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LABORATORY NOTE

Explorations of anticipatory behavioral control (ABC): a report from the cognitive psychology unit of the University of Würzburg

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Abstract The report comprises recent theoretical considerations, experimental research, and simulations which all aim at a clarification of anticipatory mechanisms of behavioral control.

Keywords Anticipation · Motor control · Feedback · Feedforward

The ideo-motor principle: actions are determined by anticipations of their sensory effects

The mechanisms by which the mind controls what the body is doing are still a mystery: How does it happen, for example, that if I want to drink, my hand moves to the cup, grasps it, and brings it to my mouth so that my wish comes true? The ideomotor principle (IMP) which can be traced back in Germany to Herbart (1825) and in England to Laycock (1845) (cf. Stock and Stock 2004) gives a surprisingly simple and suggestive answer to this fundamental question: according to the IMP, movements of the body become connected to their sensory consequences in a way that the mere image of such consequences receives the power to trigger those movements which formerly brought them about. In other words, body movements become determined by anticipations of their own sensory consequences.

At the second half of the nineteenth century the IMP became generally accepted among the leading psychologists at this time. In particular, there was the agreement in that, as James (1890/1981, p.1112) put it. ‘‘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.’’ (cf. also Harleß 1861; Lotze 1852; Münsterberg 1889). However, for the arising paradigm of behaviorism the notion that behavior might be determined by something unobservable, like anticipations, was a sacrilege. Behavior, so the behavioristic tenet, is exclusively determined by stimuli (e.g., Watson 1913; Thorndike 1913). Unfortunately, the S–R doctrine was maintained when later the cognitive approach displaced behaviorism: For example, in the first textbook on Cognitive Psychology, Ulric Neisser (1967, p. 4) also considered cognitive processes as being determined by stimuli when he defined ‘‘cognition’’ as referring ‘‘...to all the processes by which the sensory input is transformed, reduced, elaborated, stored, recovered, and used’’. Thus, it happened that in cognitive psychology a fundamental fact about organismic behavior remained unreflected upon for decades—namely that behavior and cognition are primarily determined not by stimuli but by the goals that organisms in general and humans in particular strive for.

In the recent years the scientific interest on the IMP has resurged (e.g., Hoffmann 1993; Prinz 1990, 1997; Hommel 1998) and our laboratory has joined this ‘‘movement’’ in three respects. First, we contributed to the theoretical debate in that we developed a framework for the learning dependent development of structures for goal driven anticipatory behavioral control (ABC). Second, we contributed to the experimental efforts to validate basic assumptions of the IMP and to refine them according to the ABC framework. Finally, we started with simulations in

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order to better understand the structural requirements for ABC. In the remainder of the text we will give a short overview of these three efforts.

The ABC framework: anticipatory behavioral control

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. Animals likewise behave to attain various goals as for example to escape from an predator, to catch prey, to feed their offspring, etc. The IMP already accorded to the purposive character of almost all behavior in assuming that behavior is not triggered by stimuli but by to-be-produced effects. For this to work, behavioral acts have to be connected to the effects they produce. Otherwise it is impossible to see how an anticipated effect may address the behavior, which brings them about. Thus, in contrast to behaviorism, we assume that behavioral competence emerges by the acquisition of action-effect instead of stimulus-response associations.

However, stimulus conditions come into play if action-effect contingencies systematically depend on the situational context: For example, taking the brake results into different consequences on a dry compared to a slippery road, and the effects of pressing the mouse button depend on the current position of the cursor, etc. In this and a thousand other cases, we typically take into account the respective critical conditions in what we are doing. Even rats easily learn that, for example, pressing a lever results in food pellets under noise, but in a sugar solution under light (Colwill and Rescorla 1988, 1990). Thus, action-effect learning has to be supplemented by mechanisms, which ensure a 'contextualization' of action-effect relations if needed.

