ABC: A Psychological Theory of Anticipative Behavioral Control

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Abstract. Almost all behavior is purposive or goal oriented. People behave, for example, in order to cross the street, to open a door, to ring a bell, to switch on a radio, to fill a cup with coffee, etc. Likewise, animals behave to attain various goals as for example to escape from a predator, to catch prey, to feed their offspring, etc. The ABC framework accords with the purposive character of almost all behavior by assuming that behavior is not determined by the current stimulation but by the desired or the 'to-be-produced' effects. For this to work, behavioral acts have to be connected to the effects they produce in such a way that anticipations of effects gain the power to address the behavior that brings them about (often called the ideo-motor principle). Moreover, if action-effect contingencies systematically depend on the situational context, the formed action-effect relations have to be contextualized. Accordingly, the ABC framework assumes the formation of representations that preserve information about which effects can be realized by which behavior under which conditions. In the present article we review some of the empirical evidence in favor of the ABC approach and discuss the structures by which sensory anticipations might be transformed into the motor patterns that move the body to bring the desired effects about.

1 The limits of the information processing approach

In the second half of the last century, information processing replaced behaviorism as the leading approach in theoretical and experimental psychology (cf. [44]). This development was induced by new insights in other sciences in particular in mathematics, communication, and system analyses: Norbert Wiener [63] established "Cybernetics" as a new science for the analysis of informational processes in machines and animals. One year later, Shannon and Weaver [54] provided a mathematical calculus for the measurement of information. Concurrently, Alan Turing [59] discussed intelligence as a feature of computing machines and John von Neumann [61] delivered the architecture for such intelligent machines. All these developments awaked the belief that also humans can be described and analyzed as information processing systems.
This belief in the applicability of the information processing approach on the analysis of psychic processes was strongly nurtured, when Hick [21] reported

that the latencies of simple choice reactions increased linearly with the entropy of the presented stimulus. And when Newell and Simon [46] implemented the first computer program that was able to solve challenging problems, such as the 'Tower of Hanoi', many psychologists became convinced that higher mental processes must be studied from an information processing perspective. Thus, the information processing approach emerged and research efforts henceforward were concentrated on mental processes such as perception, attention, language, reasoning, and memory.

Although the information processing approach overcame the theoretical restrictions of behaviorism on merely stimulus-response relations, the now explored mental activities were still considered as determined or driven by stimulation. For example, in his seminal book "Cognitive Psychology", Ulric Neisser [45] defined cognition as referring ...to all the processes by which the sensory input is transformed, reduced, elaborated, stored, recovered, and used. Thus, also in the new information processing perspective, the unfortunate doctrine of behaviorism survived, which posits that 'all' starts with the impact of stimuli on the organism. The question of how the stimuli drive behavior was merely shifted to the question of how stimuli are processed in order to create an internal representation of the information they transmit.

In the present article, I propose that this view is misleading if not basically wrong. There are at least two arguments, which put the information processing approach into question.

1. The information processing approach suggests that stimulus information is processed to build a veritable mental representation of the 'information source', i.e. the 'environment'. However, there is no unique environment, which is to be represented. For example, if you look at Figure 1 you certainly will see, i.e. you will mentally re-present, this stimulus as being two interwoven squares. However, there are also eight triangles or the shape of a house with some extra brackets, etc. In general, stimulations from the environment contain information about countless properties from which we always perceive or process only an evanescent part. Thus, the question is not how we, or any other animal, process the given stimuli in order to create a veritable representation of the transferred information, but rather the question is what determines the particular information that is selected for processing.

   If one compares the perception of different species, it becomes obvious that what a species can perceive is primarily determined by the behavioral requirements the species has to face. For example, bats are in particular sensitive for sound waves of 50 kHz because they use such waves for echo-navigation and frogs are especially sensitive for small, fast moving dots in their visual field because the dots signal the presence of a potential prey etc. Thus, organism perception is above all determined by the information they need in order to behave successfully.
2. Any movement of our body produces changes in the sensory input the so called reafferences [60]. Whether you move your finger, your eyes, and even if

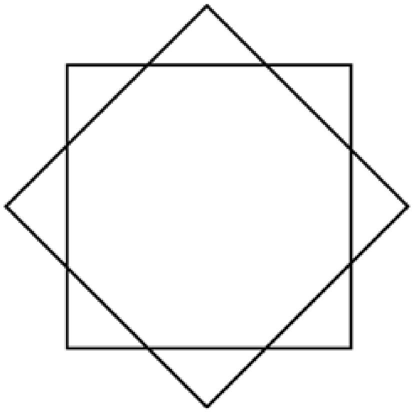

Fig. 1. Two squares, eight triangles, or the outline of a house with additional angles.

> you talk, you produce various new sensory input sorts of sensory stimulation. Accordingly, you have to distinguish which aspects of the current stimulation were produced by yourself and which ones might have other causes. And this is true for any and every animal, even for such primitive organisms like an earthworm: Without distinguishing the sensory consequences of one's own behavior from other sensory inputs, active organisms could not make at all any meaningful use of stimulus information. Thus, every active organism has to learn what the sensory consequences of its own behavior are.

