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SPECULATIONS ON THE ORIGIN OF STM

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Introduction

Memory generally is understood as being "a system for storing and retrieving information" (e.g. Baddeley, 1997, p.9). Accordingly, memory has been investigated almost exclusively by presenting some stimulus materials to the participants, such as a list of words or a series of pictures, and by testing the ability of the participants to retrieve the stimuli after some time. However, memory is more than the ability to reproduce earlier presented word lists or to recognize earlier presented pictures. In some sense memory is involved in any activity we perform. Already perceiving is in essence recognition. When we see a birch, the visual stimulus activates what we know about birches: how they look like, the features they possess, and how they are called. Likewise, acting is also in essence recall. When we sign a document, we have to recall how to move our hand in order to produce the signature; the same is true for walking, speaking, and every other activity we are familiar with. We always have to reproduce what to do in order to attain the intended goal. Under this broader perspective, memory not only refers to storing and retrieving information but to the preservation of experiences in general. In other words, memory underlies aftereffects of current experiences on future behaviour. This general description resembles very much the definition typically used for learning. Thus, it appears that learning and memory are not distinct processes but rather two different sides of one and the same coin.

It is well known that the very first experimental investigation of human memory already acknowledged the inseparability of learning and memory. In his seminal study Hermann Ebbinghaus (1885) measured memory performance not by the amount of retrieved information but by the savings in the relearning of the information – the more savings the better the information remembered or, in other word, memory expressed itself in the degree to which a formerly reached performance level can be maintained over time. Unfortunately, Ebbinghaus' methodological approach was not continued, so that learning research and memory research diverged. In the following I will argue that the separation of learning and memory is not only a methodological pitfall but also occludes our view of the original functions of memory. If one asks why evolution brought about structures for storing information then it certainly is not for the reproduction of wordlists or for the rote learning of poems. The reasons for the emergence of memory, in particular short term memory, are related to the improvement of learning.

Elementary mechanisms of learning

The concept "learning" refers to behavioural changes resulting from individual experiences. Thus, an appropriate learning theory should clarify i) the structures by which behaviour is controlled, ii) the changes in these structures that may occur, and iii) how these changes may come about as a result of experience. As far as elementary learning is concerned (and not the acquisition of knowledge), the answers to these three issues are still largely influenced by behaviorism: Elementary behaviour is thought to be primarily elicited by stimuli according to stimulus-response associations, and the possible changes are conceptualized as changes in the structure and the strength of such stimulus-response connections, which are assumed to result from reinforcements and/or punishments. However, the behavioristic approach suffers from a crucial failure which has best been expressed by Anthony Dickinson (1994, p.48) when he complained: "The most perverse feature of … stimulus-response theories has always been the claim that knowledge about the instrumental contingency between action and outcome plays no role in the performance of the action."

In animal learning, it is acknowledged already since the 1980s that anticipations of outcomes have a stronger influence on animal behaviour than the stimulus itself. Consider, for example, a study by Colwill and Rescorla (1985): Rats in a Skinner box were first reinforced with food pellets after pressing a lever (R_1) and with a sucrose solution after pulling a chain (R_2). Once the instrumental training was completed, one of the two reinforcers (e.g., the sucrose solution) was devalued by associating it with a mild nausea in a different environment. Finally, the rats were put back in the Skinner box and given the choice between the two responses, but with the outcomes omitted. In this test-phase, rats showed a clear preference of performing the response that in the first phase resulted in the non-devalued outcome (i.e. they preferred pressing the lever in the example with the devalued sucrose solution). Obviously, the rats had not only associated the two actions with the situation in which they were reinforced, but they had also learned which actions lead to which outcomes (R_1-food pellets, R_2-sucrose solution). So, not the situation (the Skinner box, the lever, the chain) but anticipations of the to-be-expected outcomes determined the behaviour in the test: The rats avoided the response they knew would be followed by the devalued outcome (even though in the test phase no outcomes were given). It is as if the rats reasoned: "Well, in this situation I can get either food pellets or sucrose solution – I don't like the sucrose any more but the food pellets are fine – so, let's have some tasty food pellets …" and they do what they have learned to do in order to receive the food pellets.

