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Bernhard Hommel

The cognitive representation of action: Automatic integration of perceived action effects

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Abstract Actions have been assumed to be cognitively represented by codes of relevant action features. Six experiments investigated whether irrelevant action features – conditioned response-contingent auditory events – are also coded and integrated into action codes. Subjects responded to visual stimuli by pressing a left- versus right-hand button or by touching a single key once versus twice. Responses produced certain action effects: tones on the left versus the right or tones of low versus high pitch. After subjects had some practice, an "inducing stimulus" was presented together with the reaction stimulus; this inducing stimulus shared features with the action effect of the correct or incorrect response. If action effects were integrated into action codes, inducing stimuli should activate or prime the associated response. Indeed, substantial effects of correspondence or compatibility between inducing stimuli and irrelevant action effects were found in a variety of tasks. Results are interpreted as evidence for an automatic integration of information about action effects and taken as support of an action-concept model of action-effect integration and stimulus-response compatibility.

Introduction

An old psychological idea has it that actions are cognitively represented by codes of their sensory consequences. Authors such as Lotze (1852), Harleß (1861), or James (1890) stated that in order to perform an intended action, the actor only needs to think of (or imagine) the intended *action effects*[1] to trigger the appropriate movement automatically. This implies that there is a cognitive code, a kind of action concept referring to the features of the event that a particular action might produce, and a motor program (i.e., some kind of memory structure capable of controlling the action's performance) connected to this code. Whenever and by whatever means an action effect code, or an action concept comprising several effect codes, is activated (e.g., by imagination or external stimulation), the motor program is activated, too, at least to a certain degree.

In line with previous applications of some of Lotze's, Harleß's, and James's ideas to phenomena of stimulus-response compatibility (Greenwald, 1970; Kornblum, Hasbroucq, & Osman, 1990; Prinz, 1990), Hommel (1993a, 1996) suggested an action-concept model to account for the Simon effect (Simon & Rudell, 1967). This effect can be observed in tasks where the spatial relationship between stimulus and response varies. Suppose, for example, red and green stimuli signal left- and right-hand responses, respectively: When a red stimulus appears on the left side, responses are faster than when it appears on the right side, and a green stimulus yields faster responses when it appears on the right than on the left. Hence, even though

B. Hommel (✉)
Max Planck Institute for Psychological Research,
Leopoldstrasse 24, D-80802 München, Germany;
e-mail: hommel@mpipf-muenchen.mpg.de;
Fax: + INT. (89) 342473

[1]Throughout this paper, I will use the terms *action feature* and *action effect* interchangeably. One may object that features of an action, such as its location or the effector that is used (denoted as *R* in Fig. 1), should be distinguished from action effects, such as obtaining a reward or causing a crash on the stock market (denoted as *E*). However, actors can experience features (or effects) of their actions only through perception, that is, through perceiving the effects of an action on their sensory organs (Wolff, 1984). This implies that inasmuch as internal action coding is concerned, there is no logical difference between more proximal or even internal action effects, such as on the retina or on joint receptors, and more (temporally and/or spatially) remote effects, such as the echo of a hand-clap. In either case, the actor can only learn something about his or her action by performing a movement and perceiving its effects.

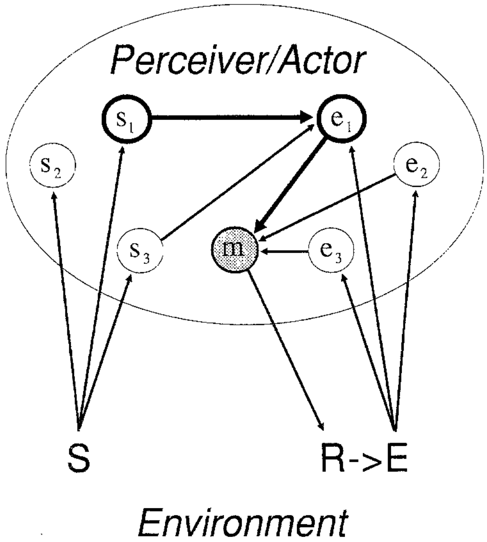

Fig. 1 An action-concept model of S-R compatibility

stimulus location is neither relevant nor informative, spatial correspondence between stimulus and response affects choice performance.

From an action-concept approach, correspondence effects can be explained in the following way: According to the core assumption, actions are cognitively represented by codes of their perceivable effects. Figure 1 depicts an example where there are three of these codes, e_1, e_2, and e_3, all resulting from the actor's perception of the external event(s) E, that again is produced by overt response R. For instance, e_1 may represent the observation that R is carried out on the left side, e_2 may represent perceived response force, and e_3 may code the color of the response key. Let us further assume that R is performed by activating motor program m, that again is set up by activating the associated code of the relevant response feature, say, e_1. In the example, R is a reaction to that attribute of stimulus event S that is represented by code s_1, say the color red, while s_2 and s_3 represent task-irrelevant stimulus features, such as a particular stimulus form or location.

Effect codes refer to – and thus code – perceptual events with particular features. Therefore, these codes will be naturally activated by any perceptual event that resembles – hence, shares features with – the action effects they represent. As activating an effect code will automatically produce some motor activation via *e-m* links, a stimulus will tend to activate an action to the degree it resembles the associated action effect(s). In other words, stimuli will prime "similar" actions (Greenwald, 1970; Kornblum et al., 1990; Prinz, 1990). In our example, the location code of a left-side stimulus, say s_3, would be more similar to the code of the left-hand action (e_1) than of the right-hand action, while the opposite is true for a right-side stimulus. If so, left (right) stimuli would activate left (right) responses via the LEFT (RIGHT) action-effect code. With correspondence, the correct response would be activated via two routes (cf. De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Kornblum et al., 1990), one connecting the relevant stimulus feature with the relevant response (effect) code (s_1–e_1) and one connecting the irrelevant location code with the similar action-effect code (s_3–e_1), so that the response is initiated faster. With noncorrespondence, however, the code of the relevant effect – and thus the correct response – would be activated only by the relevant stimulus code, while the incorrect response would be activated to a certain degree by the irrelevant stimulus, thus producing a response conflict (Berlyne, 1957).

