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Anticipatory Control of Actions

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Abstract

The article presents an overview of notions of anticipatory control of behavior, meaning the control of behavior through advance representations of sensory effects. First, a brief historical overview of concepts regarding sensory effects as the intra-psychic raw material of actions is presented. These concepts are generally subsumed under the term ideo-motor principle. Evidence is presented that associations between actions and their sensory effects are formed even if the effects are not intended by the actor. Specifically, the impact of redundant tone effects on the acquisition of movement sequences is discussed. Further evidence suggests that effect anticipations also influence the selection and initiation of choice responses. This is exemplified above all by a phenomenon referred to as *response-effect-compatibility*. It is then specified that the impact of effect anticipations on the preparation and the execution of responses differs, suggesting that different processes are influenced by them. In conclusion, the importance of sensory anticipations for motor control is acknowledged and a number of open questions are pointed out.

Key Words: behavioral control, anticipation, motor learning

Sensory Anticipations Accompany and Precede Voluntary Behavior

Every movement of the body affects subsequent sensorial input. This is true not only for the complex motion sequences typically considered in sports psychology but also for actions as simple as lifting a finger or turning one's head. Organisms that could not distinguish between sensory changes caused by their own behavior and sensory changes occurring for other reasons would be unable to make any reasonable use of the sensory input at all. This is a fundamental problem for all active organisms. The most probable solution of the problem is the reafference principle (RP, von Holst & Mittelstaedt, 1950). According to the RP, each efferent activation pattern goes along with a collateral activation – the efference copy – which is assumed to carry the information about the sensory effects of the ongoing action. The tenet of the RP says that the efference copy and the reafference cancel each other out (von Holst & Mittelstaedt, 1950, p.467-468) so that higher stages of perception exclusively reflect those sensory changes that are not due to own behavior. Thus, even for apparently motor-unrelated perceptual processes it is mandatory that actions are accompanied by anticipations of their reliable sensory effects.

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Behaviorally induced sensory anticipations, however, do not only serve to stabilize perception but also affect the online control of action execution. Feed forward of sensory anticipations provides a *reference* signal to which the real feedback of the ongoing action can be compared – so that each deviation causes an instantaneous correction of the motor commands to compensate for it (e.g. Adams,1971). Likewise, sensory anticipations also may be used to *substitute* sensory feedback. For example, it has been shown that goal-oriented movements adapt to non-detected goal displacements even if there is neither visual nor proprioceptive feedback from the moving limb (e.g. Bard, Turrell, & Fleury, 1999). Such an adaptation without feedback convincingly suggests that there are other sources of information about the shape of the ongoing movement. Presumably, beginning the movement brings about a forward model of the dynamics of the moving limb by which the end point of the movement is predicted and continuously compared to the target location. If the anticipated destination of the moving limb deviates from the given target location (due to a displacement) a corresponding correction is immediately initiated (cf. Desmurget & Grafton, 2000). Whatever the precise mechanism, it is widely accepted that motor activations call forth anticipations of their reliable sensory effects and that deviations of the actual effects from these anticipations serve to stabilize perception as well as to control execution.

In the present paper, we will discuss evidence for the broader notion that sensory anticipations do not only accompany behavior but that voluntary behavior is also selected and initiated through sensory anticipations.

This notion, that "...a current response is selected on the basis of its own anticipated sensory feedback" (Greenwald, 1970, p.93) is the core of the ideo-motor principle (IMP) already discussed in the 19th century (Harleß, 1861; Herbart, 1825; James, 1981/1890; Lotze, 1852; Münsterberg, 1889). In contrast to feed-forward models, the ideo-motor principle reverses the cause-effect relation: While feed-forward models assume that motor activation calls forth sensory anticipations, the IMP assumes that the anticipation, the mere idea of the desired effects, calls forth those motor activations that have previously been experienced as producing the desired effects.

The IMP necessarily presumes that movements become associated with their contingent effects, as it is impossible to see how effect anticipations could otherwise attain the power to address the movements they are usually effects of. How such action-effect learning may take place was already discussed by Johann Friedrich Herbart (1825) more than 150 years ago:

> Right after the birth of a human being or an animal, certain movements in the joints develop, for merely organic reasons ... each of these movements elicits a certain feeling ... In the same instance, the outside senses perceive what change has come about... If, at a later time, a desire for the change observed earlier arises, the feeling *associated* with the observation reproduces itself. This feeling ... corresponds to all the

> inner and outer states in nerves and muscles through which the intended change in the sphere of sensual perception can be brought about. Hence, what has been desired actually happens; and the success is perceived. Through this, the association is reinforced: the action, once performed, makes the following one easier and so on. (p. 464, shortened translation by the authors).