Numerous studies of animal learning have supported the notion that animal behaviour is primarily determined by anticipation of the outcomes or effects they are currently striving for (e.g. Colwill & Rescorla, 1990; Dickinson, 1994; de Wit, Niry, Wariyar, Aitken, & Dickinson, 2007; Dickinson & de Witt, 2003; Meck, 1985; Pearce, 1997; Rescorla, 1990, 1991, 1995; Urcuioli, 2005). In contrast, the possibility that human behaviour too may be primarily driven by anticipation of the to be reached outcomes has been investigated seriously since just a couple of years. This is especially astonishing as the idea of an anticipative control of human behaviour can be traced back more than 150 years to scholars like Herbart (1825), Lotze (1852) and Harleß (1861; cf. Stock, & Stock, 2004 for an overview). William James (1890) already used the term 'ideo-motor principle' to refer to the notion that human behaviour 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." James (1890/1981, p.1112). Or, as Anthony Greenwald put it 80 years later: "…a current response is selected on the basis of its own anticipated sensory feedback" (Greenwald, 1970, p.93).

As already mentioned, the ideo-motor principle (IMP) currently experiences a renaissance. The anticipatory control of voluntary acts is not only theoretically debated again (e.g. Hoffmann, 1993, 2003, 2009, Hommel, 1998, 2003, Prinz 1990, 1998, 2005) but also experimentally explored. Consider for example the following study by Elsner and Hommel (2001). In this study participants first were instructed to choose between pressing a left key with the index finger of the left hand or a right key with the index finger of the right hand in response to a unitary go-signal. During this acquisition phase, pressing the left key was contingently followed by a high pitch tone and pressing the right key was contingently followed by a low pitch tone (or vice versa). In accordance with the IMP, the authors hypothesized that the key presses would automatically be associated to the subsequent effect tones. Therefore, they argued, the perception of the effect tones should be able to prime the associated key presses of the left or the right hand.

These assumptions were examined in a test phase in which the effect-tones were used as imperative stimuli for left or right key presses. In the non-reversal group, each tone required the key press that previously had been associated with the tone, whereas in the reversal group, each tone required the key press that previously had been associated with the alternative tone. Participants in the non-reversal group responded more quickly than participants in the reversal group. In agreement with the IMP, the authors concluded that experiencing the co-occurrence of voluntary key presses and subsequent tones leads to an association of the action code and the cognitive code of the tone. Moreover, the emerging associations are bidirectional so that perceiving the tone automatically primes the associated action. (p. 238, c.f. also Hoffmann et al., 2009, for a detailed analyses of the formed action-effect associations).

Many other studies have also confirmed the general notion that voluntary acts are preceded by anticipations of the sensory effects they produce (e.g. Elsner & Hommel 2004; Hoffmann et al., 2007; Hommel, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kunde, 2001, 2003; Kunde, Hoffmann, & Zellmann, 2002; Kunde, Koch, & Hoffmann, 2004; Koch & Kunde, 2002; Stöcker, Sebald, & Hoffmann, J., 2003; Ziessler, 1998; Ziessler & Nattkemper, 2001, 2002; Ziessler, Nattkemper, & Frensch, 2004). As an advanced anticipation of the to-be-produced effects presupposes that actions become associated with their effects, the formation of action-effect associations appears to be an elementary and presumably unavoidable mechanism underlying animal as well as human learning.

Hoffmann (1993, 2003, 2009; Hoffmann, Stöcker, & Kunde, 2004; Hoffmann, et al., 2007) proposed a tentative framework for the acquisition of "conditionalized action-effect relations". The framework is based on the following assumptions (cf. Figure 1):

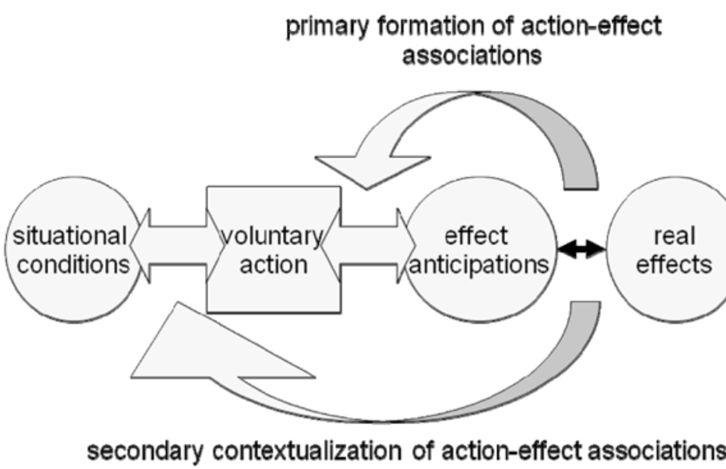

Figure 1
Illustration of the Anticipatory Behavioral Control (ABC) framework, involving the acquisition of anticipative structures for the control of voluntary behaviour