Both arguments emphasize the importance of the interplay between stimuli and behavior instead of the relations between stimuli and representations. Accordingly, one may claim that the primary function of cognition is not the processing of stimulus information but rather the control of stimulus production (cf. also [47]). In the following, I will elaborate on this claim both theoretically and experimentally.

2 The primacy of action-effect learning over stimulus-response learning

According to classical behaviorism, all behavior is finally due to stimulus-response relations and stimulus-response learning is the basis of all behavioral changes [58, 62]. The tenet is indeed supported by countless experiments in animal learning, in particular, by experiments in discriminative conditioning. In discriminative conditioning a particular behavior is reinforced only if stimulus A is present but the behavior is never reinforced if stimulus B is present. In the test it appears that only stimulus A but not stimulus B evokes the formerly reinforced behavior. Accordingly, it is concluded that an associative connection has been formed between stimulus A and the particular response so that the stimulus gained the power to evoke the associated response.

However, the conclusion is premature. For example, if one varies not the stimulus conditions and the reinforcer but the behavior and the reinforcer, it soon becomes obvious that behavior is not determined by stimulus-response but by response-effect relations. Imagine, for example, rats that experience that in the experimental cage chain pulling leads to a reinforcement by some food pellets and lever pressing leads to a reinforcement by a drop of sugar solution. After this experience has made one of the reinforcers, let us say the sugar solution, becomes devaluated by adding something that causes a mild nausea whenever the rats are drinking from it in their home cage. If then the rats again have access to the chain and the lever in the experimental cage, they clearly avoid pressing the lever, which would lead to the meanwhile devaluated reinforcer, whereas they do not hesitate to pull the chain, which would lead to the still valuable food pellets (cf. [9]).

The avoidance of respectively that behavior that would lead to the devaluated reinforcer allows to conclude (1) that the rats have formed associations between the actions and their respective outcomes, i.e. action-effect associations have been formed, and (2) that in the test the behavioral choice is determined by an anticipation of the respectively anticipated reinforcer and not by the current stimulation (i.e. the experimental cage).

Meanwhile countless experiments demonstrated that action-effect relations outrange stimulus-response relations in the determination of animal behavior (e.g. [49, 10])[1]. Surprisingly, in humans' stimulus-response and response-effect learning has been rarely, if ever, directly compared except in a study by Stock & Hoffmann [57], which is shortly discussed next.

Participants get presented one start- and one goal-symbol on a computer screen, both selected from a set of four possible figures (a star, a hexagon, a rhombus, and a "sun", cf. Figure 2). Participants were instructed to find out which one of four possible response keys were to be pressed in order to attain the current goal" in the presence of the current "start". Among others, we varied in one of a series of experiments the feedback (the reinforcer so to say): For half of the participants it was merely fed back whether the current response key led to a "hit" or a "failure". For the other half of the participants, the key presses triggered the presentation of another effect-symbol on the screen, which could either match (a hit) or could not match (a failure) the current goal-signal.

In both cases, simple stimulus-response relations had to be learned as to each of the four start-symbols one of the four keys was assigned, which was always successful, while all other keys failed in the presence of this particular start symbol. Thus, in the presence of a certain start-symbol there was a certain key to press in order to produce the feedback "hit" (in the former condition) or to trigger another presentation of the current goal-symbol whatever it was (i.e. a hit in the latter condition). This seemingly tiny manipulation of the feedback had dramatic consequences for the learning rate (cf. Figure 3): If only "hits" and "failures" are fed back, participants learn very fast that the key to select in order

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[1] This does not mean that the current stimulation lose any influence on behavior as we will discuss in section 4 of this paper.

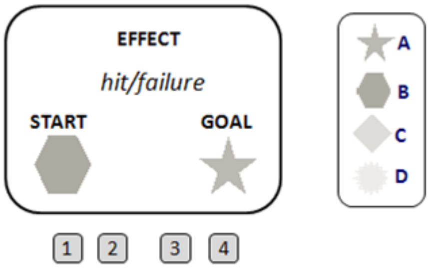

Fig. 2. Illustration of the conditions in an experiment by Stock & Hoffmann 2002. Only the feedback is shown which informs about hits and failures.

to produce a hit depends on the current start-symbol. However, if pressing the keys resulted into the presentation of another symbol on the screen only three of fifteen participants learned the critical start-key relations whereas all other participants despaired and were convinced to be fooled by the experimenter.

Figure 4 illustrates our account of this striking difference: Under the reduced feedback, participants have no other option than to strive for the feedback "hit" and they experience that every key sometimes produces a "hit" and sometimes it does not. Accordingly, participants try to find out the critical condition from which the success of each key may depend and they quickly learn that the success depends on the current start-symbol so that each start-symbol requires a certain key to press in order to launch a "hit".

In contrast, under the elaborated feedback, participants strive to find out which key is to press in order to trigger another presentation of the current goal-symbol (i.e. a hit). If accidentally the correct key has been pressed, participants try to store the experienced successful key-effect relation, that is, they try to store that the currently pressed key is appropriate to produce the currently presented goal-symbol as its effect[2]. The concurrently given start-key relations, however, are not noticed so that the participants remain blind for their regularity. In more general terms: If behavior results into different goal related effects, learning is primarily directed onto the acquisition of the proper action-effect contingencies, which in turn blocks learning of concurrent stimulus-response contingencies. Thus, the data nicely demonstrate that the primacy of action-effect learning over stimulus-response learning does not only hold for rats but also for humans.