Hoffmann (1993, 2003) and Hoffmann et al. (2004) proposed a tentative framework that takes into account the primacy of action-effect learning as well as the conditionalization of action-effect relations on critical situational contexts. The framework is based on the following assumptions (cf. Fig. 1):

1. A voluntary action (A_{volunt}) is defined as an act performed to attain some desired outcome or effect. Thus, a desired effect, as general und imprecise as it may be specified in the first place, has to be represented before a voluntary action can be performed. Consequently, it is supposed that any voluntary act is preceded by an anticipation of to-be-attained effects (E_{ant}).
2. The actual effects (E_{real}) resulting from the action are compared with the anticipated ones. If there is sufficient coincidence between what was desired and what really happened, representations of the just-performed action and of the confirmed effects become interlinked, or already existing links are strengthened. If there is no sufficient coincidence, no link is formed, or already existing links are weakened. By these actions become connected with the effects they reliably produce whereas accidental effects become eliminated. This formation of integrated action-effect representations is considered the primary learning process in the acquisition of behavioral control.
3. Situational contexts (S) 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 contextualization of action-effect relations is considered a secondary learning process.
4. An emerging need or a desire for a certain effect activates action-effect representations, whose effects coincide with what is needed or desired. Thus, anticipations of effects address actions that are represented as being appropriate to produce said effects. If the activated action-effect representations are contextualized, the coincidence between the stored context and the present situation is checked. In general, the action most likely to produce the anticipated effect in the current situational context will be preferred.
5. Contextualized action-effect representations can also be addressed by stimuli that correspond to the represented context. Thus, a situational context in which a certain outcome has been repeatedly produced by a certain action can elicit the readiness to produce this outcome by that action again.

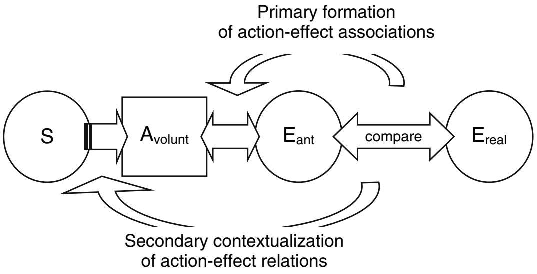

Fig. 1 An outline of the ABC framework: voluntary actions (A_{volunt}) go along with anticipations of to-be-attained effects (E_{ant}). The actually occurring effects (E_{real}) are compared to the anticipated ones. In result of the comparison, the strength of the corresponding action-effect relation is primarily adjusted. As a secondary learning process, situational contexts (S) are integrated, which either are repeatedly experienced or which systematically modify action-effect contingencies

The sketched framework integrates important aspects of behavioral learning: first, it considers the commonly accepted fact that behavior is almost always goal oriented instead of being stimulus driven. Second, it assumes that any behavioral effect which meets an anticipated outcome will strengthen the corresponding action-effect relation. Consequently, learning is not only driven by a satisfaction of needs but also by the affirmation of anticipations, which can flexibly refer to any future event or state. Third, the framework considers the given evidence that voluntary behavior is primarily determined by action-effect instead by stimulus-response associations. Finally, also stimulus driven habitual behavior is covered, as it is assumed that action-effect relations become contextualized and can be evoked by the typical contexts in which they are experienced. Certainly, all the presumed mechanisms need specification, preferentially by collecting experimental data and by designing a concrete computational model. Some of our work in these directions is presented next.

Experiments

Sensory consequences as antecedents of voluntary actions

The ABC framework postulates that voluntary actions are preceded by anticipations of their sensory effects. In order to prove this assumption, Kunde (2001) explored the impact of compatibility between required actions and the effects they produce on response times (RTs): it is an established fact that 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. Simon and Rudel 1967; Kornblum et al. 1990). Kunde (2001) reasoned that if anticipations of sensory effects really precede any voluntary action, similar compatibility phenomena, such as those between stimuli and responses, should manifest between the (anticipated) effects and the required actions as well, provided that the effects contingently followed the actions before.