According to the action-concept model, the correspondence or Simon effect (as well as other spatial or nonspatial compatibility effects) critically depends on which kind of action feature is considered in action coding. Only if an objective feature of an action effect becomes part of the action's cognitive representation can the similarity of a relevant or irrelevant stimulus to that action feature be expected to yield an effect at all. In a standard spatial compatibility task with left and right responses, there is little doubt that actions are coded in terms of left and right, as the horizontal dimension is stressed in the instruction and there is no obvious alternative. However, what features would be integrated in less clearly structured situations? Suppose, for example, a left-hand press on a left-side button flashes a light on the right side. In this case, the identical action would produce a left-side event, such as a visible finger movement or an audible button click, as well as a visible right-side event. Which event would be considered in action coding? Would the action be coded simultaneously as LEFT and RIGHT, or can only one spatial code be selected to represent an action?

As speculated by Guiard (1983) and as actually demonstrated by Hommel (1993a), an important factor in these situations is the actor's intention. In the latter study (Exp. 1), a modified Simon task with auditory stimuli was employed, where pressing the left- or right-hand key flashed a right-side or left-side light, respectively. One group received a key-related instruction (e.g., "press the left key in response to the low tone"), whereas another group was instructed with reference to the lights (e.g., "switch on the right light in response to the low tone"). As it turned out, responses were fastest with stimulus-key correspondence in the key group, but with stimulus-light correspondence in the light group. That is, the Simon effect depends on the spatial relationship between the stimulus and the intended action effect, hence the action goal.

The importance of the action goal may suggest that the actor's intention is the only determinant of action coding. For example, the actor may simply register whether the intended action effect, such as the feedback of a movement of the left-hand index finger, the clicking of a left-side key, or the flashing of a right-side light, has really occurred and, if so, integrate the code of this effect into his or her concept of the action. According to this *pure intentional-coding hypothesis*, the intended action effect would be the only effect considered for action coding, so that the spatial relationship between the stimulus and other, goal-unrelated action features should be entirely ineffective.

However, it turned out that if the spatial relations between stimulus and light (the intended action effect), stimulus and key location, and stimulus and anatomical mapping of the hand vary orthogonally, each relation yields a correspondence effect of its own (55, 12, and 5 ms, respectively), even though the effect of the stimulus-goal relationship is great enough to override the remaining effects (Hommel, 1993a, Exp. 2). This suggests that besides intended effects, nonintended action effects are integrated into action concepts as well, which is not consistent with a pure intentional hypothesis. In contrast to this, one may therefore propose an *automatic-integration hypothesis* that several or perhaps all perceived action features are coded and integrated into action concepts automatically (i.e., e_1, e_2, and e_3 in Fig. 1), while intended (and thus attended) action effects may be weighted more strongly (Hommel, 1993a; represented by emphasizing e_1 in Fig. 1). The higher the weighting of a particular code, the stronger its impact on response selection and thus on the activation level of m codes.

While the results of the Hommel (1993a) study do provide preliminary evidence for nonintentional integration of action features, one may doubt whether they really require the notion of automatic integration as a general rule. The circumstances were very special indeed: For example, both relevant and irrelevant action features were defined horizontally, that is, on the same spatial dimension. It might be easier to ignore action features that vary on a dimension that is completely irrelevant to the task. Moreover, some of the irrelevant action features were surely more familiar to the subjects than the relevant feature, and thus were more obvious candidates for action coding. There is evidence that the degree or strength of coding the two hands in terms of left and right is strongly affected by the amount of practice people have in discriminating between left and right effectors. Volleyball players, for instance, who are trained in assigning different functional roles to the left and right hand, produce much greater spatial S-R compatibility effects than soccer players (Castiello & Umiltà, 1987). Thus, one may argue that while subjects will have lifelong experience in discriminating between and in using their two hands, flashing small red lights by pressing certain buttons is not that common to them and thus may require more practice to provide a real coding alternative than the few hundred trials in the Hommel (1993a) study. In other words, if subjects failed to ignore certain irrelevant features, this may simply reflect their tendency to prefer familiar action features or effects over new, artificial action effects.

Table 1 Overview of the critical dimensions of relevant stimuli, irrelevant (inducing) stimuli or stimulus features, responses, and response-contingent stimuli (action effects) in Exps. 1–5. Note that except for Exp. 1, the only feature overlap is between inducing stimuli and action effects

Experiment	Relevant stimulus	Inducing stimulus	Response	Action effect
1	Color	Color location	Location	Tone location
2	Color	Color location	Number	Tone location
3	Letter	Tone pitch	Location	Tone pitch
4 and 5	Color	Tone pitch	Number	Tone pitch

Thus, there may have been several factors in the Hommel (1993a) study that worked against purely intentional action coding, so that irrelevant action features might have become integrated only because of suboptimal coding conditions. It may well be that more optimal conditions would permit action coding exclusively in terms of the relevant action feature, thus ruling out the general notion of automatic integration. In the experiments of the present study, it was attempted to provide such optimal conditions. As in the previous experiments, simple two-choice responses were coupled with artificial "action effects," that is, with certain response-contingent events. These action effects were always auditory, with tone location being the critical effect feature in Exps. 1–2 and tone pitch in Exps. 3–5 (see Table 1 for an overview). In contrast to the prior study, each artificial effect was completely irrelevant to the task, that is, it was neither emphasized in the instruction nor informative in any sense. Therefore, the subjects had not the slightest advantage through coding or attending these action-contingent events. If under these conditions action effects were still integrated into action concepts, this would provide strong evidence for the automatic-integration hypothesis.