The latter part of these "classic" speculations (see Hoffmann, 1993; Hommel, 1998; Prinz, 1987, 1992 for recent formulations) concerns a self-evident consideration. It can be taken for granted that goals are associated with the actions that led to achieving them, and that the strength of these associations increases with every additional success. For example, when trying to find out how to switch on a new mobile phone, one might press various buttons and try to memorize the action that was successful. When the mobile phone has to be switched on again, the previously successful action is remembered and every additional success strengthens this association. Thus, the scientific challenge of the IMP is not the formation of associations between actions and goals but rather the claim that actions become associated also to their incidentally produced effects which they did not strive for. Furthermore, it has to be demonstrated that such latently formed associations can also be activated in the reverse direction so that the idea of an effect can address an action through which this effect has only been produced incidentally before. In the next sections, experimental evidence concerning both issues are reported.

The Latent Formation of Behaviorally Induced Effect Anticipations and Their Impact on the Control of Response Sequences

An instructive example of latent action-effect learning is provided by a recent study of Hoffmann, Sebald, and Stöcker (2001). Participants responded to asterisks presented at one of four horizontally aligned locations by pressing one of four response keys which were also horizontally aligned (cf. Nissen & Bullemer, 1987). The keys were assigned to the asterisk locations in a spatially compatible fashion, i.e., the response keys from left to right were assigned to the respective asterisk locations from left to right. Each key stroke triggered the presentation of the next asterisk, so that participants performed a sequence of key strokes in response to a sequence of self-triggered asterisks. In the first two blocks, the sequence of asterisks as well as the sequence of the required responses was random. In six following blocks, a fixed sequence of stimuli was cyclically repeated resulting in a cyclic repetition of a fixed response sequence as well. In a subsequent test block the sequence of stimuli and responses was switched back to random, before, in a last block the fixed sequence was presented again. Typically, reaction times (RTs) and errors continuously decreased with repetitions of the fixed sequence and they increased in the test block. This increase indicates serial learning, as it reveals that the preceding decrease of RTs was due to acquired knowledge about the serial structure of the fixed sequence, which becomes useless if a random sequence is presented again.

Hoffmann, et al. (2001) argued that serial learning should be improved if each key stroke would produce a contingent tone-effect, so that an anticipation of the fixed tone sequence could be used in order to control the fixed key stroke sequence, just like a pianist may control his strokes by an anticipation of the melody to be played (Bangert, Parlitz, & Altenmüller, 1998). In the corresponding experiment, the four tones of a C Major chord were assigned to the keys from left to right in an ascending order (condition Contingent Tones or CT). Consequently, when participants responded to the fixed sequence of asterisks they cyclically produced a fixed sequence of tones that could be integrated into a "melody." There was a first control condition in which no tones were presented (condition No Tones or NT) and a second control condition in which the fixed tone sequence was presented one serial position ahead to the fixed asterisks/response sequence. This manipulation resulted in the same tone sequence but with the tones no longer contingently mapped to the keys (condition Non-Contingent Tones or NCT).

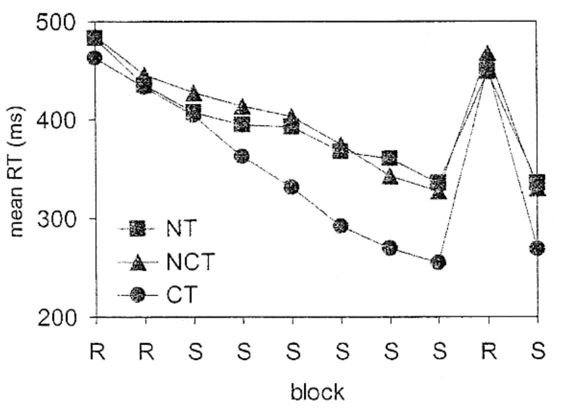

Figure 1. Mean reaction times (RT) in an SRT task in dependence on whether the responses produced contingent tone effects (CT), non-contingent tone effects (NCT), or no tones (NT), plotted against random (R) and structured (S) blocks (after Hoffmann, et al., 2002).

