%) or anticipations (Experiment 2A, 2.7%; Experiment 2B, 2.3%) were excluded. In Experiment 2A, a *t* test yielded no deviation of the response ratio from 50%—50.9% versus 49.1%,  $SE = 0.8$ ,  $t(11) = 1.16$ —confirming that the participants experienced the two R-E couplings about equally often. In Experiment 2B, left responses were significantly preferred to right responses: 52.0% versus 48.0%,  $SE = 0.8$ ,  $t(11) = 2.44$ . However, in absolute numbers, this means that participants performed 104 trials with the left and 96 trials with the right key—a marginal difference that is unlikely to affect the results in the test phase.

### Test phase

Trials with response omissions (Experiment 2A, 1.1%; Experiment 2B, 1.3%) or anticipations (Experiment 2A, 1.5%; Experiment 2B, 2.4%) were excluded. Mean response frequencies and mean RTs were calculated for each participant as a function of the

consistency of the response to the R-E mapping in the acquisition phase. That is, if in the acquisition phase a left keypress was followed by a low tone and a right keypress was followed by a high tone, left responses to low tones and right responses to high tones were counted as consistent choices, whereas right keypresses to low tones and left keypresses to high tones were counted as inconsistent choices. The percentages of responses were analyzed as a function of consistency and experiment (Experiment 2A vs. Experiment 2B).

As shown in Figure 4, responses that were consistent with the R-E mapping in the acquisition phase were selected more often than inconsistent responses in both experiments. Only the main effect of consistency was significant:  $F(1, 22) = 14.09$ ,  $MSE = 59.6$ . Two  $t$  tests revealed that the frequency of consistent choices deviated significantly from chance in both Experiment 2A, 54.7%,  $t(11) = 3.03$ , and Experiment 2B, 53.7%,  $t(11) = 2.30$ . Nevertheless, the RTs for consistent and inconsistent responses did not differ significantly: Experiment 2A, 240 ms versus 243 ms,  $t(11) = -.78$ ; Experiment 2B, 220 ms versus 223 ms,  $t(11) = -.87$ .

### Discussion

The results of Experiments 2A and 2B clearly indicate that acquired R-E associations can affect not only the speed but also the outcome of response selection. As predicted, after having perceived a former action effect, participants preferred the response they had performed to produce this effect. In line with the results of Experiment 1, the frequency difference is not dependent on the provision of postresponse effect tones: We still find a significant response bias in Experiment 2B, that is, when no response-contingent feedback was provided in the test phase.

However, there is a fly in the ointment: The stimulus-induced response bias was rather small in both Experiments 2A and 2B. This alone surely does not provide an insurmountable theoretical problem. After all, the two-stage model leads one to expect that

presenting an acquired action effect arouses only a tendency to react with the associated response. That is, the model does not deny that there may be other competing response tendencies (e.g., repetition or alternation) and that an agent can overcome such tendencies that do not fit with his or her deliberately chosen action plans. Nevertheless, the small difference between the frequencies of consistent and inconsistent responses may indicate that the participants failed to form the hypothesized R-E associations in the acquisition phase.

We doubt this conclusion for two reasons: One reason is that after Experiments 2A and 2B, most of the participants were able to recall the R-E mapping to which they had been assigned in the acquisition phase. Because the participants knew that the tones were completely irrelevant to the task and because they were instructed to ignore the tones in the acquisition phase, we believe that the assumed automatic formation of R-E associations is the most parsimonious interpretation for the availability of this knowledge.

The other reason we doubt this conclusion has to do with the RT level in the test phase, which was 241 ms in Experiment 2A and 221 ms in Experiment 2B. These RTs are much lower than in Experiment 1 and are more in the range of a simple RT task. This is the more surprising result because free-choice reactions, such as those in Experiment 2, are commonly slower than forced-choice reactions, as used in Experiment 1 (Berlyne, 1957). Apparently, participants tended to make their response decisions before the stimulus appeared—an interpretation that is also suggested by the observation of 2.0% anticipatory test responses, as compared with zero anticipations in Experiment 1. Such a situation renders it difficult for the tone to affect response selection at all. In other words, the participants may have failed to show strong evidence of a stimulus-induced response bias in Experiments 2A and 2B, not because of a lack of R-E learning in the acquisition phase, but because of the tendency to make premature response decisions in the test phase. Experiment 3 tested whether this is a tenable explanation.