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[2] Remember that in the presence of a certain start-symbol each of the keys always triggered the presentation of the current goal-symbol again, whatever it was. Accordingly there were no systematic key-goal relations to detect.

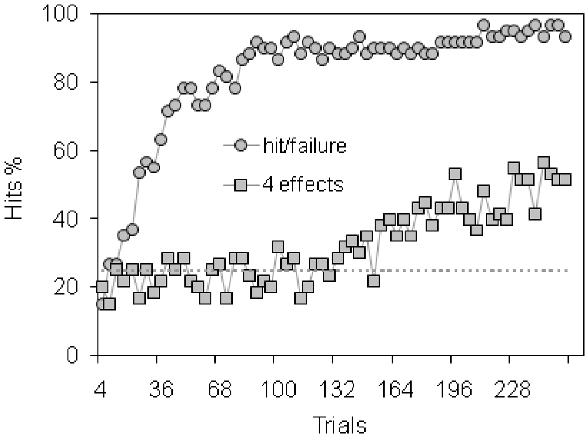

Fig. 3. The percentage of hits plotted against the number of learning trials in dependence on whether only hits and failures or four different effects are fed back.

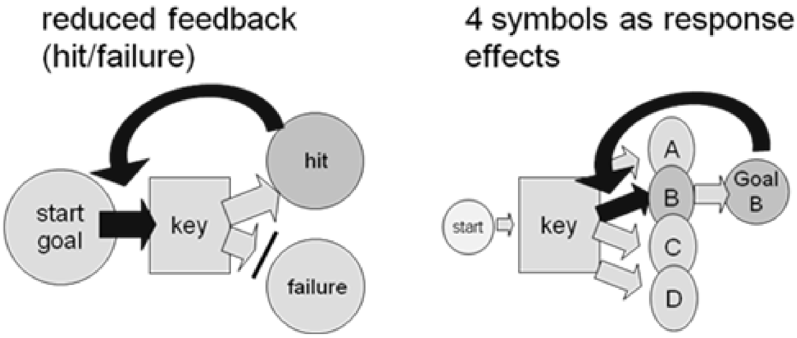

Fig. 4. An illustration of the impact different feedback has on learning: If only hits and failures are fed back associations between the successful keystrokes and the current stimuli are formed (left side). However, if the keystrokes produce distinctive effects, associations between the successful keystrokes and their current effects are formed (right side).

3 Anticipations even of non-intended effects are indispensable in the determination of voluntary behavior.

According to the preceding discussion, voluntary behavior is primarily determined by anticipations of the sensory effects the behavior produces instead of being determined by the current stimulation. This insight can be traced back more than 150 years to scholars like Herbarth [17], Lotze [43] and [15]; cf. [56] for an overview). William James [32] finally used the term "ideo-motor principle" to denominate the notion that the motor output is determined by an idea (anticipation) of the desired outcome: "An anticipatory image ... of the sensorial consequences of a movement, ... is the only psychic state which introspection lets us discern as the forerunner of our voluntary acts." [32, p.1112].

If we define voluntary behavior as behavior by which organisms strive for a certain goal, it follows by definition that the goal has somehow to be re-presented in advance because otherwise the respective behavior would not be voluntary. Thus, in order to verify the ideo-motor principle it needs to be not only shown that anticipations of the intended outcomes precede the voluntary behavior (this is trivial) but that anticipations also of non-intended behavioral effects take active part in the determination of the respective behavior.

Recently, the integration of incidental behavioral effects in the control of simple voluntary acts like pressing a button has become subject of numerous studies, which preferred a methodological approach already suggested by Greenwald [14]: In reaction time tasks, participants practice responses that produce distinctive but unintended sensory effects. Concurrently or subsequently, it is tested whether the incidental effects have gained the power to address the actions they were effects of. The test is mostly conducted by presenting the experienced effects as the imperative stimuli to trigger either the responses they formerly were the effects of or to trigger responses they formerly did not follow as effects. The results typically show that responses are performed faster and less error prone if they are triggered by their former effect-stimuli compared to corresponding control conditions, which indicates that the incidental effects are not only associated with the preceding responses but that they become indeed involved in response generation (e.g. [3, 11, 12, 20, 26, 28–30, 65, 66]).

The evidence discussed so far convincingly shows that the presentation of stimuli that have been experienced as response effects facilitates the generation of the responses they were previously the effect of. However, the ideo-motor principle claims that anticipations and not presentations of the effects determine voluntary behavior. Thus, the reported evidence is consistent with the ideo-motor principle but not yet "on the point".

Anticipations are subjective entities and are consequently difficult to control experimentally. However, if any access of a voluntary movement does indeed require an anticipation of its sensory effects, manipulations of the to-be-expected effects should have an impact on the access to the movement that produces these effects. Following this logic, Kunde [39] recently provided convincing evidence for the more specific claim of the ideo-motor principle that not only effect presentations but also effect anticipations contribute to the control of voluntary behavior.

