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Anticipations in Perception and Action Control

Prologue

The basics for a 'Psychology of Human Information Processing' were led in the middle of the last century: In 1949, Claude Elwood Shannon and Warren Weaver published a book entitled 'The mathematical theory of communication' which provided the mathematics for a measurement of information (cf. Shannon/Weaver 1949). One year before, Norbert Wiener argued that control and communication can be likewise studied in animal and machine (cf. Wiener 1948). Allan M. Turing discussed in 1950 'intelligence' as being a possible feature of computing machines and John von Neumann delivered the structural architecture of such 'intelligent machines' (cf. Turing 1950; v. Neumann 1958).

All these developments strongly influenced academic psychology and when William Edmund Hick from Cambridge reported that the reaction time (RT) linearly increase with the information (the entropy) of the presented stimuli, the strong belief emerged that the perception of stimuli and the selection and performance of an appropriate response can be described as processing of information (cf. Hick 1952). The arising hope, that human information processing can be finally understood by its simulation in 'intelligent machines' was confirmed, only nine years later, by Alan Newell and Herb Simon from Carnegie Mellon University (cf. Newell/Simon 1961). They implemented a computer program, the so called 'General Problem Solver', which was able to solve simple problems like the tower of Hanoi. The information processing approach was born and Ulric Neisser gave the new movement its name by a book he entitled „Cognitive Psychology". Neisser defined 'cognition' as referring „...to all the processes by which sensory input is transformed, reduced, elaborated, stored, recovered, and used." (Neisser 1967, S. 4). Accordingly, academic psychology started to analyse all these processes, i.e. perception, attention, memory, language, thinking, learning etc.

Friedhart Klix not only integrated all these new approaches in his seminal book 'Information und Verhalten' (information and behaviour) but additionally argued that organismic information processing can be only understood if it is related to its function in the control of behaviour (cf. Klix 1971). In the present text I depart from this fundamental insight. I will especially argue that the reception of information and the control of behaviour are related to each other by anticipations.

Anticipations in Perception

Any action, as simple as it may be, produces changes of the sensory input. Whether we move a finger, our eyes and even if we just talk, in any case we produce some new sensory input for ourselves. Thus, our mind continuously has to distinguish what of the sensory input has been induced by ourselves, and what has been caused otherwise. Without distinguishing self-induced sensory effects from other sensory input, no valid perception, i.e. no valid processing of the information carried by the stimuli, would be possible. An early solution of this basic problem delivered the Reafference Principle (henceforth RP). The RP has been first discussed by Erich von Holst and Horst Mittelstaedt in a paper published in 1950. In the introduction the authors explained their concern as follows (Holst/Mittelstaedt 1950 p.464):

> „Wir fragen nicht nach der Beziehung zwischen einer gegebenen Afferenz und der durch sie bewirkten Efferenz, also nach dem ‚Reflex', sondern gehen umgekehrt von der Efferenz aus und fragen: was geschieht im ZNS mit der von dieser Efferenz über die Effektoren und Rezeptoren verursachten Afferenz, die wir die ‚Reafferenz' nennen wollen?"
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> (We do not ask for the relation between an afference and the resulting efference i.e. the reflex but rather depart with the efference and ask what happens in the CNS with the afference which has been caused by it, which we call the reafference, translation by the author).

Figure 1 presents a schematic illustration of what von Holst and Mittelstaedt assumed to happen with the 'reafference'. According to the RP any efferent motor command causes via corresponding neuronal networks some action in an effector (e.g. an eye movement). Additionally changes in the environment may happen. The immediate sensory consequences of the action (e.g. the shift of the retinal image) are called reafferences and the sensory input from other sources (e.g. retinal image shifts due to environmental movements) are called exafferences. Both are fed back via corresponding neuronal networks for perception. So far it is a matter of course. The critical assumptions of the RP concern two points: 1) Any efferent motor command goes along with a corollary discharge – the so called efference copy and 2)

The efference copy and the reafference cancel each other out. As a result, only the ex-afferences are transmitted for perception.