### Experiment 3

In Experiment 3, we attempted to replicate Experiment 2 but, at the same time, to prevent the participants from making their response decisions in the test phase before the stimulus had appeared. Accordingly, we introduced a third stimulus tone: a neutral bell sound appearing in 50% of the trials. This neutral tone served as a no-go signal, while the former effect tones served as go stimuli. That is, participants were still to choose freely among the two possible responses in the test phase, but they actually performed the response only in go trials (i.e., whenever one of the former effect tones appeared). In half of the trials, no response was required, which should discourage participants from making premature response decisions. Such a manipulation should increase not only the RT level but also the chance of the former effect tones to influence response selection by means of acquired R-E associations. Therefore, we expected a more pronounced response bias (favoring acquisition-consistent responses) than that obtained in Experiment 2.

In Experiment 3A, each response triggered the same tone as in the acquisition phase so that the R-E mapping in the test trials

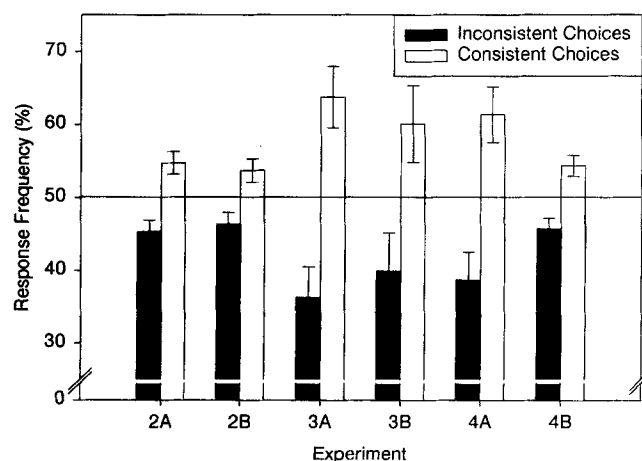


Figure 4. Percentage of acquisition-inconsistent and acquisition-consistent response choices in Experiments 2–4. In the test phase of Experiments 2A, 3A, and 4A, effect tones were still presented, but in Experiments 2B, 3B, and 4B, effect tones were no longer presented. Error bars represent standard errors.



remained unchanged for each participant. In the test phase of Experiment 3B, the keypresses were no longer followed by a tone.

### Method

Another 12 (8 female, 4 male) and 12 adults (9 female, 3 male) were paid to participate in Experiments 3A and 3B, respectively. They fulfilled the same criteria as in Experiment 1. The method was the same as in Experiment 2, with the following exceptions. In each test trial, one of three tones was presented as stimulus: either one of the two sinusoidal tones used as response-contingent effects in the acquisition phase ( $p = .25$  each) or a neutral bell chiming sound ( $p = .50$ ). If one of the sinusoidal tones appeared, participants had to react as spontaneously as possible by pressing one of the two keys, just as in Experiment 2. Whenever the bell sound appeared, participants were not to respond. As these no-go trials were introduced to increase response uncertainty—the major variable in this experiment—participants responding in 10% or more of the no-go trials were not considered in the analysis. One participant in Experiment 3A failed to meet this criterion (22% responses), and his data were therefore replaced by the data of another participant. In Experiment 3A (but not in Experiment 3B), each keypress triggered a tone according to the R-E mapping in the acquisition phase. There were 16 practice trials, 200 valid acquisition trials, and 200 valid test trials, the latter consisting of 100 go and 100 no-go trials.

### Results

#### Acquisition Phase

Trials with response omissions (Experiment 3A, 0.7%; Experiment 3B, 1.5%) or anticipations (Experiment 3A, 2.1%; Experiment 3B, 2.5%) were excluded. In Experiment 3A, response choices did not deviate from chance—49.8% versus 50.2%,  $SE = 0.5$ ,  $t(11) = 0.53$ —but in Experiment 3B, left responses were significantly preferred to right responses—52.2% versus 47.8%,  $SE = 0.6$ ,  $t(11) = 3.93$ . This means that participants performed 104 trials with the left and 96 trials with the right key—a difference that should not affect the results in the test phase.

#### Test Phase

Trials with response omissions (Experiment 3A, 0.6%; Experiment 3B, 0.7%) were excluded, and anticipations did not occur. On average, participants responded in 4.0% (Experiment 3A) and 1.1% (Experiment 3B) of the no-go trials. Data from valid go trials were analyzed as in Experiment 2. Again, there was only a significant main effect of consistency:  $F(1, 22) = 12.44$ ,  $MSE = 547.7$ . In both experiments, consistent responses were preferred (see Figure 4), and their frequency deviated from chance: Experiment 3A, 63.8%,  $t(11) = 3.25$ ; Experiment 3B, 60.1%,  $t(11) = 1.91$ . Again, no reliable effects were obtained for RTs: Experiment 3A, 458 ms versus 459 ms,  $t(11) = -.13$ ; Experiment 3B, 520 ms versus 539 ms,  $t(11) = -1.23$ .