Table 1 gives an overview of the stimuli, responses, and action effects[2] used in the present study, and Fig. 2 depicts their assumed theoretical roles. In each experiment, there was a relevant two-alternative stimulus feature (corresponding to s_1 in Fig. 2), color or letter identity, which signaled a two-choice response that was

[2]For convenience, I will often refer to experimentally introduced response-correlated stimuli as action effects, action effect stimuli, or response-contingent stimuli. I should emphasize, however, that this does not imply that these were the only effects of the actions. According to the approach defended here, *any* perceivable consequence of an action counts as action effect (see Footnote 1).

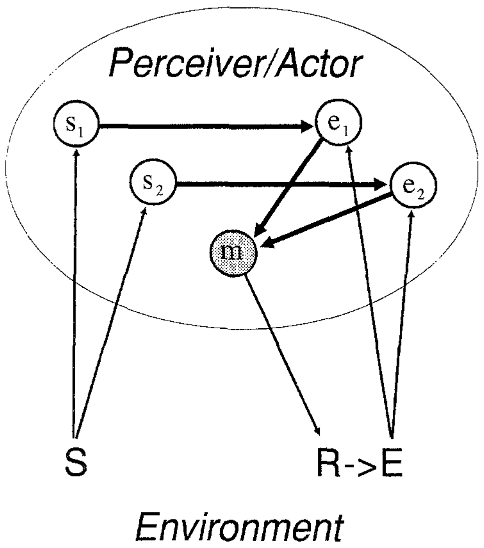

Fig. 2 Roles of relevant stimulus, irrelevant (inducing) stimulus, response, and response-contingent stimulus (action effect) in this study according to an action-concept approach

defined by location or number (e_1). Each response produced a particular auditory action effect (e_2), a tone on the left versus right side or of high versus low pitch. According to the action-concept model, these action effects should become part of the response-controlling action concept and thus should be associated with the respective response. Consequently, a particular response should be activated to a certain degree by presenting a stimulus that shares a feature with the action effect produced by that response.

In this study, such "inducing stimuli" (s_2) were presented together with the relevant stimulus, either as an irrelevant dimension of the relevant stimulus or as a different, irrelevant stimulus appearing simultaneously with, or in close temporal proximity of, the relevant stimulus. The critical feature of the inducing stimulus always overlapped with the critical feature of the action effect (see Columns 3 and 5 in Table 1). Thus, there were conditions of correspondence or compatibility between inducing stimulus and action effect, such as with the pairing of a left-side stimulus and a left-side action effect, and conditions of noncorrespondence or incompatibility, such as with pairing a left-side stimulus and a right-side action effect.

It is important to note that, with the exception of Exp. 1, these were the only existing compatibility relationships, that is, there was no feature overlap whatsoever between relevant or irrelevant stimulus and the response. This is a theoretically interesting situation, inasmuch as no S-R compatibility theory available so far would predict an effect here. Translation approaches, such as those of Fitts and Seeger (1953), Proctor, Reeve, and Van Zandt (1992), or Wallace (1971), typically focus exclusively on how the relevant stimulus information is related to the relevant response code, without taking irrelevant response attributes into consideration. The dimensional overlap model of Kornblum et al. (1990) would not exclude the coding and an impact of irrelevant response features, yet the authors are completely silent as to where response codes come from in general and whether features other than those that are movement-related, such as response-contingent tones, are considered in response coding in particular. Even in the work more directly involved with response-coding issues (Castiello & Umiltà, 1987; Gopher, Karis, & Koenig, 1985; Klapp, Greim, Mendicino, & Koenig, 1979), irrelevant response features have not been an issue. Therefore, from existing compatibility models, an effect of response-contingent, but movement-unrelated stimuli would hardly be expected. However, should the action-concept model and the automatic-integration hypothesis presented here be correct, the feature overlap between the irrelevant stimuli and the action effects should clearly produce a compatibility effect of its own. If the action effects were, in fact, automatically integrated into action concepts, stimuli similar to an action effect should activate the response associated therewith. If so, (inducing) stimulus-action effect compatibility (hence, s_2–e_2 overlap) should produce faster reaction times than would incompatibility.

Experiment 1

Experiment 1 was a kind of control experiment suggested by an equivocal result of the Hommel (1993a) study. In that study (Exp. 1, key instruction), two groups of subjects were instructed to press a left or right key in response to a low or high tone, respectively, thereby flashing a light on the same side or on the opposite side of the key. As was expected, responses were faster if the low tone appeared on the left side and the high tone appeared on the right side, hence if stimulus and response key spatially corresponded. However, although the instruction did not refer to the lights in either group, the key-light mapping modified this effect: Responses tended to be less affected (hence, facilitated or interfered with) by spatial stimulus-key correspondence (or noncorrespondence) with opposite-side than with same-side action effects. This finding is actually expected from an automatic-integration hypothesis: In the opposite-side group, the left-side flash should be automatically integrated into the action concept controlling the right-hand response, while the right-side flash should be integrated into the left-hand action concept. Consequently, each stimulus location would produce some activation of either action concept. A left-side stimulus, for instance, would activate the left-hand response via the effect code referring to key location, and the right-hand response via the effect code referring to light location. Assuming that due to the key instruction, key-related effect codes are weighted more strongly, stimulus-key correspondence would still yield faster responses than noncorrespondence. However, as stimulus-key correspondence would always imply stimulus-light noncorrespondence and vice versa (owing to the crossed light-key mapping), net facilitation or interference would be smaller than with same-side effects.