By now numerous experiments have confirmed that compatible action-effect assignments indeed result in faster and less error prone responses compared to non-compatible assignments (Beckers et al. 2002; Bosbach et al. 2005; Kunde 2003, 2004; Kunde et al. 2002, 2004; Kunde and Kiesel 2006). Here is an illustrative example: people are faster to initiate a required strong keypress if it is followed by a loud rather than by a quiet tone, whereas a soft keypress is initiated faster if it is followed by a quiet instead a loud tone. Kunde (this issue) gives a comprehensive overview about this and other related research so that we can content ourselves with stating that response-effect compatibility is a phenomenon of broad empirical validity. Note, that in all these studies the response effects were presented only after the response had been carried out. Thus, their impact on response latencies strongly suggests that effect representations indeed were activated before the response onset as assumed by the ABC framework.

The contextualization of action-effect relations

The ABC framework assumes that action-effect relations become conditionalized to contextual conditions if the context systematically modifies the contingencies between actions and effects. A recent study by Kiesel and Hoffmann (2004) provides an illustrative example for such a case: participants were presented with a cross and a ‘‘ball’’ in one of its quadrants framed by either two horizontally or two vertically arranged brackets or ‘‘goals’’ (cf. Fig. 2).

The task was to push the ball as fast as possible into the respectively adjacent goal. In one setting, for example, given 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. Moreover, if there were horizontal goals the ball moved quickly and if there were vertical goals the ball moved slowly. Accordingly, one and the same actions resulted in either a slow or a fast ball movement depending on the context.

We already knew from preliminary experiments by Kunde (2003) that RTs increase with the duration of an effect tone. Thus, we expected that the actions would be somewhat delayed if a slow movement is to be expected in contrast to a fast movement. Exactly this result was found: when the context indicated a slow movement, RTs were consistently increased in comparison to when the context indicated a fast movement of the ball (cf. Fig. 3).

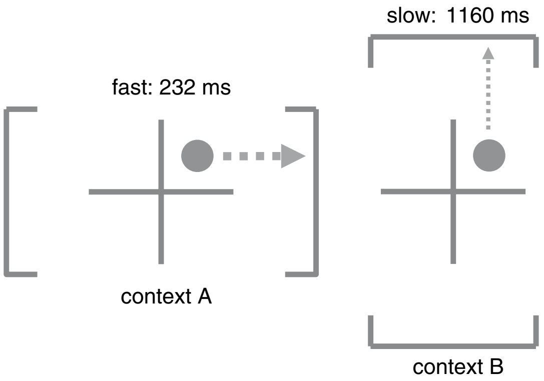

Fig. 2 Illustration of the experimental conditions used by Kiesel and Hoffmann (2004): in context *A*, responding caused a fast movement of the dot to the adjacent bracket (232 ms), whereas in context *B* the same response caused a slow movement (1,160 ms)

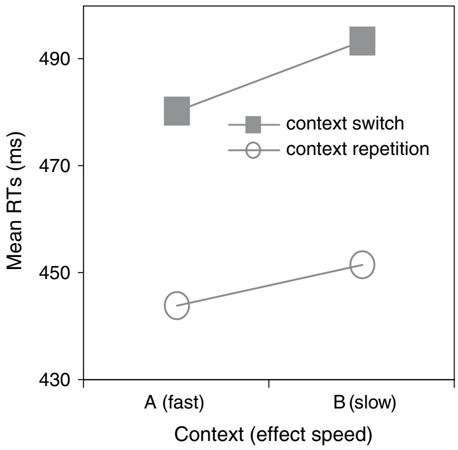

Fig. 3 Mean response times (RTs) with dependency on the context and the respectively indicated speed of the movement triggered by the response (fast vs. slow). RTs for trials in which the context was switched in comparison to the previous trial are separated from RTs for trials in which the context from the previous trial was repeated

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 determined by anticipations of the effect that was connected to the current context.

Effector-unspecific and effector-specific representations of action-effect relations

The ABC framework does not specify, so far, what kind of action representations are determined by the sensory anticipations. Do we have to assume that the concrete efferent alpha and gamma impulses, which finally control the contraction of our muscles are determined? For example, if we learn to press a certain key in order to produce a certain letter on the screen, does the desire (anticipation) to produce the letter determine the concrete efferent impulses, which move the respective finger down to the respective key? This is very unlikely for at least two reasons: first, already a slight change in the position of the hand would require changes in the to-be-executed motor parameters. Thus, it would be senseless to store concrete motor parameters as they could almost never be used again. Second, it is well known that action-effect relations, which have been acquired for a specific effector or limb, can be easily transferred to other effectors. The following experiment provides an illustrative example for intermanual transfer (Lenhard and Hoffmann 2003).