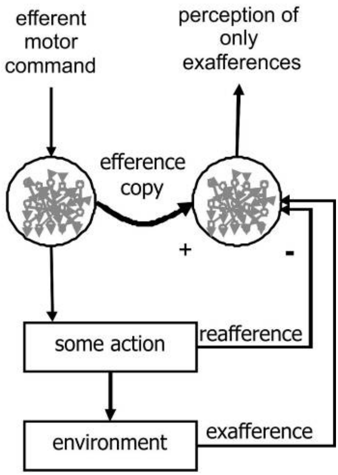

Figure 1: A simplified schematic outline of the reafference principle

There are many observations which confirm the validity of the RP (cf. Holst/ Mittelstaedt 1950): For example, in patients suffering from Polyneuritis the kinaesthetic feedback from the muscles is generally reduced. If these patients are pressing a hand against a wall, they report a feeling as if the wall would move back a little bit from the pressure of the hand. According to the RP the phenomenon appears because the kinaesthetic reafference is less strong than the efference copy so that the difference between the copy and the reafference becomes positive what corresponds to a situation in which the wall would move a little bit away, exactly what is perceived.

Or imagine an experiment conducted by the physician Kornmüller. Kornmüller paralysed eye muscles by an injection of curare but gave nevertheless the order to move the gaze to the right. Trying to look to the right, participants reported to see a short flip of the whole environment to the right. Again, the reason is that the shift of the retinal image which typically goes along with a gaze shift fails to appear what corresponds to a situation in which the environment would move with the gaze shift, exactly what the participants have seen.

The RP can be also considered as being responsible for that it is difficult to tickle oneself, what has been very nicely experimentally demonstrated (cf. Blakemore et al. 2000). The reason is that if we tickle ourselves the efference copies of our movement commands cancel out parts of the resulting sensations (the reafference) so that their tickling effect vanishes or is at least reduced.

Despite the convincing evidence in favour of the RP, there remains a problem: Efferent motor commands and afferent sensations are incommensurable to each other. Consider for example an eye movement. The motor command for an eye movement refers to the contraction of at least three pairs of muscles whereas the resulting shift of the retinal images refers to spatially distributed signals from the retinae. That is, the efference copy cannot be a pure copy of a motor command but must somehow contain anticipations of the to be expected reafference – otherwise it is impossible to see how the „copy" might cancel out the arriving reafference. Thus, the gist of the RP is: Motor commands go along with anticipations of their reliable effects which are charged against the resulting sensory input (cf. Hoffmann 1993).

Anticipations in the Control of Behaviour

It is noteworthy that another theoretical conception claimed a crucial role of anticipations in the control of voluntary behaviour already half a century before the RP: the Ideo-Motor Principle (henceforth IMP). The IMP has British and German roots. In Britain Thomas Laycock and William Carpenter and in Germany Johan Friedrich Herbart, Hermann Lotze and Emil Harless already propagated the idea that the motor outcome influences retroactively the motor control (cf. Stock/Stock 2004). William James finally tied together the ideas of all these scholars to the IMP in his seminal Book „Principles of Psychology" (cf. James 1890/1981). Figure 2 presents a schematic illustration of the basic ideas, reduced to the fewest possible terms.

In the beginning we have some external stimulation 'S' which triggers a motor command 'M' causing via corresponding neuronal networks some action and according changes in the environment, which are fed back by what has been called by James resident and remote effects 'K'. Furthermore, James assumed that by repetition new connections are formed between neuronal representations of 'K' and 'M' (Fig.2, left side). These new connections, he assumed, change the flow of activation in the following way (James 1890/1981 p. 586):

> „K may be aroused in any way whatsoever (not as before from S or from without) and still it will tend to discharge into M; or, to express it in psychic terms,

the idea of the movement M's sensory effects will have become an immediately antecedent condition to the production of the movement itself. ...Here, then, we have the answer to our original question of how a sensory process which, the first time it occurred, was the effect of a movement, can later figure as the movement's cause."