Although the effect of opposite-side action effects could be seen as providing some support for the automatic-integration hypothesis, it was unfortunately not quite significant in the Hommel (1993a) study. Considering the stimuli used, this is not too surprising. As the action effects were visual and the reaction stimuli were auditory, some subjects may have been tempted to close their eyes or use some equivalent way to filter out the task-irrelevant action effects. Moreover, visual stimuli may have poorer attention-attracting capabilities than auditory stimuli (Posner, Nissen, & Klein, 1976), so that visual action effects could be much easier to ignore than auditory effects, even with one's eyes open. Consequently, Exp. 1 aimed at repeating the original experiment with action effects that are less likely to be ignored or filtered out. A simple way to do this is merely to exchange the modalities of stimuli and action effects, so I employed visual reaction stimuli and auditory action effects. There was only one group of subjects, and all were instructed exclusively in terms of key location. Action-effect tones on the opposite side of the response were present in one half of the experiment, but were absent in the other half. If perceiving the auditory effects really leads to an automatic integration into the action concept representing the correlated response, the stimulus-key correspondence effect should be smaller with present than with absent action effects.

As a further test of a strong automaticity assumption, the intensity of the action effects was also varied. If the integration of irrelevant action effects were fully automatic, integration as such should not depend on the saliency of the effect, as long as it is clearly perceivable. Alternatively, one might assume that more salient features attract more attention and thus are weighted more strongly in the action concept. If so, more intense action features should have a more pronounced impact on (and thus the decrease of) the standard stimulus–key correspondence effect.

Method

Subjects. Forty adults (16 female, 24 male) were paid to participate in single sessions of about 45 min. They reported having normal or corrected-to-normal vision and audition and were naive as to the purpose of the experiment.

Apparatus and stimuli. Subjects were seated at a table in a dimly lit cubicle, facing an Eizo Flexscan monitor from a viewing distance of about 60 cm. Stimulus presentation was controlled by a Hewlett Packard Vectra computer that was interfaced with a Data Translation 2821 card for analog output. Visual stimuli were a white asterisk, serving as central fixation point, and red and green $1.0° \times 1.7°$ color squares, appearing 1.3° to the left and the right of the center (center to center). Auditory stimuli were 500 Hz sinus tones of 55 dB (low intensity) or 70 dB (high intensity) as measured from viewing distance, presented through one of two loudspeakers mounted at eye level 52° left and right of screen center. Subjects responded by pressing the left- or right-hand shift key of the computer keyboard with the corresponding index finger.

Procedure and design. The verbal instruction explained the presence of tones in the experiment as an attempt to distract the subjects from their task. It was pointed out that tones would not be informative in any sense and should be completely ignored. The left and right response was mapped onto the red and green stimulus, respectively. For one-half of the subjects, the auditory action effect was presented during the first half of the experiment only, while for the remaining subjects it was presented during the second half only. Each trial started after an intertrial interval of 2,000 ms with a 500 ms presentation of the fixation asterisk, followed by a 100 ms blank interval. The visual stimulus was then presented for 120 ms and the program paused up to 1,000 ms to wait for a response. In the case of a response, the auditory action effect was presented for 50 ms through the loudspeaker on the opposite side of the key being pressed. Pressing the wrong key counted as an error, and trials with latencies exceeding 1 s were considered as missed. Both kinds of trials were recorded and then repeated at a random position during the remainder of the block. If subjects felt confused or distracted, they could delay the following stimulus presentation by keeping the key pressed down.

There were four within-subject conditions, consisting of the combinations of two stimulus locations and two response locations. Intensity (high or low) and the order of presence/absence of the auditory action effect was varied between subjects, so there were 4 groups of 10 randomly assigned subjects each. Subjects worked through 40 miniblocks (5 practice, 35 test), each consisting of a randomly mixed combination of the two stimulus locations and the two stimulus colors (or response locations).

Results and discussion

Missed trials (0.4%) were excluded from analysis. For each subject, mean reaction times (RTs) and percentages of error (PEs) were calculated as a function of S-R correspondence condition and presence/absence of auditory action effect. An ANOVA of the RTs with intensity as a between-subject factor yielded a highly significant main effect of correspondence, $F(1, 38) = 75.40$, $p < .001$, that was modified by an interaction of correspondence and presence of action effect, $F(1, 38) = 6.68$, $p < .05$. Overall, correspondence produced faster responses than noncorrespondence (409 vs 432 ms), but this effect was smaller when auditory action effects were present (410 vs 428 ms) rather than absent (408 vs 436 ms). A similar result pattern was produced by the PE analysis, showing a highly significant main effect of correspondence, $F(1,38) = 16.05$, $p < .001$, modified by an interaction with presence/absence of action effects, $F(1, 38) = 4.88$, $p < .05$. Correspondence yielded smaller error rates than did noncorrespondence (2.9% vs 4.4%), but this effect was less pronounced in the presence (3.5% vs 4.2%) than in the absence (2.3% vs 4.6%) of action effects.