Participants had to perform hand movements on a virtual keypad, which was presented via a mirror, which was mounted so that the moving hand could not be seen. However, participants received feedback of their hand position by a small computer generated blue dot (cf. Fig. 4). The feedback usually presented the correct locations of the hand but was selectively manipulated in a way, which required overshoots for movements to one certain target. If, for example, the feedback for movements to the target 6 was manipulated, moving the blue spot from position 5 to target 6 required participants to move their hand to a position about 1 cm behind the target.

After feedback-training with the right hand, a test session from before the training was repeated, in which participants did not receive any feedback but were requested to perform the movements with the trained right hand as well as with the untrained left hand: movements of the trained hand to the manipulated target were clearly lengthened. Movements to adjacent targets also showed the tendency of overshooting the target location. Even movements to targets opposite to the manipulated target were somewhat prolonged in comparison to the same movements before the training, but this presumably resulted from a general tendency to reduce the initial undershooting of the targets. Most importantly however, the untrained left hand showed the same pattern of target-dependent movement changes as the trained hand (cf. Fig. 5). The newly learned relation between the visually presented location of a certain target (the goal) and the movement of the right hand to reach it (the action) was obviously re-presented in such a way that the untrained left hand also adapted spatially similarly without any additional training.

Other studies have shown as well that skills that were learned with one effector can be easily transferred to other

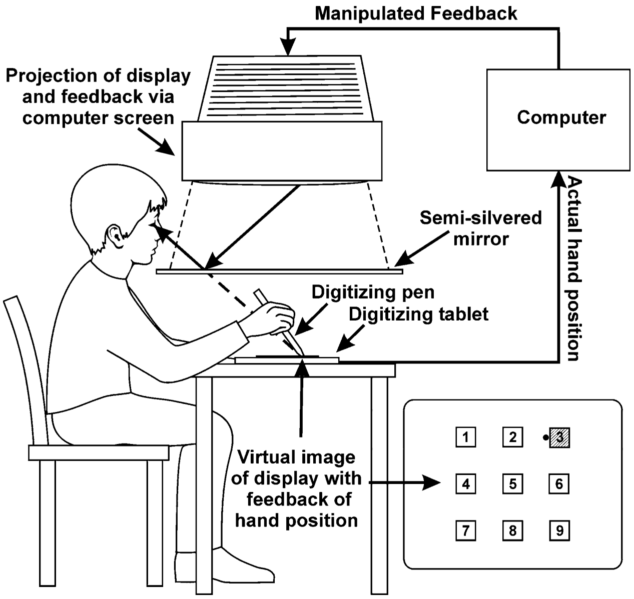

Fig. 4 Illustration of the experimental conditions used by Lenhard and Hoffmann (2003). For further explanation see text

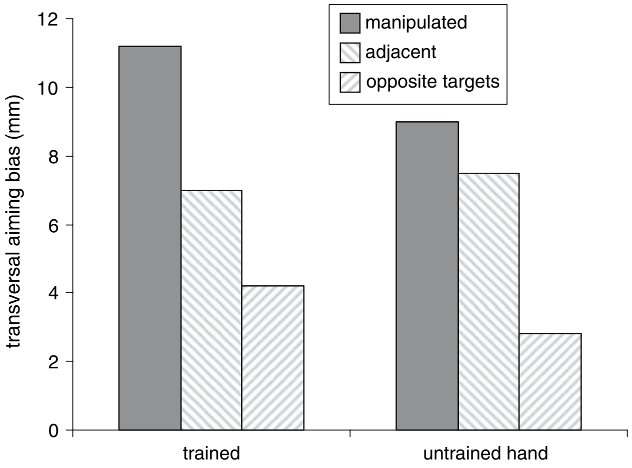

Fig. 5 Differences between the width of goal oriented transversal movements carried out (without feedback) before and after the movements have been trained with manipulated feedback (transversal aiming bias) with dependency on the type of target and separated for the trained and the untrained hand