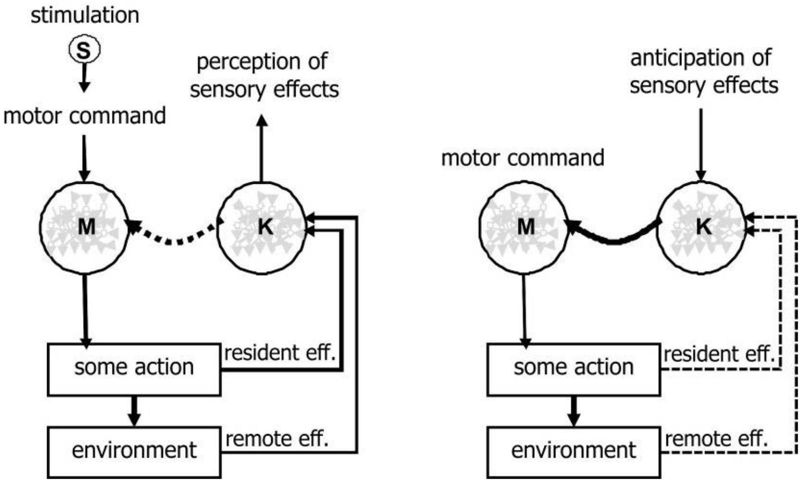

Figure 2: A simplified schematic outline of the Ideomotor Principle

The gist of the IMP is that actions become connected to their sensory consequences so that anticipations (the idea) of such consequences gain the power to trigger the movements that formerly brought them about. In other words: voluntary movements or actions become determined by *anticipations* of their own sensory consequences (cf. Fig. 2, right side).

The IMP was widely acknowledged in the beginning of the last century. However, for the upcoming behaviourism at that time, the assumption that behaviour is determined by something unobservable like an idea was a sacrilege so that behaviourists rejected the IMP in total. For example: Edward Thorndike mocked the IMP in his presidential lecture at the APA Congress in 1913, by saying (Thorndike 1913 p.101):

„Shocking as it may seem, it can be shown that the orthodox belief of modern psychologists, that an idea of a movement tend to produce the movement which is like it, is a true child of primitive man's belief that if you sprinkle water in a proper way your mimicry tends to produce rain."

Thus, it happened that the IMP remained almost without any significant influence on academic psychology for decades. However in the last twenty years the IMP experienced a renaissance especially in experimental psychology. For example, Shin, Proctor, and Capaldi noticed in a comprehensive review already in 2010 that PsycINFO listed 134 entries with ‚ideo-motor/ideo-motor' in the titles and 517 results with it as a keyword (Shin et al. 2010 p.943).

In order to verify the assumption of an impact of anticipated sensory consequences on the release of an voluntary act, many experiments used an experimental setting proposed by Anthony Greenwald (cf. Greenwald 1970): In a typical choice reaction time experiment the response alternatives are to be connected with different but distinctive sensory consequences so that a possible impact of the sensory consequences on the responses, they are the result of, can be examined. Let us take an example for demonstration (cf. Kunde et al. 2004): In the corresponding experiment, participants are requested to press a key either softly or strongly in response to imperative colour stimuli. Doing so, they produce either a quiet or a loud effect tone. The critical variation concerns the assignment of the effect tones to the keystrokes. Strong keystrokes either produced loud and soft keystrokes produced quiet tones (compatible mapping), or vice versa, strong keystrokes produced quiet and soft keystrokes produced loud tones (incompatible mapping). The results reveal that participants respond faster if their responses triggered tones of compatible intensity than if they triggered incompatible tones. Furthermore the strength (peak forces) of both, of required soft and strong keypresses, are enhanced when a quiet tone results and they are reduced when a loud tone results. The outcome shows that the sensory effects of the required voluntary acts somehow influence their release as well as their performance. These reactive influences of sensory effects has been proven to be very robust (cf. Hoffmann et al. 2007). They appear for various response modes and various effect modalities. In all these experiments, the participants were never required to produce these effects but they simply appeared incidentally after the execution of the response. That they nevertheless impact response latencies and/or response execution shows that anticipations not only of intended but also of non-intended sensory effects are active before the responses were selected and initiated.