The results are very clear in demonstrating a purely automatic integration of goal-unrelated action effects. As expected, the presence of these effects reduced the correspondence effect in both reaction times and errors, showing that opposite-side action effects do have some impact on the spatial coding of the response. As either action concept comprised LEFT as well as RIGHT codes, left and right stimuli activated both responses, thus reducing the advantage of S-R correspondence and the disadvantage of noncorrespondence as compared to more standard conditions where all action effects are located on the same side.

Interestingly, this reduction did not depend on the action effect's intensity ($p > .5$, $p > .7$, for RTs and PEs, respectively). This is not consistent with the idea that more salient action features are more strongly weighted in the action concept, inasmuch as saliency can be defined purely in terms of stimulus characteristics; instead, it suggests a pronounced automaticity of integration. However, it is important that irrelevant opposite-side action effects did not eliminate the correspondence effect, which implies that although each stimulus activates either action concept, it activates them to a different degree. As already pointed out, the approach of Hommel (1993a) predicts that codes of task-relevant action effects – referring here to the effector or key location – are weighted more heavily than the parts of the action concept representing task-irrelevant effects. Accordingly, left-hand responses with auditory opposite-side effects would be represented by a strong LEFT code and a weaker RIGHT code, while the action concepts of right-hand responses include a strong RIGHT code and a weak LEFT code. A left-side stimulus would thus activate the left-hand response concept more than the right-hand one. The result would be a diminished, but not eliminated, correspondence effect with opposite-side action effects, which is exactly what we obtained. Thus, if saliency is defined not in terms of physical stimulus characteristics (alone) but with reference to the actor's intention, saliency does have an effect.

Experiment 2

Experiment 1 adds to the preliminary evidence provided by the Hommel (1993a) study that experimentally induced, artificial action effects are coded and integrated into something like action concepts. According to our reasoning, this integration process should by no means be confined to spatial tasks, that is, tasks with spatially defined responses. Thus, in order to extend the scope of our tasks, subjects were asked to respond in Exp. 2 by touching a single response key once or twice. Action effect stimuli were tones, like in Exp. 1, though the ineffective intensity manipulation was dropped. Touching the response key once produced a, say, left-side tone, while touching it twice produced a right-side tone. The task started with an extended learning phase where the responses produced their associated effects, although the visual stimulus only appeared in the center of the display. During this phase, subjects were expected to learn the response-effect contingency and integrate the action-effect tones, so that the one-touch response would also become a LEFT response, and the double touch a RIGHT response. In the experimental phase that followed, the visual reaction stimulus was presented randomly on the left or right side, so that it corresponded to the action effect of the correct or the incorrect action. According to the action-concept model, this should activate the correct or incorrect response via its associated action concept and thus lead to facilitation or interference, depending on the correspondence condition. That is, it was straightforwardly expected that spatial correspondence of inducing stimulus and action effect would allow for faster responses than would noncorrespondence.

Method

Twelve adults (9 female, 3 male) who fulfilled the same criteria as in Exp. 1 were paid to participate in single sessions of about 20 min. Apparatus and stimuli were the same as in Exp. 1, except that acoustical stimuli always measured 55 dB and responses were given by touching a touch-sensitive metal plate mounted on a wooden board with the index finger of the preferred hand. Half of the subjects responded to the red and green stimulus by touching the response key once or twice, respectively, while the other half received the opposite stimulus-response mapping. For one half of the subjects, responding once and twice produced a 50 ms tone on the left or right side, respectively, while the other half had the opposite mapping of tone location upon responses. The verbal instruction described the action effect tones as uninformative in any way.

The experiment started with the practice phase, where the visual stimulus always appeared at screen center. Responses already produced their associated action-effect tones. There were 4 practice blocks, each consisting of 25 replications of the 2 stimulus-response alternatives (= 50 trials). A short break followed, during which the subjects were informed that the stimulus would now appear randomly on the left or right side. Then they worked through a block of 80 experimental trials, consisting of 20 replications of the 2 stimulus locations (left vs right) and the 2 responses (one vs 2 touches). Trials were ordered randomly, except that no more than 5 repetitions of the same condition were allowed within practice blocks, and no more than 3 within the experimental block.

A double response was counted if a second response onset was registered during an interval of 300 ms following the offset of the first response; otherwise, a single response was counted. Responses faster than 150 ms counted as anticipations and those with latencies exceeding 1 s counted as misses. The remaining procedure was as in Exp. 1.

Results and discussion

Missed trials (0.1%) and anticipations (0.4%) were excluded from analyses, and mean RTs and PEs were calculated for each subject as a function of correspondence or noncorrespondence between inducing stimulus

Table 2 Summary of mean reaction times (RTs, in ms) and percentages of errors (PE) in Exps. 2–5 as a function of correspondence (C) and noncorrespondence (NC) between inducing stimulus (reaction-stimulus location or tone pitch) and response-contingent stimulus (i.e., action effect: tone location or tone pitch). Reaction-time effect sizes (NC-C) are in the last column

Experiment	Measure	C	NC	NC-C
2	RT	375	384	9
	PE	0.8	2.3	
3	RT	388	403	15
	PE	3.8	4.4	
4	RT	310	315	5
	PE	1.6	2.3	
5a	RT	456	470	14
	PE	2.1	2.3	
5b	RT	369	379	10
	PE	3.5	2.6	

and action effect (see Table 2). The correspondence effect was significant in RTs, $F(1, 11) = 13.11$, $p < .005$, but was not significant in error rates ($p < .11$).[3]

This outcome agrees with the expectations from an action-concept model. Although there was no feature overlap between relevant or irrelevant stimulus and the response, the overlap between irrelevant stimulus and response-contingent action effect produced a compatibility effect. The fact that this effect occurred although the action effect was completely irrelevant to the task provides strong support for the automatic-integration hypothesis. It seems that even entirely useless events are integrated into some kind of memory structure involved in response selection, if they only accompany the response.