1. A voluntary action is defined as performing an act to attain some desired outcome or effect. Thus, a desired outcome, however general and imprecisely specified in the beginning, must be retrieved from memory before a voluntary action can be performed. Consequently, it is supposed that all voluntary acts are preceded by corresponding effect anticipations.
2. The actual effects are compared to the anticipated effects. If there is sufficient coincidence between what was desired and what happens, traces of the just-performed action and the 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 behavioural 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 a secondary learning process.
4. An ´emerging´ need or a desire activates action-effect representations whose stored outcomes sufficiently coincide with what is needed or desired. Thus, anticipations of effects activate the actions that are appropriate to produce them. If the activated action-effect representations are conditionalized, the agreement between the stored conditions and the current situation is checked. In general, the action will be performed that in the current situational context is most likely to produce 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 produced repeatedly by a certain action can elicit the readiness to produce this outcome by that action again.

The sketched framework integrates, although still rather roughly, important aspects of the acquisition of behavioural competence. First, it considers the commonly accepted fact that behaviour is almost always goal oriented instead of being stimulus driven. Second, it is assumed that any effect meeting an anticipated outcome will act as a reinforcer. Consequently, learning is not only driven by the satisfaction of needs but by anticipations, which can flexibly refer to any goal. Third, the framework considers the available evidence that voluntary behaviour is primarily determined by action-effects instead of by stimulus-response associations. Finally, also stimulus driven habitual behaviour 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.

The advantages of action-effect learning in comparison to stimulus-response learning are obvious. With the acquisition of reliable action-effect relations organisms become increasingly independent of the current situation. Instead of re-acting to the present stimulation they learn to behave in order to produce the future states they currently desire. As a consequence, stimulus driven behaviour becomes more and more replaced by goal oriented behaviour so that organisms start to create the environment according to their needs. Presumably for this reason action-effect learning was established early in the course of evolution (cf. Gerber & Hendel, 2006, for hints of action-effect learning in such primitive animals as fly larves).

Short Term memory as a requirement for the formation of action-effect relations

According to the Anticipatory Behavioural Control (ABC) framework, action-effect couplings conditionalized to critical situational contexts are the main result of the acquisition of behavioural competence. Thus, conditionalized action-effect structures constitute a prominent part of the developing long term memory structures, in particular of what is called 'procedural memory'. However, action-effect learning not only creates memory structures, it also requires memory itself to take place. William James already expressed this necessity in a simple thought (1890/1981, S.1099): "When a particular movement, having once occurred in a random, reflex, or involuntary way, has left an image of itself in the memory, then the movement can be desired again, proposed as an end, and deliberately willed. But it is impossible to see how it could be willed before". Accordingly, an action can be deliberately performed in order to produce a future state only if there is a memory of it, and it can be willed by reactivating the corresponding memory trace.

The critical part in William James's quotation refers to the idea that an action "leaves an image of itself in the memory" so that it can be reactivated later. Everybody agrees that the 'place' of memory is the Central Nervous System (CNS). Thus, the phrase that an "action leaves an image of itself in memory" can be understood as the statement that the neuronal activities underlying the selection, initiation and execution of an action leave traces in the brain, which allow their re-activation. With regard to the ABC framework, the corresponding neuronal activities comprise all the afferent and efferent activation patterns that underlie the voluntarily acting. I assume that in particular the covariations between the efferent and afferent impulses cause the changes in the related neuronal networks that facilitate a reactivation of the same activation patterns if required. It is not the place here to discuss speculations about the concrete nature of these traces (cf. Butz, Herbort, & Hoffmann, 2007; Hoffmann, et al., 2009). In the present context, I only want to emphasize that not the external stimuli leave the traces in the brain. Traces can only be left by the neuronal activities evoked by the stimulation and these activities depend both on the current stimuli and on the current actions. For example, when one sees a word, the memory trace it leaves will depend on whether one reads the word, is looking for a rhyme, or is trying to imagine what the word denotes, etc. Thus, it is not the word that leaves traces in the brain but what has been done with the word. Likewise, if one looks at a picture or is watching a scene, it are not the visual stimuli that are stored but what they have evoked in the brain, and this again depends on what one has been doing (i.e., it depends on how the gaze moved over the scene, which details attracted attention, or whether one was trying to generate a verbal description of the scene, etc.).