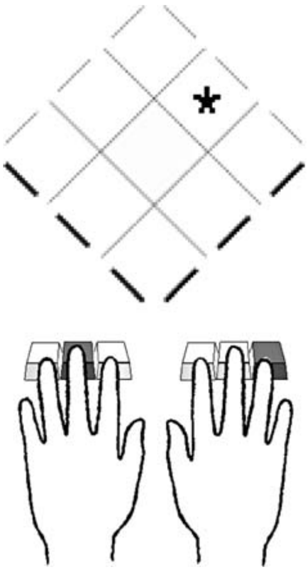

Fig. 6 Illustration of experimental conditions used by Berner and Hoffmann (2007): in each trial an *asterisk* is presented in one cell of a three by three grid. The ''row'' of the engaged cell determined the finger of the left hand, and the ''column'' determined the finger of the right hand with which the corresponding keys were to be simultaneously pressed

effectors (e.g., Criscimagna-Hemminger et al. 2003; Hazeltine 2002; Imamizu et al. 1998; Sainburg and Wang 2002). The present example, however, is of special interest as the transfer was even shown for participants who did not recognize the manipulation. Thus, neither the adaptation to the new movement-goal (action-effect) relation during training nor the transfer to the other hand can be due to an explicit strategy, but has to be mediated by autonomous learning processes, which probably refer to changes in an effector-unspecific representational format to which different effectors have equal access.

Besides the evidence for representations of action-effect relations in an effector-unspecific format, other experiments suggest that effector-specific representations can emerge as well, in particular if the corresponding actions have been highly trained. In one such experiment (Berner and Hoffmann 2007), participants practiced a repeating sequence of bimanual key presses. On each trial a bivalent stimulus indicated which pair of keys to press with the left and the right hand, and participants were instructed to respond as simultaneously as possible with the appropriate fingers (Experiment 2, cf. Fig. 6). There was a fixed repeating sequence for the fingers of the left hand and another uncorrelated fixed repeating sequence for the fingers of the right hand. Together these two hand-related sequences established a complex repeating compound sequence.

Following extensive practice (more than 640 repetitions of the hand-related sequences) either only one or both hand-related sequences were replaced with a pseudo-random sequence. Generally, RTs and errors increased when the regular sequences were replaced with random sequences indicating that the sequences had been learned. RTs increased significantly when both, instead of only one of the two hand-related sequences, were abolished. Moreover, errors tended to be hand-related, that is, only the hand that executed a random sequence made more errors, whereas the hand that continued the practiced sequence made no additional errors. Both results suggest that the acquired knowledge about the hand-related sequences is at least partly represented independently for the left and for the right hand. Although coordinated responses with both hands were required, participants seemed to have acquired separate knowledge about the order of actions performed with each hand.

In addition, the acquired hand-related sequence knowledge could not be transferred to the respective other hand: If for example, the left hand executed the sequence formerly trained with the right hand, performance was not superior to executing a random sequence with the left hand. This finding of non-transferable hand-related sequence knowledge points to effector-specific representations that store the highly trained order of the to be performed actions for the left and the right hand not only separately, but also in a format to which only the respective hand has access (for further evidence in support of effector-specific action representations see, Bapi et al. 2000; Park and Shea 2005; Rieger 2004; Verwey and Clegg 2004).

Altogether, the available evidence suggests that action-effect relations are presumably not represented only once but in a manifold manner. At least effector-unspecific representations, which allow knowledge transfer between different effectors, are to be distinguished from effector-specific representations, which allow for what one may call ‘‘embodied control’’ of highly trained actions. We will continue to discuss this issue of multiple action-effect representations in the next section.