Figure 1 shows the mean RTs for the three groups plotted across experimental blocks. The results indicate that the mere presentation of an additional tone sequence does not affect RTs, as there were no differences between the conditions with no tones (NT) and with non-contingent tones (NCT). In contrast, RTs decreased substantially more when the tones were contingently mapped to the key strokes (CT). As RTs increased in the test block to the same level as in both control groups, the data confirm that the contingent toneeffects improved the acquisition and use of serial knowledge about the fixed sequence. Obviously, key presses and tone effects became associated so that anticipations of the tones gained control over the to-be-executed fixed sequence of key presses, otherwise their impact on response speed would be hard to explain (cf. also Greenwald, 1970; Ziessler 1998; Ziessler & Nattkemper, 2001).

Note that the tone effects were completely irrelevant with regard to the task demands. The fact that the tones, nevertheless, influenced the performance strongly supports the notion that effects need not be intended in order to become associated with the actions they are results of. Rather, it seems that attending the effects and temporal overlap of code activation suffices in order to integrate action and effect representations in a bidirectional connection (cf. also Elsner & Hommel, 2001, 2004).

Subsequent experiments aimed at an elaboration of the impact the contingent tone effects had on performance (Stöcker & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003). In particular, the experiments were aimed at clarifying the mechanisms through which the tones led to faster sequence acquisition and faster responses.

In one study (Stöcker & Hoffmann, 2004), participants practiced short sequences of key presses they had to enter with the ring, middle, and index fingers of both hands. Six element sequences were contrasted with three element sequences. Typically, this kind of experimental setup yields a specific pattern of results called the sequence-length effect: Longer sequences take longer to initiate than shorter ones, that is, participants take longer to press the first key in a longer sequence (e.g. Hulstijn & Van Galen, 1983; Rosenbaum, Gordon, Stillings, & Feinstein, 1987; Verwey, 2003). This is usually interpreted as a sign for time-consuming preprogramming of the sequences, occurring before sequence execution begins. Preprogramming is considered a process by which advance representations of movements are constructed that allow fast execution afterwards, independent of error feedback.

In the study in question, some participants practiced the sequences by responding to visual stimuli, with the instruction to try to memorize the sequences so they would eventually be able to enter them without key-specific stimuli, "by heart." In another group, participants had the same task but their key presses also produced tones of different pitch. Both groups practiced the same sequences, only the presence or absence of tone effects separated them.

In correspondence to the results from the serial-learning experiments reported above, the tone effects again helped acquiring, initiating, and executing the sequences. Interestingly, the tones led, in one experiment, to a significant reduction of the sequence-length effect, that is, participants who experienced tone effects initiated the six element sequence almost as quickly as the three-element sequence (35 ms sequence-length effect vs. 101 ms in the control condition). In another experiment the sequence-length effect in the tones group was also reduced in comparison to the sequence-length effect in the no-tones group (from 112 ms to 24 ms). Thus, preprogramming seems to have benefited from the effects: Longer sequences could be preprogrammed almost as fast as short ones. This is usually the case only after extensive practice (cf. Klapp, 1995), and is interpreted as a sign of movement chunking. Chunked-together movements can be preprogrammed as a single unit, saving preparation time. Converging evidence for this interpretation comes from interresponse time data. As Figure 2 shows, the interresponse time profiles, that is, the profiles of the times between two subsequent key presses within one sequence were far more homogenous in the group producing tone effects than those of the control group. This indicates that the sequence of six single movements is not only efficiently sampled into proper subsequences but also that the formed subsequences are integrated into a representation which comprises the whole sequence. Tone effects seem to aid the development of compact representations for movement control by facilitating chunking of single units into larger groups. This fits well with the evidence presented so far: Tone effects facilitate the generation of anticipatory representations for movement production – keep in mind that initiation times are measured before the first tone effect is presented. These anticipatory representations lead to more efficient preprogramming, faster initiation, and faster execution of the sequences. It is hard to imagine that this could occur without those sensory effects becoming integrated in the respective motor representation or "motor program."