Experiment 3

Experiment 2 provided evidence for the assumption that effects of correspondence between irrelevant stimulus features and conditioned action effects do not depend on responses being defined in spatial terms. However, the correspondence relation itself was still defined spatially, leaving unanswered whether correspondence effects can be generalized to other dimensions. Experiment 3 was carried out to overcome this limitation. Though left and right responses were used, the irrelevant stimulus features as well as the action effects did not vary on a spatial dimension, but were low- and high-pitched tones. By pairing responses with tones, the tones should become part of the corresponding action concept. If so, presenting a compatible or incompatible tone together with the reaction stimulus proper should activate the correct or incorrect response, this facilitating or interfering with response selection, respectively.

Method

Twelve adults (10 female, 2 male) who fulfilled the same criteria as in Exp. 1 were paid to participate in single sessions of about 20 min. The apparatus was the same as in Exp. 1. All visual stimuli were white and appeared at the center of the screen. An asterisk served as a fixation mark, and the uppercase letters *O* and *X* as reaction stimuli. Auditory stimuli were low (200 Hz) and high (500 Hz) sinus tones of 100 ms duration, presented simultaneously through the left and right loudspeaker (66 dB). Tones were used as action effects mapped onto response keys and as inducing stimuli accompanying the reaction stimulus. Responses were given by pressing the left- or right-hand shift key of the computer keyboard with the corresponding index finger.

One-half of the subjects responded to the *O* and *X* by pressing the left and right keys, while the other half received the opposite stimulus-response mapping. For one-half of the subjects, pressing the left and right keys produced the low and high tones, respectively, while the other half had the opposite assignment of tones upon keys.

A practice trial started after an intertrial interval of 1,500 ms with a 500 ms presentation of the fixation mark, followed by the visual stimulus, which appeared for 150 ms. In case of a response, the associated auditory action effect was presented. Remaining procedural details were as in Exp. 2. Experimental trials differed only in that a low or high tone (i.e., an inducing stimulus) appeared simultaneously with the visual stimulus.

The design was virtually identical to that in Exp. 2: There were 200 practice trials without inducing tones (2 S-R pairs × 100 replications) and 80 experimental trials with low- and high-pitched inducing tones (2 S-R pairs × 2 tones × 20 replications). Trial ordering was random, except that the same condition was repeated no more than 5 times in a row.

Results and discussion

Missed trials (0.6%) were excluded from the experimental trials, and mean RTs and PEs were calculated analogously to Exp. 2 (see Table 2). The effect of correspondence was significant in the RT analysis, $F(1, 11) = 7.85$, $p < .05$, but not in the error analysis ($p > .4$). As expected, responses were faster with correspondence than with noncorrespondence, that is, if the pitch of the inducing tone matched the pitch of the correct response's action effect. These results demonstrate that effects of correspondence between irrelevant stimulus features and irrelevant action effects are not restricted to spatial dimensions but can occur in other dimensions as well. This suggests that the integration of task-irrelevant action effects into action concepts does not depend on the type of information these action effects provide. Instead, the integration seems to be rather general and nonselective.

[3]An interesting outcome of finer-grained analyses was that there was no indication of an increase of RT with response number, which might have been expected from studies showing a positive correlation between RT and response complexity (Klapp & Erwin, 1976; Klapp, Wyatt, & Lingo, 1974). If anything, this relationship was negative, which also applies to Exps. 4 and 5.

Experiment 4

As a further test of the generality of the effect of correspondence between inducing stimulus and action effect, Exp. 4 aimed at going one step beyond the preceding experiments in eliminating any spatial stimulus and response feature from the task. As the only spatial feature left in Exp. 3 was response location, response number was used as the relevant feature here. Subjects responded to stimulus color by touching the response key once or twice, thereby producing a high- or low-pitched tone. As in Exp. 3, after the learning phase the relevant stimulus was accompanied by a high- or low-pitched tone serving as inducing stimulus.

Method

Twenty-eight adults (12 female, 16 male) who fulfilled the same criteria as in Exp. 1 were paid for their services. The method was identical to that in Exp. 2, with three exceptions. First, the visual stimulus always appeared at screen center. Second, the critical action-effect feature was pitch, as in Exp. 3, not tone position. There was only one speaker, centrally positioned under the monitor, that emitted a 50 ms action-effect tone of 200 or 500 Hz (60 dB), depending on the response (response key touched once vs twice). Third, tones also appeared as inducing stimuli accompanying the visual stimulus, just as in Exp. 3.

Results and discussion

Missed trials (0.1%) and anticipations (0.5%) were excluded from the experimental trials, and mean RTs and PEs were calculated analogously to Exp. 2 (see Table 2). Although correspondence produced faster responses than noncorrespondence, and error rates were lower under correspondence than under noncorrespondence, neither the RT analysis nor the PE analysis yielded a significant effect ($p > .13$ and $p > .27$).

The outcome was certainly unexpected. In contrast to the preceding experiments, there was no effect of correspondence between the irrelevant stimulus and the learned action effect. Since the crucial difference from the preceding experiments consisted in the elimination of spatial stimulus and response features from the task, such a result may indicate that correspondence effects of the present sort depend on the presence of some kind of spatial task characteristics. However, there is an alternative interpretation. Note that the overall RT level in Exp. 4 is about 70–80 ms lower than in the similar Exps. 2 and 3 (see Table 2), most likely because the stimulus always appeared at the center and was easy to discriminate. This suggests the possibility that the relevant stimulus was often identified some time before the accompanying tone, so that responses would have been selected before the inducing stimulus started to produce an effect. Consequently, the lack of a correspondence effect would be a rather trivial outcome of the temporal lead of the relevant over the irrelevant stimulus information, but not an indication of a critical role of spatial task characteristics.