On the role of feedback in behavioral control

Concerning the IMP, Anthony Greenwald (1970, p.96) already noticed that ‘‘...the problem of explaining response execution... has been set aside temporarily until a more precise formulation of the ideo-motor linkage is available’’. This claim dates back more than 30 years and we still lack a comprehensive account of the mechanisms by which anticipations of to-be-reached sensory effects are transformed into the concrete motor patterns, which generate what has been anticipated. However, it can be taken for granted that the ‘‘sensory-motor transformation’’ requires proprioceptive as well as exteroceptive feedback: For example, Cole (1995) describes in his book ‘‘Pride and the Daily Marathon’’ how a deafferented patient is unable to maintain an upright position in darkness, which reveals that proprioceptive feedback is indispensable even for the simplest motor control (cf. also Jeannerod 1988; Bard et al. 1999; Sainburg et al. 1993; Cole and Paillard 1995). And, in an experiment by Proteau et al. (1987) blocking of visual feedback causes more disturbances after 2,000 than after 200 repetitions of a simple grasping movement, which shows that exteroceptive (visual) feedback is indispensable even for the simplest movements. Thus, in considering control of action-execution, loops for proprioceptive and exteroceptive feedback are to be taken into account (cf. Adams 1971; Desmurget and Grafton 2000; Schmidt 1975). Moreover, if we additionally consider the insight that action-effect relations are presumably represented in an effector-unspecific as well as in an effector-specific way, at least three levels of feedback are to be distinguished: (1) feedback concerning the concrete movements of a certain effector, (2) feedback concerning to-be-reached (anticipated) effector-unspecific action parameters, and (3) feedback concerning the achievement of the desired effects in the environment (cf. Fig. 7).

With the introduction of different feedback loops dynamic aspects of action-control come into focus, which have been neglected so far. Because feedback needs time and because the required amount of time differs between the different levels of feedback, the slower loops must determine the faster ones in order to hold control steady. Accordingly, the picture of hierarchically organized feedback loops emerges: 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 the attainment of environmental effects are controlled (cf. Powers 1973). On each of these levels the current deviations from the anticipated values probably determine the updating of the ‘‘set points’’ of the directly subordinate loops. Thus, at each level the respective desired (anticipated) state and the current state define the input, and the desired state of the subordinate level (the set point) defines the output. This ‘architecture’ corresponds to the structure of an inverse model with the goal and the current state as input, and the action as output. Accordingly, instead of hierarchically organized feedback loops we can also speak of a cascade of inverse models. In such a structure, learning would have to refer to a continuous and simultaneous adjustment of all 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 learned, so that finally the emergence of a desired effect automatically prompts the body to move in a way that brings about the desired effects.

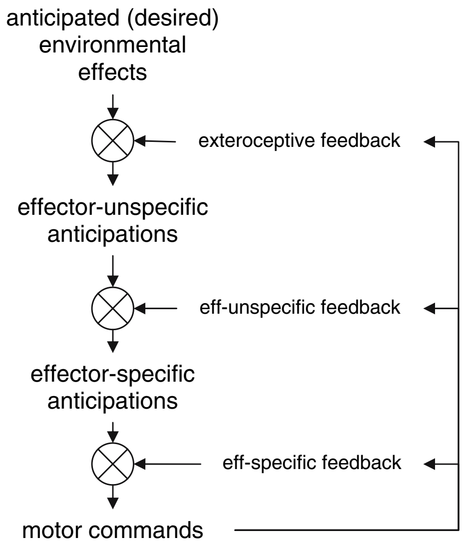

Fig. 7 A rough sketch of the assumption that anticipated sensory effects might be transformed into appropriate motor commands by a hierarchy of feedback loops or a cascade of inverse models: Perceived distances to the desired environmental effects (the goal) determine the required values of effector-unspecific movement parameters; and the perceived deviations from these parameters determine in turn the required values of effector-specific motor parameters. Concrete motor commands are finally determined by the closed loops, which control the contraction-pattern of appropriate muscle groups

These speculations of action control by cascades of sensory-motor loops or inverse models are still rough and imprecise calling for experimental validation and concretization as well. On the experimental side we will, in particular, explore the impact of different feedback distortions on behavioral control. Additionally, we are developing more precise models by corresponding simulations, which we shortly review in the next section.