Kunde [39] started from the well established stimulus-response compatibility effect: If in a choice reaction time experiment the imperative stimuli and the required responses vary on a common dimension (dimensional overlap), compatible S-R assignments are faster accomplished than incompatible assignments (cf. Kornblum, Hasbroucq, & Osman, 1990). Consider for example, spatial compatibility: if participants have to respond to left and right stimuli with the left and right hand, they respond faster with the left hand to a left stimulus and with the right hand to a right stimulus than vice versa (e.g. [55]). Ongoing from S-R compatibility, Kunde [39] proceeded to argue that if selecting and initiating a response does indeed require the anticipation of its sensory effects, the same compatibility phenomena should appear between effects and responses as between stimuli and responses.

Imagine, for example, that participants are asked to press a button either softly or strongly in response to an imperative color signal. Each key press produces either a quiet or a loud effect tone. In the compatible assignment a soft key press produces a quiet tone and a strong key press produces a loud tone. In the incompatible case, the assignment is reversed. The results show that participants responded significantly faster if their responses triggered tones of compatible intensity than if they triggered incompatible tones. This response-effect compatibility phenomenon meanwhile has been proven to be a very robust one. The phenomenon occurs in the dimensions of space, time, and intensity [39, 40, 38, 41, 37]. As in all these experiments, the effects were not intended but appeared incidentally after the execution of the response. Their impact on response latencies proves that representations also of these non-intended effects were activated before the responses were selected and initiated. The use of response alternatives that differ in intensity additionally allowed a qualification of response execution. For example, if participants are required to complete a soft or a strong key press the peak force that is reached provides an appropriate measure of response execution, allowing to explore whether response-effect compatibility would affect not only reaction times but also response execution. This was indeed the case. The intensity of the effect-tones uniquely affected the peak forces of soft as well as of strong key presses in a contrast like fashion. As Figure 5 illustrates, loud effect-tones reduced and quiet effect-tones intensified the peak forces of intended soft key presses as well as of intended strong key presses.

For an appropriate account of the found contrast, it is to notice that peak forces indicate the intensity of the tactile feedback by which participants start to reduce the force of their hand because they feel the intended force (strong or soft) to be reached. In this view, the data show that less strong tactile feedback is required to feel the intended force completed if a loud effect-tone follows and stronger tactile feedback is needed if a quiet effect-tone follows. Figure 6 illustrates two possible accounts for this contrast. A simple feedback loop for the execution of a prescribed pressure force is depicted: The imperative stimulus determines the

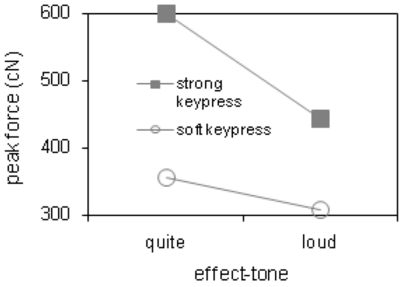

Fig. 5. The peak force for intended strong and soft key presses in dependence on the intensity of the effect-tones the keystrokes produced.

set point (the proximal reference), i.e. the proprioceptive feeling is anticipated which has to be reached in order to realize either a strong or a soft key press. The difference between the set point and the current feeling (the current proximal feedback) determines the appropriate motor commands which are activated until the proprioceptive feedback from the finger tip and from the muscles signal that the set point is reached.

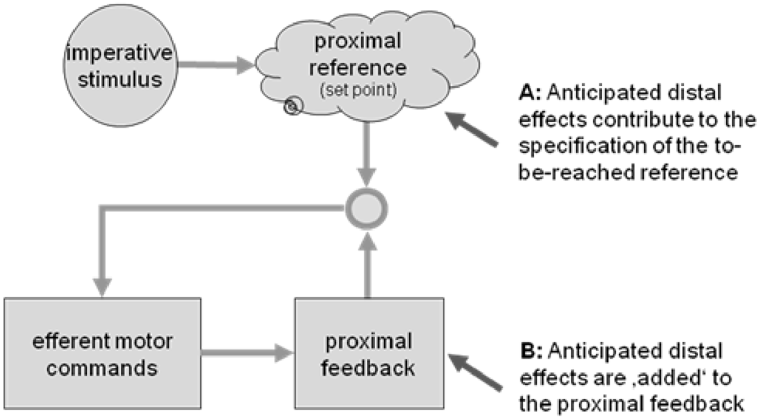

Fig. 6. Illustration of two possible points of action at which anticipated effects might affect behavioral control.

Within this loop the additionally anticipated intensity of the distal effect-tone might on the one hand (A) influence the set point so that the set point is somewhat enhanced if a quiet tone is anticipated, and the set point is somewhat reduced if a loud tone is anticipated. In this way the intended force of the key press would be adjusted in order to compensate for the anticipated force of the effect tones. On the other hand (B) it might be that the anticipated intensity of the distal effect-tone is charged to the feedback so that an anticipated loud tone earlier evokes the feeling that the set point is reached and an anticipated quiet tone delays somewhat this feeling. Both mechanisms provide an account for the contrast effect and it might be that they both conjointly contribute to it. In any case, the present data provides profound evidence that anticipations even of unintended response effects are not only involved in the selection and initiation of voluntary actions but also take part in the control of their execution.