One important implication of such a horse-race hypothesis is that, although relatively fast responses may be unaffected by correspondence, correspondence effects should show up in slower responses. To test this prediction, individual means for each of the five fifths of the rank-ordered RTs (i.e., quintiles) were calculated as a function of correspondence condition (see Ratcliff, 1979, for procedural details) and used as input into a 2 (correspondence) $\times$ 5 (quintile) ANOVA. Apart from the expected main effect of quintile, the interaction of correspondence and quintile was significant, $F(4, 108) = 3.19$, $p < .05$. As shown in Fig 3, there was no effect of correspondence in fast responses, that is, with lower quintiles, but the effect grew with increasing reaction time. As this is exactly what the race interpretation predicts, the failure to find an overall correspondence effect may well be due to the temporal relationship between relevant and irrelevant stimulus information.

Experiments 5a and 5b

According to the proposed horse-race hypothesis, the outcome of Exp. 4 may not reflect the absence of correspondence effects in a purely nonspatial task, but rather the temporal characteristics of coding relevant and irrelevant stimulus information. If so, there are at least two ways to increase the likelihood of an overall

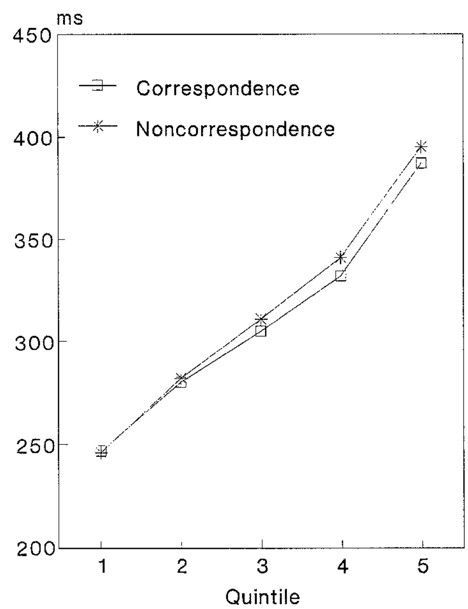

Fig. 3 Exp. 4: Means of individual mean RT quintiles as a function of correspondence or noncorrespondence between irrelevant stimulus and action effect

correspondence effect. One way is to delay the identification of the relevant information so that the lead of the relevant over the irrelevant information decreases or disappears. Consequently, the irrelevant information would no longer be too late to affect response selection, so that a substantial correspondence effect would be expected. In Exp. 5a, identification of the relevant color stimulus was prolonged by making the two stimulus alternatives highly similar. As the same inducing stimulus was used as in Exp. 4, this should considerably decrease the temporal advantage of the relevant over the irrelevant stimulus, so that a correspondence effect should be obtained.

Another way to achieve the same result is to present the irrelevant information some time before the relevant one, as this should compensate for the prior temporal disadvantage of the irrelevant information relative to the relevant. In an attempt to obtain converging evidence, this was done in Exp. 5b, where the inducing tone was presented 100 ms before the visual stimulus. Again, a substantial correspondence effect was expected.

Method

Twelve adults (7 female, 5 male) took part in Exp. 5a, and 24 adults (12 female, 12 male) in Exp. 5b. They fulfilled the same criteria as in Exp. 1 and were paid for their services. The method was nearly identical to that in Exp. 4. However, in Exp. 5a, the two stimulus colors were much harder to discriminate. This was achieved by setting the green, red and blue registers of the graphics card to similar values (0, 55, and 40, respectively, and 0, 55, and 44), thus yielding a reddish and a bluish purple color tone[4]. In contrast to Experiment 4, the stimulus remained visible until the response or 1,000 ms had passed. In Experiment 5b, the same colors were used as in Experiment 4, yet the 50 ms inducing tone was not presented simultaneously with the visual stimulus but 100 ms earlier (onset to onset).

Results and discussion

Missed trials (0.1% and 0.5% in Exps. 5a and 5b, respectively) and anticipations (0.0% and 0.6%) were excluded from the experimental trials, and mean RTs and PEs were calculated as in Exp. 2 (see Table 2). Both experiments showed the same results pattern. In RTs, the correspondence effect was significant for Exp. 5a, $F(1, 11) = 6.48$, $p < .05$, as well as for Exp. 5b, $F(1, 23) = 6.73$, $p < .05$, while error analyses were far from significant for both experiments ($p > .8$ and $p > .24$). As the error effect was numerically inverted in Exp. 5b, it was checked whether a speed-accuracy tradeoff might have occurred. However, the correlation between RT effects and error effects was small and positive ($r = 0.07$), which rules out a tradeoff account. As in Exp. 4, the correspondence effect increased with increasing RT, thus producing correspondence-by-quintile interactions in Exp. 5a, $F(4, 44) = 3.14$, $p < .05$, and in Exp. 5b, $F(4, 92) = 3.33$, $p < .05$.

As predicted, both experiments yielded significant and comparable correspondence effects, and even the interaction with quintile observed in Exp. 4 could be replicated. Therefore, correspondence effects can clearly be obtained in a purely nonspatial task if only the relevant information is slow enough to allow for effects of the inducing stimulus. This supports the proposed race interpretation of the unexpected failure to get a correspondence effect in Exp. 4 and provides a further demonstration of the generality of the effect of correspondence between stimulus and action effect.