The statement that only what happens in the brain can leave traces in the brain is trivial. However, the idea that the brain activity responsible for the formation of memory structures depends as much on the actions performed as on the external stimulus is usually overlooked and deserves careful consideration, because it explains why brain activity leaves memory traces that can be used to facilitate the reactivation of the traces. Given that the environment is permanently available as an outside memory, it is not self-evident why organisms would store information about the environment in their brains (cf. O'Regan, 1992). The argument is that not "information about the environment" is stored but "images of actions performed in the environment". These images comprise sensory (afferent) as well motor (efferent)representations and they are stored to be able to select an appropriate action in order to generate a desired future state, i.e. in order to enable goal oriented behaviour. In this sense one may state that memory did not emerge in order to recollect the past but to anticipate the future.

Memory relies on the traces "actions" leave in the brain

The notion that any action leaves an "image" in the mind finds its counterpart in several theoretical approaches of memory, which highlight that memory primarily consists of the processes (actions) applied to the stimulus materials. The most prominent approach of this kind is the concept of *working memory.* Working memory has been described as "the means by which human beings maintain, manipulate, and reinterpret, on a moment to moment basis, information that is required for successful performance on a range of everyday tasks …" (Logie, 2003, p.37). Accordingly, memory is not seen as a store for externally presented information but as an inevitable by-product of everyday activities, in the same way as the ABC framework hypothesizes that all voluntary acts leave traces in the mind.

Working memory comprises the traces left by the ongoing interactions with the environment. Different types of interactions leave different traces, depending on the aspects of material that have been processed. Accordingly, working memory has been conceptualized as a "multiple component mental workspace" (Logie, 2003). When the concept of working memory was initially proposed by Alan Baddeley and Graham Hitch (1974), three such components were identified: "…we proposed a model of working memory in which a controlling attentional system supervises and coordinate a number of subsidiary slave systems. We termed the attentional controller the central executive and choose to study two slave systems in more detail, the articulatory or phonological loop, which was assumed to be responsible for the manipulation of speech based information, and the visuo-spatial scratchpad or sketchpad, which was assumed to be responsible for setting up and manipulating visual images" (Baddeley, 1997, p.52)[1].

Since the initial formulation of the model, countless studies have investigated the impact processes in the phonological loop and the visuo-spatial sketchpad have on memory performance (cf. Baddeley 2007). The results soon pointed to further differentiations. For example, it has been shown that processing "speech based information", in particular lists of words or lists of letters, not only involves the phonological loop but also visual processes. The memory performance for word lists is influenced not only by the phonological similarity but also by the visual similarity of the presented items (e.g. Logie, et al., 2000). Likewise, the processes in the visuo-spatial sketchpad required further fractionation, such as a distinction between the processes dealing with the visual appearance of objects and the processes dealing with locations and movements in space. For example, the retention of visual appearance information, such as the colour or geometric form of a stimulus, is disrupted by a concurrent presentation of irrelevant visual stimuli, whereas the retention of the locations of objects is disrupted by a concurrent movement discrimination task, but not vice versa (e.g. Logie & Marchetti, 1991). Neuropsychological evidence also supports a distinction between visual and spatial memory, because both types of memories can be impaired independently by damage to the brain (cf. Logie 2003, Logie & van der Meulen 2009 for comprehensive overviews).

[1]Baddeley (2002) introduced the "episodic buffer" as another slave system for storing reactivated information from Long-Term-Memory.