The Interplay of Reafference and Ideomotor Principle: Structuring the 'Mental World' by Anticipations

The experience and behaviour of humans are the central matter of psychology. The RP deals with a basic part of experience – perception, and the IMP deals with a basic part of behaviour – the control of voluntary actions. In both conceptions anticipations play a crucial role: in the RP, anticipations of action effects assure the stability of perception and in the IMP, anticipations of action effects allow the determination of voluntary actions. On the one hand it is assumed that sensory anticipations are triggered by actions and at the other hand it is assumed that anticipations trigger actions. In any case, perception as well as behavioural control seem to rely on coincidences between motor and sensory activations.

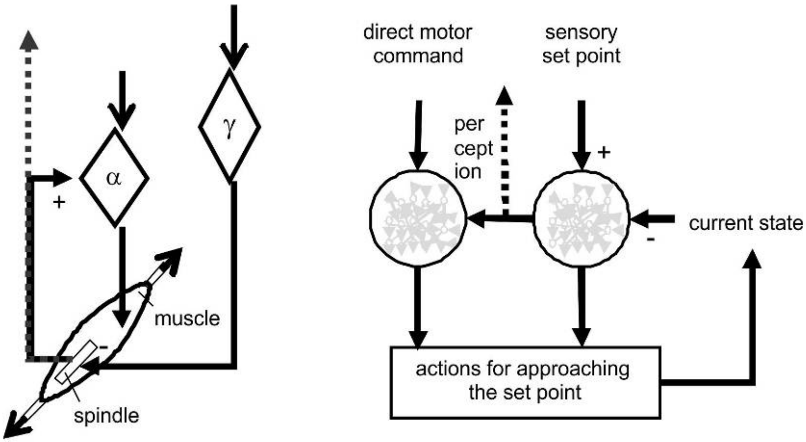

Figure 3: A simplified illustration of the basic elements of the Gamma-spindle-loop (left side) and its principle structure (right side)

Coincidences between motor and sensory activation already play an important role in the control of the most elementary motor unit – the muscle. Figure 3 (left side) illustrates the basic elements of the so called gamma spindle loop: A skeletal muscle with enclosed spindles is depicted. The spindles serve as sensors for the current length of the muscle. They start to fire if the muscle is stretched or if the spindle itself (i.e. not the muscle) is contracted by gamma activation. Additionally there is alpha activation by which the skeletal muscle can be contracted. The critical point is that the spindles have an excitatory connection to the alpha neurons so that a loop control of muscle length is created. Accordingly, there are two principle routes by which a muscle can be and is typically contracted, by direct commands via alpha neurons and by a control loop in which Gamma activation delivers a set point and the spindles work as controller.

On the right side of Figure 3 the principle structure of the gamma-spindle loop is depicted in general terms: A set point is generated which can be understood as the anticipation of a desired state or a goal (e.g. the desired length of a muscle by gamma activation). A comparison of the desired to the current state (e.g. accomplished by spindles) delivers the impulse for some action by which the difference between the current and the desired state is reduced (e.g. alpha activation via the excitatory connection between spindles and alpha neurons). Simultaneously, the differences are forwarded for perception and used in order to tune the activations of an additional direct motor pathway for triggering actions to achieve the set goal (e.g. direct alpha activation).

The point of the matter is the redundant control via two paths: a direct motor pathway and a sensory feedback loop. It might well be that this principle is not only realized for the control of muscles but on all levels of a hierarchical structure for the control of voluntary actions.

Figure 4 illustrates a tentative structure: For the sake of simplicity only four levels are distinguished. On the highest level desired effects (goals) in the environment are specified (e.g. to grasp a cup of coffee). On the next level corresponding effector unspecific set points are generated (e.g. the egocentric location of the cup is fixed to which all limbs have equal access). At this point it is not yet decided e.g. whether to grasp the cup with the right or the left hand. Next, corresponding set points for a certain limb are specified (e.g. the posture of the right arm that brings the right hand to the cup). Finally, the set points for the corresponding muscles are generated (in our example Gamma activations for the muscles of the right arm and hand might be fixed in order to execute a corresponding grasping act). Concurrently, direct motor activations are tuned step for step and level for level in dependence on the continuously reported differences between the forwarded set points and the confirmed current states. These differences simultaneously provide the data for perception.