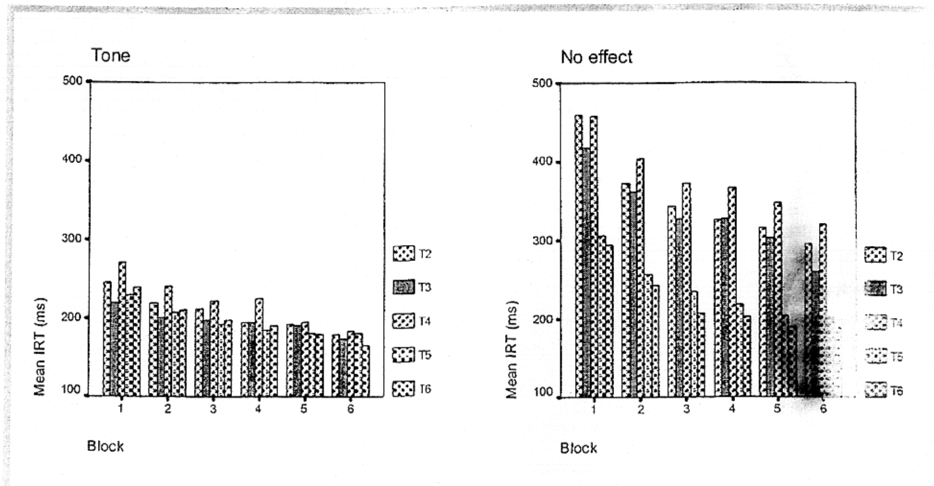

Figure 2. Mean interresponse-times (T2 – T6) for 6 element sequences, shown separately for the groups with and without tone effects.

Effect Anticipations Influence the Selection and the Initiation of Choice Responses

Probably the most challenging assumption of anticipative behavioral control is that actions are exhaustively represented in terms of their reafferences. Consequently, there would be no other way to recruit a movement than by recollecting these effects. In other words, every voluntary movement must be preceded by an anticipation of the movements' sensory consequences.
Kunde (2001) suggested an experimental paradigm for the study of these proposed anticipatory effect codes. He based his argument on well-established findings from stimulus-response compatibility research: In choice reaction tasks with overlapping stimulus-response sets, responding is faster and less error prone with compatible S-R assignments than with incompatible S-R assignments (cf. Kornblum, Hasbroucq, & Osman, 1990). For example, responding to a left stimulus is accomplished faster with a left response than with a right response, and responding to a right stimulus is accomplished faster with a right response than with a left response (e.g. Simon, 1969; Simon, Hinrichs, & Craft, 1970). Kunde reasoned that if generating a response actually requires an anticipation of its sensory effects, similar compatibility phenomena as those between stimuli and responses should manifest between (anticipated) effects and responses as well.

Such Response-Effect (R-E) compatibility effects occur indeed. Figure 3 illustrates an example. Participants were requested to press one of four horizontally aligned keys in response to the presentation of one of four centrally presented color patches. Each key press contingently produced the onset of one of four visual effects, which were horizontally aligned on the screen. In the compatible condition, each key stroke triggered a spatially compatible effect on the screen, whereas in the non-compatible condition the assignments of the effect locations to the key locations were scrambled. As participants had to press the keys to imperative color signals, dimensional overlap existed exclusively between the response set and the set of the response effects. Responding was significantly faster (490 ms vs. 511 ms) and less error prone (4.9% vs. 5.3%) if the keys triggered spatially compatible effects than if they triggered spatially incompatible effects.

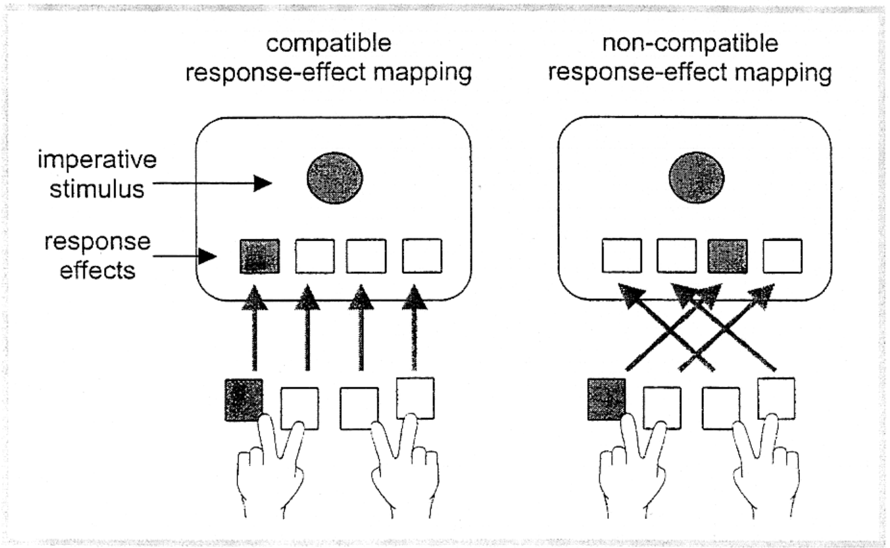

Figure 3. Illustration of spatially compatible as well as incompatible visual effects of key presses as used by Kunde, 2001.