In two further analyses, we compared the response frequencies and RTs of Experiments 2 and 3 as a function of consistency and experiment. For response frequencies, only the main effect of consistency reached significance:  $F(1, 44) = 20.47$ ,  $MSE = 303.6$ . For RTs, only the main effect of experiment reached significance,  $F(3, 44) = 87.14$ ,  $MSE = 6,566.1$ , indicating that the RTs in Experiment 3 were significantly slower than in Experiment 2.

### Discussion

Experiment 3 aimed at increasing response uncertainty in order to prevent premature response decisions and to enable the tone stimuli to influence the outcome of response selection. The results indicate that this attempt was successful. The RT level in Experiment 3 was much higher than in Experiment 2 (459 and 530 ms in Experiments 3A and 3B, as compared with 241 and 221 ms in Experiments 2A and 2B), suggesting that this time, responses were not prepared before the stimulus had been presented and identified. The response uncertainty should have increased the tone's chance to influence response decision and, indeed, responses consistent with the response-tone mapping of the acquisition phase were chosen significantly more often than inconsistent responses, no matter if postresponse tones were presented in the test phase (Experiment 3A) or not (Experiment 3B). Thus, the data support our assumptions that the small consistency effects of Experiments 2A and 2B were not due to insufficient R-E learning in the acquisition phase but rather to premature response selection in the test phase.

### Experiment 4

In Experiment 4, we addressed a perhaps obvious and intuitively plausible objection against the findings of a response bias under free choice. How can we rule out that this bias indicates a deliberate strategy of our participants rather than an automatically induced response activation—as our model assumes? Couldn't it be that the participants intentionally used knowledge about R-E relationships from the acquisition phase to make their response decisions in the test phase?

Before we go into how we attempted to exclude this possibility, we wish to emphasize that such an argument is not as watertight as it seems. First, a significant response bias was observed under mean RT levels as low as 221 ms (in Experiment 2B), and it is improbable that strategic considerations can affect response decision in such a short time. Second, even if knowledge about the former response-tone mapping was used strategically in the test phase, it must have been acquired in the acquisition phase. Thus, the data support at least one of our assumptions, namely that the participants learn about the contingent but irrelevant response-tone relationships in the acquisition phase.

Third, the weight of the strategy argument depends on how one conceives of a strategy. We neither deny that people use strategies nor that these strategies can influence the impact of response-associated stimuli. In fact, we have little doubt that, in principle, our participants would be able to inhibit the tendencies induced by the tones and to do the opposite, or to do nothing at all. Therefore, the participants' decision to give way to tone-induced response tendencies may be an important precondition for the effects we observe. However, our argument relates to what the participants give way to, not to whether they do. That is, what our model predicts is the direction of a stimulus-contingent response bias, not the likelihood of its occurrence.

However persuasive one may find these considerations, we thought that adding an empirical argument would help to make our case even more convincing. Therefore, we sought to show that a stimulus-induced response bias can also occur under cognitively demanding conditions that are likely to work against the applica-

tion of strategic response-decision processes in the test phase. Therefore, we asked participants to perform the same task as in Experiment 3 while counting backward (in the test phase). As we explain later, this created a rather complicated dual-task situation, which our participants found extremely—and sometimes too—difficult to deal with. Admittedly, if under these conditions we found no response bias, this would be difficult to interpret: It may point to an important role of strategies but also to some other side effect of the dual-task situation. However, in case we found a reliable response bias even under these conditions, we could be more confident that this bias was not created by a deliberately used strategy.

### Method

Another 12 (8 female, 4 male) and 12 adults (10 female, 2 male) were paid to participate in Experiments 4A and 4B, respectively. They fulfilled the same criteria as in Experiment 1. The method was the same as in Experiments 3A and 3B, except that the participants performed an additional backward-counting task throughout the whole test phase. The experimenter presented a randomly determined three-digit number, from which the participant started to count backward by three aloud—while performing the required keypress responses—until a criterion of 15 correct answers was reached. Then, or whenever the participant made an error, a new number was presented and the counting started again.