Not only the theory of working memory is in line with the ABC framework. Also the *levels of processing* approach defended the notion that memory relies on the processing done on the stimulus materials (Craik & Lockhart, 1972). In this approach it was assumed that stimulus processing typically starts with a "shallow" analyses of the simple sensory features, then goes on to recode the stimulus in another modality (for example a phonological re-coding of visually presented words), and finally proceeds to a "deep" semantic analysis of the presented information, whereby the strength of the memory traces is assumed to increase with the depth of processing. In agreement with the levels of processing approach it was shown that words are better remembered (recognised) when the words have been judged with respect to their meaning (deep processing) than when they have been judged with respect to their visual appearance (shallow processing, Craik & Tulving, 1975). Later it was shown that the "processing depth" does not so much modulate the strength of the resulting memory traces but their quality, i.e. the aspects that are stored. For example, if subjects are asked to make rhyme judgments on the stimulus words, phonological features of the words are preferably stored and if they are asked to make semantic judgments on the words the meaning of the words is preferably stored, both in approximately comparable strength (Morris, Bransford, & Franks, 1977). In this respect, the metaphor of processing levels is misleading, because it suggests a unitary dimension with quantitative differences, whereas the evidence is more line with qualitative differences (different types of memory traces). Nevertheless, the tenet of the *levels of processing* concept was that memory is determined by the processes (the actions) applied to the presented material.

The theories of *working memory* and *levels of processing* still primarily deal with the ways in which mental processes like rehearsal, imagery, and judgments affect memory. In contrast, the ABC framework focuses on the control of motor behaviour. Evidence that motor actions indeed have impact on the formation of memory traces comes from a new paradigm of memory research, which has been called *self performed tasks* (Engelkamp & Krumnacker, 1980; Cohen 1981). In this paradigm, participants are asked to remember a list of short statements like "close a book", "comb your hair", "strike a match", or "open a bottle" either by performing the denoted actions during the encoding or by reading or hearing the commands. The main result is that memory performance is much better after performing the actions than after merely reading or listening to the list of statements. It was even found that incidental memory after action performance was superior to verbal memory after an explicit memorizing instruction; that is, merely acting seems to suffice to lay down memory traces which were, under the tested circumstances, easier to retrieve than traces formed by explicit memorizing strategies such as rehearsal (cf. Zimmer, & Cohen, 2001). These results made

Kausler (1989) conclude that "…memory for the content of our own activities seems to be an everyday example of rehearsal independent memory" (p.63). Kausler's conclusion is completely in line with the hypothesis that any action automatically leaves an image of itself in memory. Numerous further studies have been run to specify which subprocesses of action contribute to the memory improvement, such as planning the action, executing it, or monitoring its sensory feedback. It is not the place here to discuss this research (cf. Zimmer, et al., 2001). It is enough to mention that the strong impact motor actions have on the formation of action specific memory traces confirms the central function these traces have in the ABC framework for the formation of anticipative structures to control voluntary behaviour.

If one assumes that memory relies on the actions or the processes performed on the presented stimulus material, it follows that no traces will be laid out, or at least no enduring traces, if the material is not processed at all. There are many examples for such "memory neglects". For example, it is common knowledge that we have difficulties recalling the exact appearance of things in our daily environment even though we see them numerous times a day, as for example our arm watch or the coins we use (e.g. Nickerson & Adams, 1979; Rubin & Kontis, 1983). Typically, the details of such objects are not or erroneously reported, presumably because they are irrelevant for use so that they are not attended to. However, not only tiny details fail to leave a memory trace; also salient stimuli are not remembered if they have not been attended to or were otherwise involved in the participant's behaviour. An illustrative example for such a failure to build memory traces of salient stimuli can be found in a study by Hoffmann and Sebald (2005).

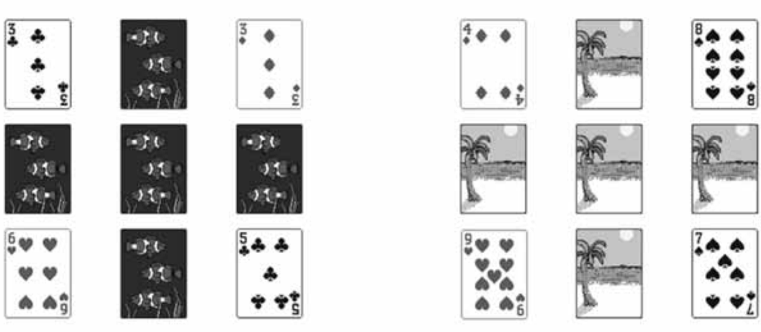

Figure 2

Illustration of the displays used by Hoffmann & Sebald (2005). Participants were asked to respond to two target cards (e.g., 6 of hearts and 7 of spades) with a right and a left keypress respectively. The salient pictures on the back of the cards (A - fish or B - palms) reliably predicted the required response in 10 consecutive blocks