4 Anticipative behavioral control becomes conditioned to the situational context.

As convincing the evidence for the determination of voluntary behavior by anticipations of its intended and non-intended effects might be, it would be silly to deny the contextual impact situations have on behavior. For example, if a bus driver who drives home in his private car stops at a bus stop, his behavior is obviously not determined by his goal to drive home but rather by perceiving the bus stop, which immediately evokes the habit to stop there [16]. Indeed, several theoretical conceptions in psychology acknowledged the fact that situations may attain the power to evoke associated behavior. For example, Lewin (1928) spoke in this context of the “Aufforderungscharakter” of objects, Ach [1] coined the term 'voluntive Objektion', and Gibson [13] argued that objects are not only to be characterized by their physical features but also by their 'affordances'. All these terms refer to the fact that suitable objects often afford us to do the things we mostly do with them and that they immediately trigger habitual behavior if one is already ready for doing it. For example, if one intends to post a letter, the sight of a mailbox immediately triggers the act of posting and in driving a car, flashing stop lights of the car ahead immediately evokes applying the brakes.

In order to reach a more complete picture of the representations that underlie behavioral control, the integration of situational features also need to be considered. The situational context presumably becomes integrated into behavioral control either if a particular context repeatedly accompanies the attainment of a particular effect by a particular action or if situational conditions systematically modify action-effect contingencies (cf. [25]). Especially the latter deserves attention as it points to the frequent case that the effects of an action change with the situational context, as, for example, the effect of pressing the left mouse button may dramatically change with the position of the cursor. There is no doubt that people learn to take into account critical situational conditions in order to attain the intended effects, but the issue to what extent the situational context might also affect anticipations of situation-specific non-intended effects remains to be discussed.

If one is going to explore whether the same action is preceded by different effect anticipations in dependence on the situational context, first, one has to vary the effects of the same responses in different contexts and second, one has to show that respectively those effects are anticipated that correspond to the current context. A corresponding study was recently reported by Kiesel and Hoffmann [36]: In a choice reaction time experiment participants were presented with a cross and a dot in one of its quadrants framed by either two horizontally or two vertically arranged brackets (cf. Figure 7).

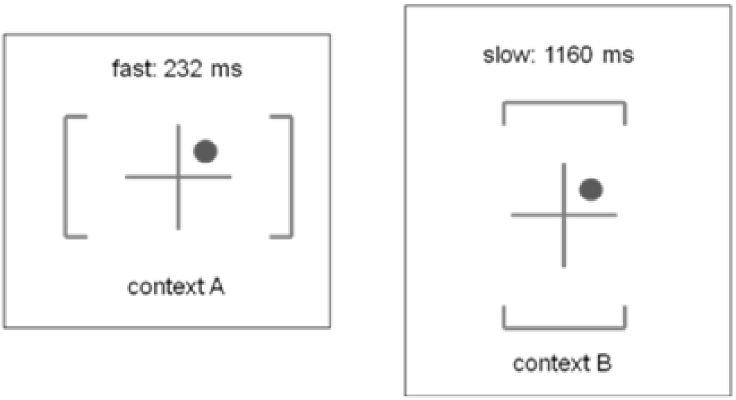

Fig. 7. Illustration of the experimental settings in Kiesel & Hoffmann [36]. Participants were told that the dot represents a "ball" and the brackets represent "goals" and that they are requested to push the ball as fast as possible into the respectively adjacent goal. When the goals were horizontally arranged, balls in the left quadrants had to be pushed with the left button and balls in the right quadrants had to be pushed with the right button whereas, when the goals were vertically arranged, the upper quadrants were assigned to the right and the lower quadrants to the left button. In all cases the ball moved to the respective goal as soon as the correct button was pressed. However, in order to vary a non-intended property of this visual effect, the ball moved quickly (in 232 ms) if the goals were horizontally arranged and the ball moved slowly (in 1160 ms) if they were vertically arranged. Accordingly, one and the same action resulted in either a slow or a fast ball movement depending on the current context.

Experiments by Kunde [40] had shown that reaction times increase with the duration of the effect tone the currently required response produces. Figure 8 shows this finding. Thus, if the velocity of the ball-move would indeed be anticipated, the responses should be somewhat delayed when a slow movement is to be expected compared to when a fast movement is to be expected. Exactly this result was found (see the right graph of Figure 8): When the context indicated a slow movement, reaction times were consistently increased in comparison to when the context indicated a fast movement of the ball. Additionally, it took some extra time if the context had been switched in comparison to the previous trial, but the influence of the effect duration clearly was independent of these "switch costs". Thus, the data confirmed that the very same actions were not only preceded but also affected by anticipations of either a fast or a slow movement depending on the current situational context, which indicates that participants acquired and used context-specific effect anticipations.