Similar results were obtained with response-effect sets that overlap with respect to intensity (Kunde, 2001), duration (Kunde, 2003), spatial-tonal location (Koch, Keller, & Prinz, this issue), or verbal meaning (Koch & Kunde, 2002). Thus, response-effect compatibility is a phenomenon of broad empirical validity. Importantly, in all these studies response effects were presented only *after* the response had been carried out. Thus, their impact on response latencies strongly suggest that effect representations were activated *before* response onset, hence during response selection or initiation.

Although these results suggest that anticipatory effect codes precede response onset, they do not specify for which aspects of response production such codes are particularly important. To explore this question Kunde, Koch, and Hoffmann (2004) combined the response-effect compatibility paradigm with a response-preparation paradigm. Participants responded to a color stimulus with a soft or forceful key press. In the compatible condition, soft responses produced a quiet tone and forceful responses produced a loud tone, whereas in the incompatible condition this mapping was reversed. In most trials the response was validly cued ahead of the response signal allowing participants to prepare the afforded response in advance. In the remaining trials there was a non-informative neutral cue.

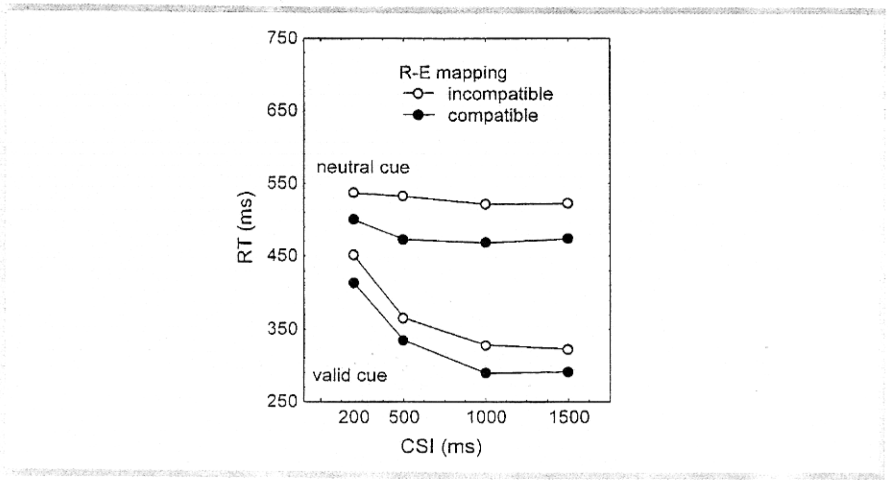

Figure 4. Mean response times in dependence on cue validity for trials with compatible vs. incompatible response-effect-mapping, plotted over the different cue-stimulus-intervals.

Figure 4 depicts the reaction times for compatible and incompatible R-E mappings, as a function of cue type (valid vs. neutral) and cue-stimulus interval (CSI: 200 ms...1500 ms). Three results are particularly important: First, cuing was effective. With valid cues RTs decreased the longer the CSI. After 1000 ms, response preparation seems to be completed as a further prolongation of the CSI provokes no further response acceleration. Second, there is a significant response-effect compatibility effect: responses with compatible effects are faster than responses with incompatible effects. Finally, and most important, the compatibility effect is reduced in valid trials in comparison to neutral trials but is still significant even in trials in which the required response is already selected and only remains to be initiated. This compatibility effect for completely prepared responses convincingly demonstrates that response effects not only have an impact on the selection of the response but also on its initiation (cf. Brass, Bekkering, & Prinz, 2001; Kunde & Weigelt, 2003, for similar observations).