Conclusions

The six experiments of this study examined how actions are coded and, in particular, whether completely irrelevant response-contingent action features are integrated automatically into action-related cognitive codes. Experiment 1 showed that a standard Simon effect can be reduced by presenting response-contingent tones in the opposite direction of the response key. Experiment 2 demonstrated a novel kind of compatibility effect: between an irrelevant stimulus feature and an irrelevant action effect. Experiments 3–5 showed that this effect occurs not only in tasks with spatial stimulus or response features or spatial compatibility relationships but is a very general phenomenon that can be obtained through a variety of tasks. Taken together, these findings strongly suggest that action features are coded automatically and become integrated into action concepts, as proposed by Hommel (1993a, 1996). In contrast, the data do not support a pure intentional coding hypothesis, according to which actors have absolute control over action coding, that is, over which features of their actions are cognitively coded. Clearly, intention is not ineffective, which is demonstrated by the fact that compatibility effects can be inverted by manipulating the action intention (Hommel, 1993a) but are only diminished by presenting or withholding irrelevant action effects (Exp. 1). Still, what is affected by intentional processes seems to be the relative weighting of integrated action effects rather than the likelihood of their integration.

According to these considerations, intentional and automatic processes do not exclude each other but cooperate. On the one hand, automatic integration of information about action effects serves to form more or less complete action concepts, in the sense that they

[4]These values were chosen because pilot work in our lab (conducted by Jale Özyurt) suggested that they would produce an RT level at least 100 ms above the level in Exp. 4.

include codes of each perceived action effect. This permits the actor to learn about possible future action goals, that is, to acquire knowledge about what other effects – besides the currently intended one – a particular action produces. In order to reach a novel goal, the actor would then only need to activate the code of another effect of the same action. On the other hand, intentional selection of intended action effects may lead to focusing attention onto the most relevant events, which does not seem to prevent irrelevant action features from being coded, but does seem to modify the relative weights of several (possibly conflicting) codes in order to conform to the actor's intention.

The action-concept model proposed here is not meant to replace, but rather to supplement existing approaches to S-R compatibility, and in doing so it may contribute to closing an important theoretical gap in the understanding of S-R compatibility phenomena. Actually, most theories and models agree – and so does the action-concept model – that compatibility is produced by some kind of overlap between stimulus and response features. Yet, as pointed out in the introduction, very little is known about which features are important and how or when they are coded. Process-oriented approaches like that of Kornblum et al. (1990), Hommel (1993b), or De Jong et al. (1994) merely assume the existence of those feature codes without explaining where they come from, to which parameters of an action they refer, and according to which rules they are formed. True, some coding rules and conditions have been discussed by more structure-oriented models (e.g., Proctor et al., 1992; Umiltà & Nicoletti, 1992; Wallace, 1971; Weeks & Proctor, 1990), but the range of tasks and phenomena covered is usually very small and restricted to spatial features or stimuli with space-related meanings. In contrast, the action-concept model is in some sense more general in assuming that any perceivable effect of an action is automatically processed and cognitively coded, integrated into an action concept, and associated with the motor program that produces both the action and its effects. According to this view, response codes that may or may not overlap with stimulus codes to produce facilitation or interference do not necessarily refer (hence, are not restricted) to features of movements, but may code any kind of event that is somehow connected with a response. In other words, action concepts truly represent actions, not movements, although in order to have an effect at all, action oncepts must be associated with movement-related motor control structures.

In emphasizing the role of action effects in the formation of response-related representations, the present action-concept approach bears an obvious relationship to learning theory. Indeed, the consequences of behavior have been assigned a crucial function in response learning ever since Thorndike (1905) formulated the *Law of Effect*, and later on throughout the operant conditioning literature along the lines of Skinner (1938; see Wilcoxon, 1969, for a historical overview). However, the role of action effects as proposed here differs considerably from that envisioned by operant theorists. First, in operant learning much has been made of the drive-reducing or need-satisfying value of behavioral consequences, with the assumption that more satisfying consequences have a greater impact on learning. However, it is hard to see which drive is reduced and which need is satisfied in presenting task-irrelevant, response-contingent tones. Second, traditional theories of operant conditioning assume that it is an association between S and R that is learned through reinforcement, not one between R and S. The present findings, however, strongly suggest that some R-S learning occurred, this providing the structural basis for the impact of similarity between inducing stimulus and action effect. Third, and relatedly, in traditional theorizing, reinforcing behavioral consequences has been thought to merely provide the "glue" for coupling S and R (Walker, 1969), but not as something that may become part of the emerging knowledge structure itself. Thus, action outcomes are seen as a necessary requirement for learning rather than something to learn about. This neglect of the informational (apart from the motivational) value of behavioral consequences was broadly criticised by Tolman (e.g., Tolman, Hall, & Bretnall, 1932), Bolles (1972), or Baum (1973), who stress the critical role of response-effect relationships – and thus of R-S or S-R-S learning – for learning theory. Although nothing in the present data is inconsistent with the traditional operant S-R learning view, the results provide strong support for the Tolmanian perspective, which is well covered by the proposed action-concept approach.

Altogether, the present findings point to an important role of action effects – and thus response- or movement-contingent events – in the formation of cognitive representations of actions. Clearly, more research is needed on issues of what factors control and constrain action-effect integration, whether the temporal relationship between action and effect is relevant, whether contingency is relevant, and so forth. Nevertheless, the outcome of this study suggests that the proposed action-concept model can be applied to a vast variety of tasks and compatibility phenomena and thus may serve as a promising starting point and a useful theoretical framework for investigating the details of action coding.

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