On each of these levels the principal architecture of the gamma spindle loop with two paths is replicated: a sensory control loop and a direct motor path. And if we look on the architecture on the whole we find the reafference principle, i.e. the anticipation of to be expected reafferences (the set points or desired states) as well as the ideomotor principle, i.e. the determination of motor commands by anticipated sensory input, distributed over different levels.

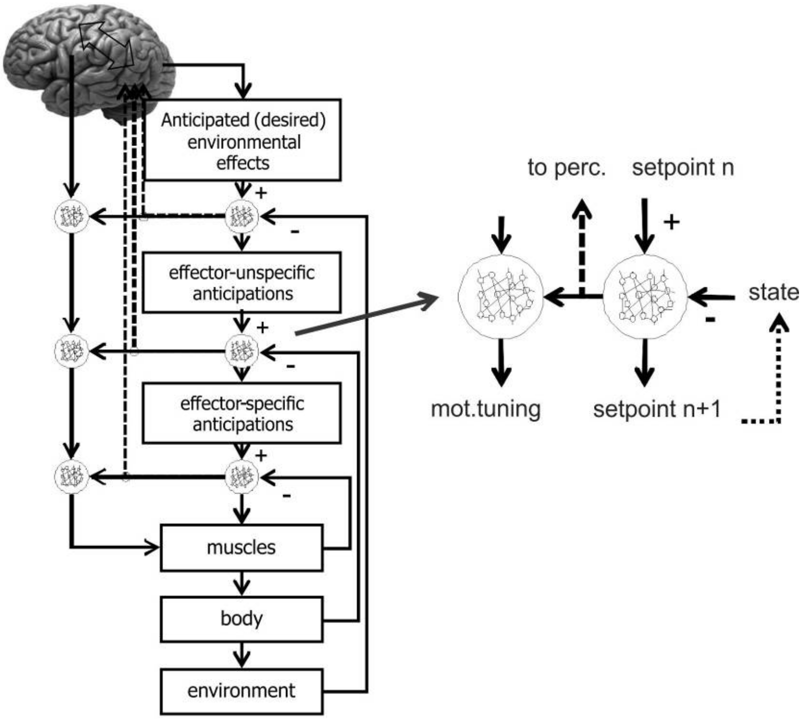

Figure 4: A tentative cascade of anticipative sensory loops and direct motor commands for the control of voluntary behaviour (left side) with an enlarged illustration of one level (right side)

A concrete act will be finally realized by a continuous cascade of sensory control loops running down from top to bottom und back from bottom to top as well as by consecutively tuned direct motor activations.

The learning dependent formation of such hierarchic structures for the control of voluntary acts would lead to the creation of memory structures at different levels (cf. Hoffmann/Engelkamp 2017): At the top, representations of states which are worth to aim at (set points or goal anticipations) are to be fixed by conceptual structures representing for example desired objects, tools, situations to strive for, etc. Furthermore, it has to be learned which differences between anticipated goals and current states are relevant for the determination of set points or goal anticipations on the respective next subordinated level. In other words, the sensory features that are to attend to in order to behave successfully are accentuated and fixed. Finally, it has to be learned how to tune the accompanying direct motor commands according to the current sensory input that will transform the given states to the desired states. Thus, by a continuous adaptation of sensory anticipations and motor commands on different levels of abstraction we do not only learn how to behave in order to reach our goals, but at the same time we form our perception and the conceptual structure of our mind in accordance to our purposes, or how Friedhart Klix has put it already in 1971:

> „Merkmalstransformationen durch aktive Verhalteneingriffe verändern die Umgebungszustände... Dieser Prozeß eröffnet die Ent-deckung der Tiefenstruktur von Informationsquellen. Er gestattet kognitive Strukturbildungen in individuellen Gedächtnissen zu fixieren..."
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> (The transformation of features by voluntary acts changes the environmental states ... this process allows for a dis-covery of the deep structure of the information sources. It allows the fixation of the created cognitive structures in individual memories ... translation by the author). (Klix 1971 p. 548).

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