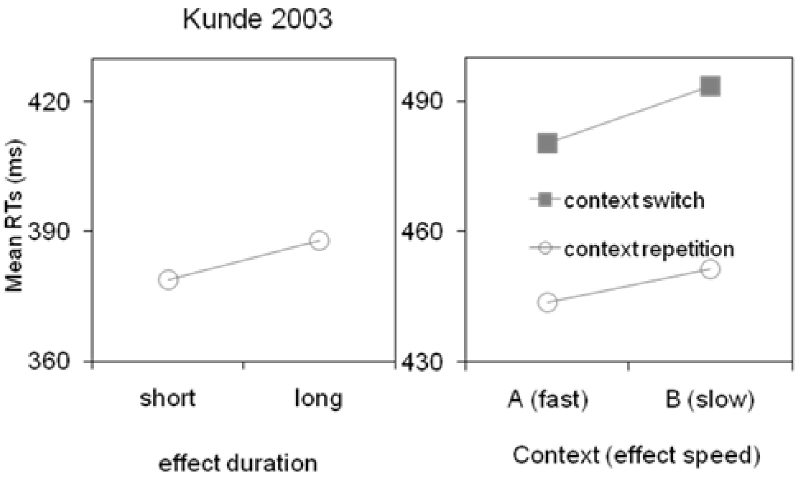

Fig. 8. Reaction times (RTs) in dependence of the duration of the sensory effects produced by the currently required response.

5 ABC: an integrative framework

In order to integrate the discussed relationships between voluntary actions, their effects, and situational contexts [23, 24, 27, 22] proposed a tentative framework that takes into account the determination of voluntary behavior by effect anticipations and the conditionalization of action-effect relations on critical situational contexts as well. The framework is based on the following assumptions (cf. Figure 9):

1. A voluntary action is defined as performing an act to attain some desired outcome or effect. Thus, a desired outcome, as general and imprecise as it might be specified in the first place, has to be represented in some way before a voluntary action can be performed. Consequently, it is supposed that any voluntary act is preceded by corresponding effect anticipations.
2. The actual effects are compared with the anticipated effects. If there is sufficient coincidence between what was desired and what really happened,

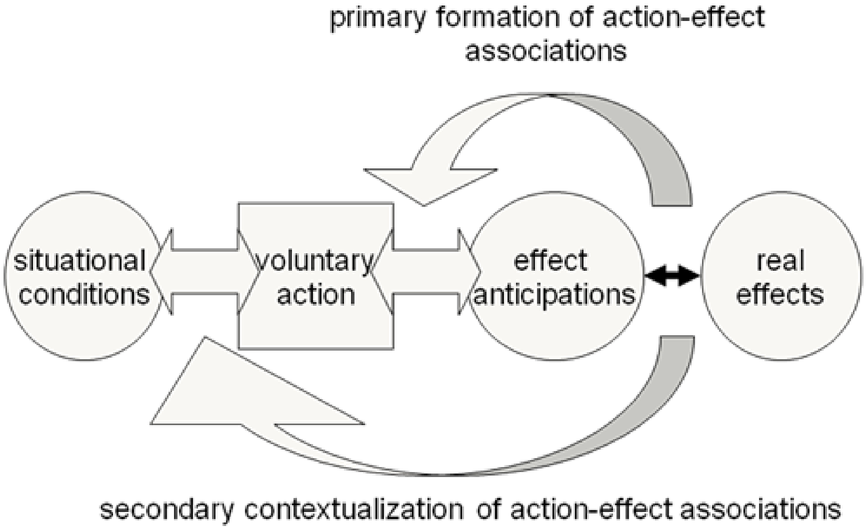

Fig. 9. Illustration of the ABC framework: The acquisition of anticipative structures for the control of voluntary behavior.

representations of the just-performed action and of experienced effects become interlinked, or an already existing link is strengthened. By this, action representations become linked to intended as well as non-intended effects provided that the effects are contingently experienced as outcomes of the preceding act. If there is no sufficient coincidence, no link is formed, or an already existing link is weakened. This formation of integrated action-effect representations is considered as being the primary learning process in the acquisition of behavioral competence.

3. It is assumed that situational contexts become integrated into action-effect representations, either if a particular action-effect episode is repeatedly experienced in an invariant context or if the context systematically modifies the contingencies between actions and effects. This conditionalization of action-effect relations is considered as being a secondary learning process.
4. An awakening need or a concrete desire activates action-effect representations whose outcomes sufficiently coincide with what is needed or desired. Thus, anticipations of effects address actions that are represented as being appropriate to produce them. If the activated action-effect representations are conditionalized, the coincidence between the stored conditions and the current situation is checked. In general, an action will be performed that in the current situational context most likely produces the anticipated effect.
5. Conditionalized action-effect representations can also be addressed by stimuli that correspond to the represented conditions. Thus, a certain situational context in which a certain outcome has been repeatedly produced by a cer-

tain action can elicit the readiness to produce this outcome by that action again.

The sketched framework integrates, still rather roughly, important aspects of the acquisition of behavioral competence: First, it considers the commonly accepted fact that behavior is almost always goal oriented instead of being stimulus driven. Second, it is assumed that any effect that meets an anticipated outcome will act as a reinforcer. Consequently, learning is not only driven by a satisfaction of needs but by anticipations, which can flexibly refer to any goal. Third, the framework considers the given evidence that voluntary behavior is primarily determined by action-effects instead of by stimulus-response associations. Finally, also stimulus driven habitual behavior is covered, as it is assumed that action-effect relations become conditionalized and can be evoked by the typical contexts in which they are experienced.

Although on a conceptual level the ABC framework is consistent with a huge body of empirical evidence it still fails to give an account on how sensory anticipations are transformed into the motor patterns, which let the body move so that the anticipated effects are really produced. We now discuss this concern in further detail.