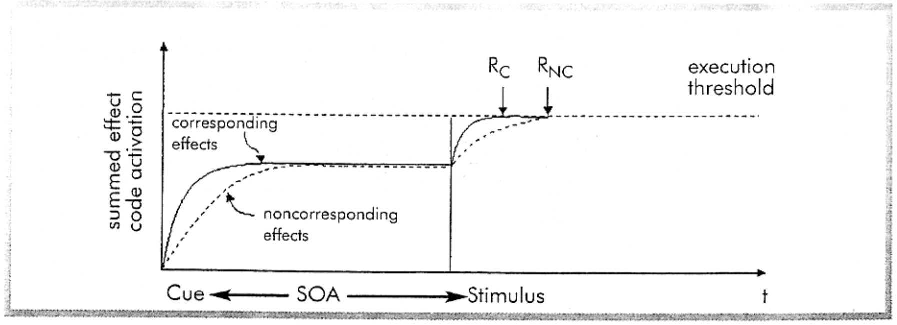

Figure 5. A simple threshold model to illustrate the assumed impact of corresponding and non-corresponding effects on response selection and initiation.

These results accord with a simple threshold model of effect-based response production (Figure 5). The model assumes that motor responses are recruited by increasing the activation of the distal (e.g. auditory, visual) and proximal (e.g. proprioceptive, tactile) response-representing effect codes. If overall code activation exceeds a certain execution threshold, the effect-associated motor patterns are automatically emitted. Distal and proximal effects prime each other by virtue of similarity, which allows mutually compatible effects to reach execution threshold earlier than mutually incompatible effects. If response execution has to wait for the presentation of a go-signal, as in the described experiments, activation must be stopped intentionally to avoid premature responding. After go-signal presentation, response times reflect the residual activation increase necessary to push the motor pattern over the execution threshold. This results in still significant but numerically reduced influences of response effects. This admittedly simple model certainly requires further specification, but even in this preliminary state it allows some testable predictions. For example, response production is assumed to proceed simultaneously to stimulus processing, rather than having to wait until stimulus processing is completed (e.g. Kornblum, et al., 1990; Sanders, 1980). Therefore, an orthogonal manipulation of the ease-of response production by effect compatibility and of the ease-of-stimulus processing, e.g, by varying stimulus quality, should exert interactive rather than additive influences on response times (cf. Sternberg, 1969) — a prediction that has been confirmed in a recent series of experiments (Kunde, Paelecke, & Kiesel, 2004).

Effect Anticipations Have a Different Impact on the Preparation and the Execution of Responses

So far we focused on the impact of action effects on the mental antecedents of motor actions apparent in response times. Yet, sensory effects also affect the way actions are carried out, albeit in a different manner.

Figure 6 illustrates an example. The figure shows the peak forces for required strong and soft key presses with either quiet or loud tone effects. The data reveal a remarkable difference to the impact of response-effects on RTs: Loud effect-tones reduce peak forces in comparison to quiet effect tones, irrespective of whether a strong or a soft key press is required. Thus, there is no longer a compatibility effect as with response latencies but a contrast effect: Intense effects reduce response intensities and weak effects increase response intensities. Moreover, response times and peak force are uncorrelated on a trial-by-trial basis. These findings suggest that with response onset a new process evolves where anticipated tone effects have a different impact on response execution than they have on response selection/initiation. This impact can be described as contrast bias: Anticipated quiet tones generally increase response force, and anticipated loud tones decrease response force. Similar contrast effects have been found for responses and effects of varying duration. Short tones increase response duration and long tones decrease response duration (Kunde, 2003).

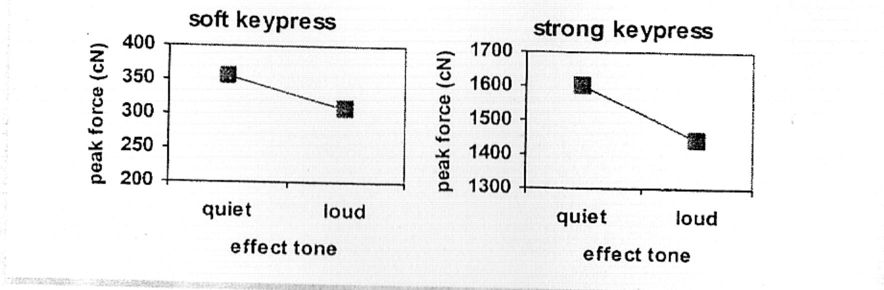

Figure 6. The impact of quiet and loud effect tones on the peak forces of intended soft and strong key presses (after Kunde, et al., 2004).