Performing the two tasks simultaneously turned out to be very difficult so that the maximum RT was increased to 1,500 ms, and participants were allowed to make up to 40 errors on the 100 no-go trials and to miss up to 40 responses (the latter being repeated at a random position of the remaining block). Nevertheless, 2 participants had to be excluded from Experiment 4A and 1 from Experiment 4B for responding on too many no-go trials, and 3 were excluded from Experiment 4B because of too many response omissions. Moreover, 2 further participants were excluded from Experiment 4A and 1 from Experiment 4B because they had used one key in more than 75% of the test trials. The data of these participants were replaced by the data of other participants so that the analyses are based on the data of 12 participants in each experiment.

Again, in Experiment 4A, each test response triggered the same tone as in the acquisition phase, whereas in Experiment 4B, the test responses were not followed by a tone.

### Results

#### Acquisition Phase

Trials with response omissions (Experiment 4A, 0.5%; Experiment 4B, 0.8%) or anticipations (1.8% in Experiments 4A and 4B) were excluded. In Experiment 4A, the response frequencies did not deviate from chance: 49.8% versus 50.2%,  $SE = 0.6$ ,  $t(11) = 0.26$ . In Experiment 4B, the participants performed 102 trials with the left key and 98 trials with the right key: 51.0% versus 49.0%,  $SE = 0.4$ ,  $t(11) = 2.34$ .

#### Test Phase

The participants concentrated on the counting task. On average, they named a total of 196 digits ( $SE = 15.2$ ) in Experiment 4A and 190 digits ( $SE = 13.9$ ) in Experiment 4B with error rates of only 4.7% ( $SE = 1.0$ ) and 1.8% ( $SE = 0.4$ ). Statistically, neither the numbers of digits nor the error rates differed between experiments.

From the free-choice data, trials with response omissions (Experiment 4A, 14.6%; Experiment 4B, 11.6%) or anticipations (0.1% in Experiments 4A and 4B, respectively) were excluded. On average, participants responded in 13.9% (Experiment 4A) and 21.5% (Experiment 4B) of the no-go trials. Data from valid go trials were analyzed as in Experiment 2. Again, only the main effect of consistency reached significance,  $F(1, 22) = 14.60$ ,  $MSE = 201.8$ , indicating that response choices deviated from chance in both experiments (see Figure 4). Consistent responses were preferred to inconsistent responses: Experiment 4A, 61.3% versus 38.7%,  $t(11) = 2.96$ ; Experiment 4B, 54.3% versus 45.7%,  $t(11) = 2.98$ . For RTs, a significant main effect of experiment shows that RT in Experiment 4A was significantly slower than in Experiment 4B:  $F(1, 22) = 7.05$ ,  $MSE = 16,282.7$ . Nevertheless, the RTs for consistent and inconsistent choices were about the same in both Experiments: Experiment 4A, 854 ms versus 835 ms,  $t(11) = 1.15$ ; Experiment 4B, 745 ms versus 749 ms,  $t(11) = -0.38$ .

The comparison between Experiments 3 and 4 yielded only a significant main effect of consistency for response frequencies,  $F(1, 44) = 24.98$ ,  $MSE = 374.8$ , and only a significant main effect of experiment for RTs,  $F(3, 44) = 62.06$ ,  $MSE = 12,721.9$ .

### Discussion

The comparison of Experiments 3 and 4 revealed that the dual-task situation had no systematic effect on response selection: Although the response bias was less pronounced in Experiment 4 than in Experiment 3, the bias was reliable in both and did not differ significantly. Given the fact that the backward-counting task must have occupied attentional resources to a considerable degree, working against the application of strategies, these findings suggest that the response bias is automatic.

### General Discussion

The present study was conducted to test several predictions from our two-stage model of the emergence of human action control. A central assumption of the model holds that perceiving several co-occurrences of a self-produced movement and a movement-contingent sensory event leads to an automatic association of the motor code representing the movement and the cognitive code representing the event—even if the event is completely irrelevant to the task at hand. Moreover, the model claims that the emerging associations are bidirectional so that perceiving an event that resembles the acquired action effect will automatically prime the associated action.