In this study participants were asked to respond with a left or a right key press to a particular detail of a series of displays which additionally varied in one salient feature (cf. Figure 2). In 10 blocks of 50 trials, the required response was reliably predicted by the salient feature, so that, for example, feature A always went along with a left and feature B always went along with a right key press. In Block 11 this covariation was abolished. Eight of the 16 participants detected the covariation, i.e. they formed a relation between the salient feature and the response. Correspondingly, reaction times (RTs) of these participants continuously decreased up to block 10 and increased again in block 11 where the relation no longer worked. In contrast, the RTs of the other participants, who failed to notice the relationship, showed merely marginal training effect, despite the fact that S-R combinations had been experienced in a total of 500 trials (cf. Figure 3). If the existing S-R relation was explained after the experiment, these "unaware" participants were extremely surprised. They reported to have noticed the salient feature but had not related it to the required response decision. Consequently, the salient feature was not integrated into the "images" of the performed actions (cf. Hendrickx, et al., 1997; Jiménez, & Méndez, 1999; Wolfe et al., 2000; for further evidence).

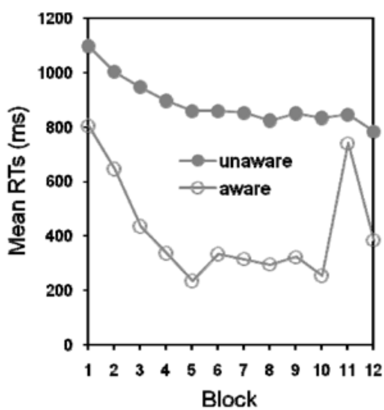

Figure 3
Mean RTs of the participants in the study of Hoffmann & Sebald (2005), who were either aware or unaware of a predictive covariation between a salient but irrelevant feature of the used displays and the required response. In Block 11 the covariation was abolished.

Returning to the *working memory theory*, the central executive within this theory remains to be discussed. As mentioned before, the central executive was initially considered as a unitary attentional system supervising and coordinating the different slave systems like the phonological loop and the visual-spatial sketchpad. However, as the research on working memory advanced, the central executive met the same fate as the "slave systems": it was fractionated into several autonomous executive processes (e.g. Baddeley, 1996; De Rammelaere, & Vandierendonck, 2001; Vandierendonck, 2000; Vandierendonck, De Vooght, & Van der Goten, 1998). Among the processes discussed are memory retrieval, orienting of attention, response selection, and monitoring. All these processes are constituent parts of voluntary behaviour: In order to achieve a current goal appropriate actions (i.e. situation-action-effect triples) must be retrieved from Long Term Memory, the most appropriate act has to be selected, attention has to be oriented to the situational conditions stored as critical for success of the selected behaviour, and, finally, the behavioural consequences must be monitored to control whether the goal is coming closer or not. Thus, it appears that the processes typically associated with the central executive also have their origin in the mechanisms of goal oriented behaviour.

Resume

The present essay was about the origin of memory, in particular the origin of short term memory. The basic speculation is that short term memory emerges to support the transition from stimulus driven behaviour to goal oriented behaviour. Goal oriented behaviour presupposes that all behavioural acts leave "images" in the mind. Accordingly, neuronal structures have evolved which are able to preserve traces of the senso-motor activation patterns associated with the action, so that previously performed acts can be re-activated if their outcomes are desired later again. Thus, the traces left by action performance constitute the contents of short term memory. We do not store stimuli but we store what we have done with the stimuli, and if we have done nothing with a stimulus, no trace of it is left. According to the ABC framework, there are as many qualitatively different memory traces as there are types of processing and acting that can distinguished of . These traces are formed to preserve the different processing aspects in which the sensory and motor systems have been engaged. Whether these traces are to be clustered into a few "slave" systems for the memorization of information or whether it is more appropriate to think of them as mere bundles of autonomous, action-dependent, processes (e.g. Cowan, 1999, Oberauer, 2002) is not decisive in my view. In both perspectives the contents of short term memory originate from voluntary actions .

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