How can one explain these contrasting influences? We suggest that the proximal (tactile, proprioceptive) response intensity that has been anticipated prior to response onset (i.e. for response selection), serve as a reference value for response execution control. The perceived feedback is continuously compared with this reference value and force output stops when feedback and reference value match. Distal (e.g., auditory) effects could affect this comparison in two ways: First, distal effects might affect the setting of the proximal reference value. Conceivably, proximal and distal intensity become combined into an overall reference value (cf. Figure 7a). For a given intended overall intensity, proximal intensity (and thus force) must consequently be higher the lower the distal component of the combined reference value is, and vice versa. A similar account was quite successful in explaining contrasting influences of delayed auditory feedback on the timing of actions (Aschersleben & Prinz, 1997). Second, anticipated distal effects might bias the feedback of proximal consequences (cf. Figure 7b). Following this view, the perceived proximal feedback is biased towards the anticipated distal intensity. In other words, a given force output "feels" more intense when expecting a loud tone than when expecting a quiet tone. As a result, force output stops earlier with a forthcoming loud tone than with a quiet tone, and vice versa. These accounts are not mutually exclusive. Thus distal effects might affect the setting of a proximal reference signal (Figure 7a) as well as the feedback of proximal reafferences (Figure 7b).

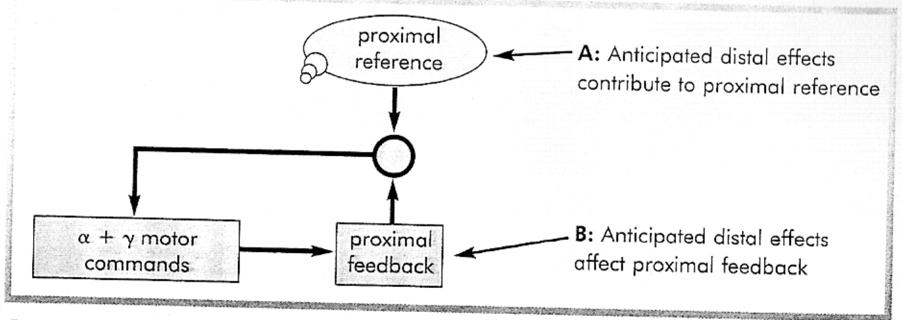

Figure 7. Illustration of the presumed impact of irrelevant distal response effects on execution control.

Review and Outlook

We started with the statement that sensory anticipations not only essentially accompany voluntary behavior but also precede it. That voluntary behavior has to be preceded by an "idea" of the to-be-attained goal is self evident. How could a behavioral act be called goal oriented if the goal is not present in advance? Thus, the theoretical challenge is not the claim that an idea of a to-be-attained goal precedes voluntary behavior, but rather that anticipations of the concrete sensory consequences determine the motor activations through which the corresponding behavior is generated.

The notion that voluntary behavior is determined by the anticipation of its sensory effects can be traced back more than 150 years. In the 19th century, the ideo-motor principle was a common speculation on the determination of voluntary behavior (e.g. Harleß, 1861; Herbart, 1825; James, 1981/1890; Lotze 1852; cf. also Stock & Stock, 2004). At the beginning of the 20th century, however, the IMP was discredited, since the notion that behavior might be determined by mental states like an idea was a sacrilege for the rising school of behaviorism. Only recently the notion of an anticipatory control of behavior is being discussed theoretically again (e.g. Hoffmann, 1993, 2003; Hommel, 1998; Prinz, 1987). At the same time, the ideas of anticipatory control of behavior are experiencing substantial experimental elaborations (e.g. Hommel, 1996; Kunde, 2001; Ziessler & Nattkemper, 2001)

In the present paper we discussed some of the available experimental evidence in support of an anticipative control of voluntary behavior. We have shown that intentional acts are also associated with their non-intended effects, and that these incidental effects exert an influence on action generation. When practicing fixed stimulus-response sequences, contingent effects lead to a switch of execution control from the imperative stimuli to the anticipated effects. Moreover, effects like tones that are easily integrated, facilitate the generation of representations for sequence fragments, and thus aid the parsing of the sequence into adequate chunks as well as their integration into a unitary-sequence representation.

In further experiments it was demonstrated that effects influence the selection as well as the execution of responses. If responses and effects share common dimensions, responses with compatible effects are selected and initiated faster than responses with incompatible effects. This corresponding influence of action-effect compatibility on selection and initiation suggests that both processes are based on the same mechanism that can presumably be described as an accumulation of activations. According to the tentative activation model (Kunde, et al., 2004) the selection as well as the initiation of a response is achieved through a gradual activation of effect representations, execution being initiated when a threshold is exceeded (see Figure 5). Corresponding effects from different sensory modalities activate each other while activations of non-corresponding effects interfere. This way, the model explains the finding that responses with compatible effects are selected and initiated faster than responses with incompatible effects.