6 How sensory anticipations might be transformed into appropriate motor patterns.

It can be taken for granted that "ideo-motor" transformations comprise proprioceptive as well exteroceptive effects of the intended behavior. For example, if Cole [8] describes how a deafferented patient (i.e. a patient without any proprioception) is unable to maintain an upright posture in darkness, it becomes obvious that proprioceptive feedback is indispensable even for the simplest motor control (cf. also [33, 2, 52, 7]. Also exteroceptive, especially visual feedback is fundamental even for simple and highly trained grasping movements. For example, blocking of visual feedback causes strong disturbances of a simple grasping movement despite the movement was extensively trained [48]. Thus, it appears that motor patterns are controlled by anticipations of the to-be-produced exteroceptive as well as proprioceptive effects. However, there are reasons to assume that exteroceptive and proprioceptive effects play a different role in the determination of concrete body movements.

Proprioceptive effects covary very systematically with the efferent activation patterns they are produced from, so that each of the various properties of a certain body movement as for example its strength or its velocity finds its counterpart in a corresponding proprioceptive feeling [50]. Accordingly, anticipations of proprioceptive effects can be specified to a degree which determines all parameter of a definite movement. In contrast, aspired exteroceptive effects like opening a door, switching on a device, grasping an object etc. are almost never accomplished by the very same movements. The same outcomes rather can and are typically attained by numberless body-movements this is the well known redundancy problem in motor control [4]. Accordingly, anticipations of exteroceptive effects in most cases do not specify a definite movement but rather a whole set of possible movements (e.g. [5, 51]). Finally, even if one has learned to attain a certain exteroceptive effect by a certain movement of one limb, the learned goal-movement relation can be easily transferred to another limb. For example if one trains to reach a goal by the left hand, the learned trajectory is immediately transferred to the untrained right hand (e.g. [42, 53]).

Altogether the preceding considerations convincingly suggest that a desired exteroceptive effect, an environmentally related goal so to say, almost never specifies a definite body movement to bring the effect about[3]. It rather appears to be likely that anticipated exteroceptive effects first are transferred into states of a body-related space to which all limbs have equal access. Accordingly, desired exteroceptive effects become recoded into desired bodily related but still effector-unspecific effect. Only then, such effector-unspecific goal representations might be transformed into effector specific anticipations of to-be-produced proprioceptive feelings, which finally determine the corresponding movement of a certain limb.

According to this view, at least three modes of anticipations are involved in behavioral control: anticipations of to-be-reached states in the environment, anticipations of to-be-reached states in an effector-unspecific "body space", and finally anticipations of to-be-reached states of a definite effector. If we add the idea that for each of these modes sensory feedback is used in order to control the progress of goal achievement, dynamic aspects of action-control come into focus, which we have neglected so far. Because feedback needs time and because the required amount of time differs between the different modes, the slower loops must determine the faster ones in order to hold control steady. Accordingly, the picture of hierarchically organized feedback loops emerges (Figure 10; cf. [47] for a comparable account):

On the lowest level, we can think of fast (partial spinal) loops with which the length and the tension of muscles, joint angles, and postures might be controlled. At a higher level, destinations or trajectories in an effector-unspecific body space might be controlled. And finally, yet at another dimensional level, the attainment of environmental effects is controlled.

On each level it is assumed that the current deviation from the anticipated state determines the updating of the "set points" of directly subordinated loops. Thus, at each level the respective desired (anticipated) and the currently given state (provided by sensory feedback) constitute the input, and the desired state of the subordinate level (the set point) constitutes the output. This "architecture" corresponds to the structure of an inverse model with the goal and the current

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[3] In the "Theory of Event Coding" (TEC, [31]), the authors emphasize that actions are primarily represented by codes of the aspired exteroceptive or distal effects. However, TEC explicitly deals only with 'early' cognitive antecedents of actions that stand for, or represent, certain features of events that are to be generated in the environment. TEC does not consider the complex machinery of the "late" motor processes that subserve their realization (i.e., the control and coordination of movements). Here it is argued that anticipations of the proprioceptive effects of actions are indispensable to "translate" desired distal effects into appropriate motor patterns.

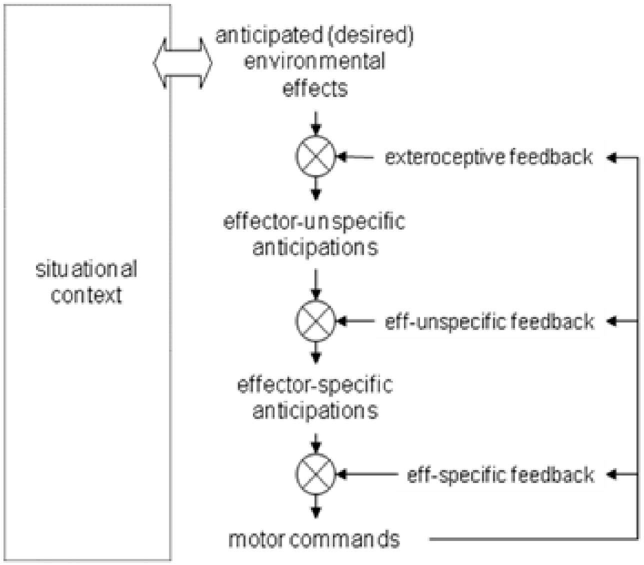

Fig. 10. A rough sketch of the assumption that anticipated sensory effects might be transformed into appropriate motor commands by a hierarchy of feedback loops or a cascade of inverse models.

state as input, and the action as output (e.g. [34, 35, 64]). Accordingly, instead of hierarchically organized feedback loops we can also speak of a cascade of inverse models. In such a structure, learning would refer to a continuous and simultaneous adjustment of the distributed inverse models: On each level the conversion of desired and perceived values into desired values for the next subordinated level would have to be adjusted, so that finally the emergence of an exteroceptive anticipation (an aspired goal state in the environment) automatically prompts the body to move in a way that brings the anticipated effects about.