Simulations

We developed two basic frameworks of anticipatory processing: (1) The anticipatory learning classifier system (ACS) is a rule-based system, which forms predictive environmental models and can exploit those models for efficient anticipatory behavioral control. (2) The sensorimotor, unsupervised redundancy-resolving architecture (SURE_REACH) is a neural network model, which mimics multiple aspects of behavioral flexibility and adaptivity observed in animals and humans. We now provide a short review of both architectures, pointing out their most prominent anticipatory behavioral features.

The anticipatory learning classifier system

The anticipatory classifier system (ACS) was introduced by Stolzmann (1998). ACS learns a predictive world model in the form of condition-action-effect schemata, similar to Drescher's (1991) schema mechanism. ACS can then exploit its world model to act goal-directed manner. The basic learning mechanism in ACS is based on the ABC framework, introduced above. While the initial system had only rule specialization mechanisms, the advanced ACS2 system learns to generalize rules online by means of an anticipatory specialization mechanism that interacts with genetic generalization (Butz et al. 2002; Butz 2002).

Our simulations with ACS have shown that the system can accurately mimic various latent learning experiments in rats. For example, it was shown that ACS behaves similarly to rats in T-maze experiments, in which latent learning was necessary (Stolzmann 1998). Moreover, the aforementioned experiments of Colwill and Rescorla (1990) were simulated with the ACS2 system (Butz and Hoffmann 2002). The simulations confirmed that some anticipatory mechanism was required to successfully mimic the behavior observed in the experiments with rats. Moreover, the question was raised if the observed anticipatory behavior was due to an online planning process or an offline associative process in the predictive model.

More recent advances decoupled the previously integrated reinforcement learning mechanism in ACS2 from the model learning mechanism, yielding the XACS system (Butz and Goldberg 2003). It was shown that XACS can form optimally generalized internal models and, meanwhile, optimally generalized state-value maps of its environment. In this way, behavior can be goal-directed in that the inherent forward model probes available future states and executes that action that leads to the one, which is currently most desirable. In this way, multiple motivations can be co-active and XACS will pursue the satisfaction of the motivation that can currently be most effectively reached. The interaction of environment, predictive world model, and motivational module is schematically illustrated in Fig. 8. Due to this anticipatory interaction, XACS is able to assure the maintenance of multiple homeostatic variables, representing system needs by interactively exploiting its environmental model to behave effectively.

While ACS is well-suited to mimic basic anticipatory capabilities and interesting interactions with a motivational module, in its current form, ACS is bound to symbolic representations. In order to also investigate more basic anticipatory motor control mechanisms, we designed the modular neural control architecture SURE_REACH.

SURE_REACH

The sensorimotor unsupervised redundancy resolving control architecture (SURE_REACH) learns to control redundant bodies, such as an arm, purely unsupervised (Butz et al. 2007). With respect to Fig. 7, SURE_REACH models the two hierarchical layers before motor execution. SURE_REACH is a neural network model that covers internal spaces with population codes, which enable the activation of multiple goals and the application of dynamic-programming based motor control.

Figure 9 shows the basic layout of SURE_REACH. A hand space represents the location of a target in effector-unspecific extrinsic space while a posture space represents the arm posture in joint-angle space. An inverse kinematics model associates hand end-point coordinates with all posture codes that yield that particular end-point. An inverse sensorimotor model associates arm posture transitions action dependently, effectively encoding action-dependent contingencies of arm postures.

In accordance with the IMF learning results in a goal-directed control architecture. Initially, random actions are executed and the neural networks extract inverse kinematic and sensory-motor body models. Once the inverse models are sufficiently accurate, goal-oriented actions can be executed. For example, given some goal activation in hand