Finally, it was shown that incidental response effects also influence response execution via a contrast bias: High-intensity effects reduce response intensity while low-intensity effects increase response intensity. Correspondingly, long-lasting effects reduce response duration, while short effects increase it. We assume that this contrast bias is mediated by a modulation of anticipative execution control. Distal effects either affect the setting of a proximal reference value or they bias the proximal reafferences.

Altogether, the given evidence convincingly confirms the impact of incidental distal response effects on the generation of voluntary responses and the control of their execution. Moreover, the reported results allow detailed speculations on the mechanisms by which these influences are mediated. There remain, however, unresolved questions.

Among the numerous issues which are still to be resolved, the conditions under which action-effect relations are latently formed deserves attention. Are actions inevitably associated with all sensory effects that contingently accompany their execution or must certain conditions be met for the latent formation of action-effect associations? In the majority of the reported experiments, it was shown that actions become associated with irrelevant effect-tones which participants did not intend to produce. However, the effect tones were salient as they were the only effects of the to-be-performed actions which could hardly be ignored. Thus, it might well be that only attended effects become associated. Likewise, it remains to be explored to which extent delayed effects also become associated and which degree of contingency is needed for a latent formation of an action-effect association (cf. Elsner & Hommel, 2004).

Another open issue concerns the integration of initial conditions into the representations of actions. It is obvious that contingencies between actions and effects often depend on the given context. For example, pressing the right-mouse button results in very different effects depending on the location of the cursor. However, if the initial conditions are fixed, the effect of a mouse click is almost always the same. Like in this case, the success of most of our actions depends on giving the proper initial conditions. Consequently, the generation of an appropriate action does not only require the anticipation of the to-be-produced effects, but also an anticipation of the initial conditions that usually have to be given for this action to be executed successfully. For example, if one is going to mail a letter one instantaneously looks for a mail box, that is, one anticipates the image of a mailbox as the necessary situational context to accomplish the intended act.

Besides Kurt Lewin (1926), who coined the "mail box" example, the interdependence of "goal anticipations" and anticipations of suitable initial conditions was already acknowledged by Ach (1913). According to him, a voluntary act has to be characterized, besides other features, by an objective moment (gegenständliches Moment) which relates an image of what one strives for (Zielvorstellung) to an image of the situation to which the intention refers (Bezugsvorstellung). There are first data indicating that participants very flexibly adapt referential anticipations (Bezugsvorstellungen) of required responses to the concrete initial conditions, i.e. imperative stimuli, they experience (Kunde, Kiesel, & Hoffmann, 2003). However, we are still far from understanding the learning mechanisms the formation and adaptation of referential anticipations are based on.

Finally and perhaps most important, the processes by which sensory anticipations, i.e., anticipations of afferent activation patterns, are converted into actions, that is efferent activation patterns, are not yet appropriately understood. Saying that the transition from anticipation to behavior is ensured through bidirectional connections between both is rather vague and obscures the associated problems more than solving them. For example, it is obvious that not every anticipation results in action. One can very precisely anticipate the sensory effects which will appear when raising one's right hand without doing so. Thus, the anticipation of sensory consequences does not suffice in order to evoke the corresponding action. James (1981/1890, p.1112) already claimed that "on certain occasions" not only anticipations but also a "fiat" that the anticipated consequences shall become actual is necessary in order to make the body move. However, what is a "fiat" and on what does it depend whether it is needed or not? What opens the gate that lets a fully prepared action be carried out and what prevents its execution despite full preparation?

Another fundamental problem is raised by the great number of degrees of freedom of body movements. Consequently, any particular outcome can be attained by practically innumerable body movements, so that the relations between the efferent activation patterns and the resulting afferent activation patterns which refer to distal effects are almost always ambiguous. In other words, a distal effect can never determine a concrete movement but only a class of possible movements, at best. By which mechanisms are the countless remaining alternatives narrowed down to the movement finally performed?

Thus, we finish with more unsettled issues than we started with. Nevertheless, the evidence given confirms anticipative control as a proper groundwork for further exploration of what is still a mystery: The learning-dependent establishment of structures and processes by which the mind controls the body in such a way that what is desired really happens.

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