The proposed structure of distributed feedback loops or adaptive inverse models, which are related among each other by sub- and super-ordinations, is still rather speculative and is subject to future exploration. However, recent simulations have shown that already a "cascade" of two control levels suffices for the modeling of goal oriented arm movements [5, 19, 18]. Figure 11 illustrates the basic structure of the SURE_REACH model, which consists of two modules. First, there is a posture memory, which accomplishes the transformation from an exteroceptive goal, represented as a desired hand location in an external space, into a set of all those arm postures that have been experienced as realizing the desired hand location. It thus transforms an exteroceptively defined goal into a set of proprioceptively defined postures. Second, there is a motor controller, which generates motor commands that move the arm toward the closest goal posture. Motor control is realized in two steps. First, the motor controller prepares a sensory-to-motor mapping, which provides suitable motor commands to achieve the desired hand location. It can be considered an online generated inverse model. Next, the sensory-to-motor mapping is used as a proprioceptive closed-loop feedback controller, which moves the hand to the target.

It is important to note that in SURE_REACH the mappings of desired hand locations into possible arm postures as well as the mappings of pairs of start- and goal postures into appropriate motor commands, which move the arm from the start to the goal, are learned from scratch by completely unsupervised learning mechanisms. In other words, SURE_REACH completely autonomously develops structures for the control of goal oriented arm movements by merely monitoring covariations between "visually" represented hand positions and proprioceptively represented arm postures on the one hand and proprioceptively represented changes of arm postures and motor commands on the other hand. Certainly, SURE_REACH is of minor complexity compared to the huge number of degrees of freedom natural behavior has to face. Nevertheless, the high flexibility and adaptability of the simulated behavior makes SURE_REACH a promising starting point for future elaborations.

7 Outlook

The replacement of the information processing approach by an "intentional approach", which acknowledges that cognition first and foremost serves the control of goal oriented, voluntary behavior instead of serving the processing of stimulus information is still in its beginning. Substantial progress is already made in elucidating the anticipatory mechanisms by which simple voluntary acts are controlled [6]. These mechanisms already give a sense on how anticipations might shape perception and attention in accordance to behavioral requirements. However, to show, how from sensory-motor control higher cognitive abilities like planning, language, or reasoning emerge is still a long but promising way.

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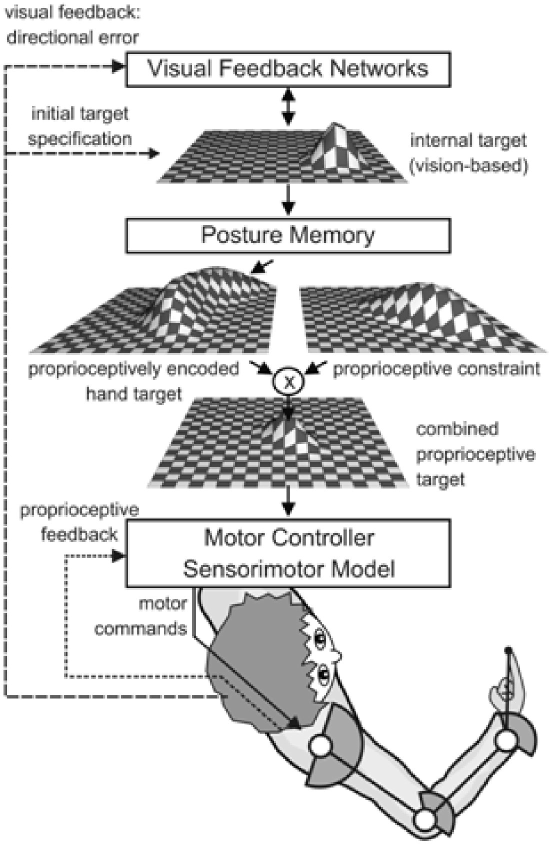

Fig. 11. The SURE_REACH model consists of a variety of target repre-sentations ("checkerboards") and neural controllers (boxes). In the cartoon, the target in the workspace of the hand is represented by visually defined population codes (top- most checkerboard). The Posture Memory converts the visually defined target into a set of appropriate arm postures which are repre-sented by proprioceptively defined population codes (left checkerboard). The right checkerboard represents possible additional proprioceptive constraints of the target postures. The bottom-most checkerboard finally represents target postures that realize both, the desired hand location and the desired proprioceptive constraints. The Motor Controller then plans the transition from the initial posture to the nearest target posture based on a learned sensorimotor model. Proprioceptive feedback drives the execution of the movement plan. Visual Feedback Networks may adjust the visual goal representation if discrepancies between desired and actual hand locations cannot be corrected by the proprioceptive controller.

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