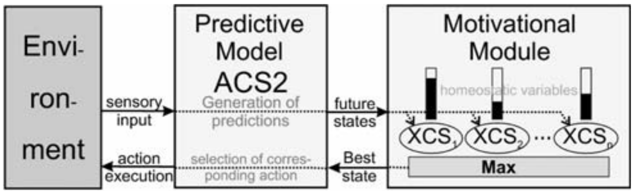

Fig. 8 XACS learns a predictive model of its environment during motor babbling by means of ACS2-based learning. Goal-directed actions can be triggered via the ACS2 model, mediated by a motivational module that maintains multiple homeostatic variables. XCS-based state-value learners represent the proximity of goal states with respect to the homeostatic variables. ACS2 then anticipatorily executes that action that promises to lead to the closest currently relevant goal state

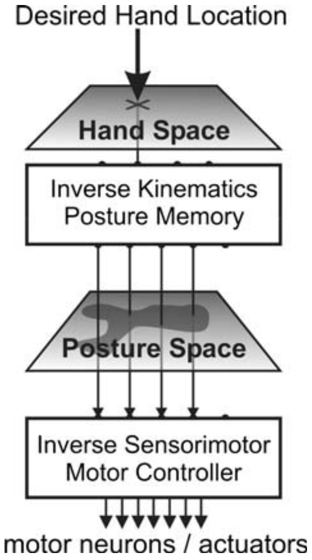

Fig. 9 SURE_REACH comprises a hand space and a posture space, as well as an inverse kinematics posture memory and an inverse sensorimotor-based motor controller. Obstacle representations can invoke neural inhibitions in hand space or in posture space. Other constraints may be invoked in posture space by simple neural inhibitions or excitations. Based on the current posture state and the goal activation, the motor controller invokes efficient actuator signals

space, the inverse kinematics model co-activates all suitable goal postures in posture space. The inverse sensorimotor model then propagates goal activity inversely in posture space by means of dynamic programming, yielding a sensory-to-motor mapping that triggers closed-loop controlled, goal-directed movements. The result is a highly flexible and adaptive control mechanism. The combination of unsupervised learning mechanisms with population encoded body spaces enables SURE_REACH to resolve redundancy opportunistically online—always choosing trajectory and goal states that require the least movement effort. The system chooses both to approach the closest posture and to execute the closest trajectory to that posture, resolving redundancy on the kinematic and the motor command level.

Besides this capability of efficient redundancy resolution, SURE_REACH was shown to mimic various behavioral phenomena observable in animals and humans: (1) Training in SURE_REACH not only affects the accuracy of movements, but also movement times and reaction times. (2) Priming effects can be simulated. (3) The end postures reached during goal-directed control depend on the starting postures and (4) intermediate postures can be approached in anticipation of the targeted end posture. (5) Disabling movements of one limb only slightly affects movement accuracy and does not require exhaustive relearning. (6) Finally, other experiments showed that the control architecture can flexibly account for coping with an arthralgic joint or avoid obstacles in hand or posture space. All these features either emerged simply due the design of the architecture or were accomplished by the addition of simple neural inhibitions and excitations. They require no additional learning but can be incorporated instantly (Butz et al. 2007; Herbort and Butz 2007).

Currently, SURE_REACH does not utilize any form of forward prediction during motor control. Rather, control is closed-loop in that the currently perceived arm posture state is used to trigger the corresponding action code in the generated sensory-to-motor mapping. However, since the sensorimotor inverse model in posture space is an associative model, it might also be used as a forward model to predict sensory flow. Additionally, we are planning to include a similar associative inverse model in hand space to stabilize motor control further. The incorporation of forward models is expected to also enable smooth motor control when confronted with delayed or unavailable sensory feedback.

Outlook

In view of causality, anticipatory behavioral control is a curious phenomenon because anticipated sensory consequences (the effect) seem to determine the actions (the cause) by which the anticipated outcome is produced. This picture, however, is not complete: It is not the anticipated outcome alone, which provides the cause for acting but rather its differences to the present. It is striking that the same holds true also for perception, since the seminal formulation of the reafference Principle by von Holst and Mittelstaedt (1950) we know that what we perceive is not determined by the present but by its differences to what has been anticipated. Thus, anticipation appears to be a fundamental principle not only for behavioral control but also for perception. To elucidate in detail how the perceptual world become structured according to and in dependence on the completion of anticipations in behavior certainly is one of the most striking challenges for future research.

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