The four experiments reported here provide converging evidence in favor of these assumptions. In the forced-choice test phase of Experiment 1, the nonreversal group, which had to respond to the former effect tone by pressing the key that preceded this tone, responded more quickly than the reversal group, which had to respond to the tone by pressing the alternative key. As the group difference was still reliable in Experiment 1B, in which effect tones were no longer presented in the test phase, the acquired R-E associations seem to be rather robust and resistant to extinction. In the free-choice test phase of Experiments 2–4, participants preferred to respond to the former effect tone with the response they had performed to produce this effect. Experiment 3

showed that this response bias increased when premature response selection was prevented by a go-no-go design, and Experiment 4 revealed that the response bias was still present when the participants performed the task while counting backward in the test phase.

Thus, both RT and response frequency data are consistent with the idea of automatic action-effect integration and automatic response activation through stimuli corresponding to learned action effects. In particular, if people perceive a sensory event that they learned to be produced by a certain response, they tend to perform that response more quickly and more frequently than another response associated with an alternative effect. Because this is true even if participants are heavily distracted by another, attention-demanding task, automatic response priming through previously acquired associations is the most likely cause of the obtained results. Thus, the present experiments suggest an automatic acquisition of action-effect knowledge and the impact of this knowledge on action control.

By assuming an associative basis of action control, we place our approach in the context of associative learning theory. Indeed, the designs in our study more or less correspond to those used in the investigation of animal learning, and the performance of our human participants bears obvious similarities to that of rats, cats, and pigeons. In our view, the theoretical connection between our model and associative learning approaches is helpful and potentially inspiring for either side, but it is also important to see that not all of our assumptions and findings are consistent with conventional learning theory. Let us discuss the most relevant difference: The notion of backward use of associations.

Most associative learning theories suppose that associations can only be used in the acquired direction but not "backwards" (see Hall, 1984, for an overview). However, we claim that whenever a stimulus follows a movement in time, the representations of the two events will be associated such that re-perceiving the stimulus will tend to activate the movement. Hence, we assume—and claim to have demonstrated—backward conditioning. It is interesting to note that our findings and their interpretation are in line with several animal studies on instrumental learning that favor the notion of bidirectional R-E learning (i.e., Meck, 1985; Urcuioli & DeMarse, 1996).

One way to account for backward conditioning from a traditional learning-theory approach is to introduce the concept of *expectancies* that are capable of mediating response selection (cf. Greenwald, 1970b; Urcuioli & DeMarse, 1996). Although the effect of a movement will always and necessarily follow this movement, an anticipation of the effect can be formed before the effect is actually perceived and, thus, can precede the movement in time. Such models postulate different codes for the anticipation and the actual perception of a movement effect, and they assume several forward associations between the two effect codes and the response code. Obviously, this is not a very parsimonious way to account for backward effects, and we are not aware of independent evidence supporting it. The two-stage model assumes only one bidirectional association between one code that mediates both the perception and the anticipation of the effect and another code that represents the response. Thus, we think the proposed model is a reasonable and parsimonious theoretical alternative.

It is important to emphasize that, although our two-stage model assumes an associative basis of voluntary action, we admit that

there are other than associative mechanisms in action control, such as rules or computations. We only suggest that simple, associative mechanisms create a basic pattern of relations between cognitive representations, which can then be acted upon by the powerful "higher order" human cognitive processes, such as action planning (cf. Mackintosh, 1997). We further assume that action-planning processes operate on codes of action outcomes or, more precisely, on codes of the sensory consequences of actions. Selecting these codes specifies the action's intended features and characteristics (i.e., the action goal), and activating them leads to the action's actual execution.<sup>2</sup> In other words, actions are controlled by anticipating their effects.

However, if perceiving an event that resembles an action effect really activates the corresponding action to a certain degree, it is open to question why people do not always perform the primed action. Humans are able to overcome automatic response tendencies if these are incompatible with other more important action goals. How is this done? One possible mechanism that could free people from complete stimulus control is *inhibition* (e.g., Diamond, 1990; Tipper, Bourque, Anderson, & Brehaut, 1989), that is, a process suppressing present, but unwanted, response tendencies. Another, not necessarily alternative, control mechanism is *feature binding*, which has been claimed to transform and bind activated action-related feature codes into coherent, executable action plans (Hommel, 1998; Stoet & Hommel, 1999). Whatever the details of these mechanisms, a comprehensive theory of action control certainly requires some more specifications than our two-stage model offers. Nevertheless, we hope that even in its present, preliminary state the model is helpful in coming to grips with the emergence and the goal-oriented nature of voluntary action.

<sup>2</sup> This is, of course, a simplification. If actions are coded in terms of action features and, thus, represented in a distributed fashion, additional mechanisms are required that serve to bind the features belonging to the same action plan (Stoet & Hommel, 1999).

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