

## Chapter 2

# Learning Principles

In past decades, educational research has put major efforts into the development and evaluation of ‘modern’ learning environments which are characterized by an emphasis on (structured) self-directed learning, the acquisition of insightful, conceptual, knowledge, and collaborative learning. They also embed the content in a (multimodal and multi-representational) realistic context (Mayer, 2001). The current chapter focuses on the representation of learning materials in relation to the functioning of the brain, the role of cognitive load in learning, the role of implicit learning, characteristics of insightful knowledge, higher order skills associated with (structured) self-regulated learning and learning in social situations through observation and imitation. Though the latter may also be considered an aspect of collaborative learning, to our knowledge, collaborative learning is an aspect from contemporary educational theories that has not yet been addressed by neuroscientific research.

## 2.1 Multimodal Processing

### 2.1.1 Education

Dual coding theory (Paivio, 1979, 1986) states that recall is enhanced by presenting information in both visual and verbal form. The theory assumes that there are two cognitive subsystems, one specialized for the representation and processing of non-verbal information and the other specialized for dealing with language. Baddeley’s model of working memory states that there is a central executive and two separate ‘slave’ systems for dealing with auditory and visual information, the phonological loop and the visuo-spatial sketchpad, respectively (Baddeley & Hitch, 1974). Later, another component was added: the episodic buffer (Baddeley, 2000). Although there has been criticisms of Paivio’s theory (see e.g., Fliessbach, Weis, Klaver, Elger, & Weber, 2006; van Hell & de Groot, 1998), dual coding theory often forms the basis of educational design. Inspired by Paivio’s and Baddeley’s work, research on multimedia learning has tested the assumption that spreading information over auditory and visual modalities (pictures/animations and spoken text) leads to lower cognitive

load on working memory and better learning outcomes than presenting information in a single modality (pictures/animations with written text). These results were often found (at least under restricted time conditions) and have come to be known as the ‘modality effect’ (see Low & Sweller, 2005).

### 2.1.2 Cognitive Neuroscience

In cognitive psychology, a distinction is made between verbal and non-verbal working memory, and within both types, between auditory and visual working memory. However, as is also the case in Paivio’s theory, not all authors define their terms very clearly and sometimes grey areas remain (e.g., would visual stimuli that can be named be classified as verbal or non-verbal?). In recent years there has been a tremendous amount of research investigating how aspects of working memory, verbal learning, and how the use of strategies and/or the organization of memory performance are related to brain function through the use of functional brain imaging (fMRI or PET).<sup>1</sup> The following account provides three examples of cognitive neuroscience research pertinent to educational science and practice.

Beauchamp, Lee, Argall, and Martin (2004) found an enhanced activation of the posterior superior temporal sulcus and middle temporal gyrus (pSTS/MTG) when auditory and visual object features (of man-made objects (tools) and animals) were presented together, as compared to presentation in a single modality. Crottaz-Herbette, Anagnoson, and Menon (2004) investigated similarities and differences between visual verbal working memory and auditory verbal working memory. Their findings suggest that although similar regions are involved in both auditory and visual verbal working memory, there are modality differences in the way in which neural signals are generated, processed, and routed. Another study that is interesting in this respect comes from Kirchhoff and Buckner (2006). In an attempt to explain differences in memory abilities between individuals, they used fMRI to investigate the effects of the use of different encoding strategies on memory performance (in their study: retrieval of object associations). They showed that individuals’ use of verbal elaboration and visual inspection strategies independently correlated with memory performance as operationalised by retrieval of object associations and that these strategies engage distinct brain regions that may separately influence memory performance.

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<sup>1</sup>In this volume, basically three techniques for measuring brain activity are mentioned. *fMRI* (Functional magnetic resonance imaging) is a neuroimaging technique that registers changes in blood flow and blood oxygenation in the brain (haemodynamic response) related to neural activity. fMRI’s are acquired in an fMRI scanner. *PET* (Positron Emission Tomography) images of the brain are also taken in a scanner and also images blood flow in the brain. In PET, a radioactive isotope must be injected into the blood stream. *EEG* (Electroencephalography) measures electrical activity produced by the brain via electrodes that are placed on the scalp. EEG measurement has a higher temporal resolution than fMRI and PET, and, in contrast to fMRI and PET techniques, EEG allows for data acquisition in natural settings.

### **2.1.3 Future Directions**

The findings by Beauchamp et al. (2004) were based on features that are different in modality but belong to the same object (e.g., animal, tool) and were relatively simple, so the question remains whether this finding would hold, for example, for a stimulus consisting of spoken text and picture about a certain topic. Investigating implications for the redundancy effect (e.g., presenting the same text in written and spoken form should hamper processing as compared to using one representation) from a neural perspective would also be interesting, as the findings by Crottaz-Herbette et al. (2004) suggest that the same brain regions are activated in response to stimuli in auditory and visual verbal working memory but different processes occur.

## **2.2 Learning from Multiple Representations**

### **2.2.1 Education**

A representation is something that stands for something else (Palmer, 1978) and nowadays many such representations, usually conveying the same information, are combined to form multiple representations, for example in textbooks, where text and illustrations (photographs, and, or line drawings) try to convey a message to students or in multimedia environments where (interactive) videos, text, diagrams and other representations are combined.

In an overview on learning with such multiple representations de Jong et al. (1998) mention three reasons for introducing more than one type of representation in one learning environment. These reasons concern aspects of specificity, expertise, and sequence. According to de Jong et al. (1998) information that is specific for a certain topic should be displayed in a format that is best suited for that topic, hence in a specific representation. Given the vast variety of information to be conveyed in a complete set of learning materials, this would require several types of representations. de Jong et al.'s second reason for the use of multiple representation concerns expertise because, according to the authors, expertise is quite often seen as the possession and coordinated use of multiple representations of the same domain. A third reason for the use of multiple representations is based upon the assumption that a specified sequence of learning materials is beneficial for the learning process (de Jong et al., 1998). When learning with such multiple representations, learners are confronted with several tasks. They have to learn to understand the particulars of each separate representation, they have to understand the relation between the representation and the domain it is representing, and they have to understand the relation between separate representations (cf. Ainsworth, Bibby, & Wood, 1997). The beneficial effects of multiple representations depend on various factors, including the specific type of multiple representation employed (i.e., concurrent presentation or transitional (dynamic linking) presentations), type of domain to which the learning material belongs, the type of test used to assess the effect,

subject variables, and aspects related to instructional help (see e.g., Seufert, 2003; van der Meij & de Jong, 2006).

### 2.2.2 *Cognitive Neuroscience*

The debate in cognitive neuroscience concerning the question as to whether there are separate representations associated with different input modalities (e.g., Paivio, 1991) or whether inputs from different modalities combine into a common (set of) representations (e.g., Rapp, Hillis, & Caramazza, 1993) is still unsettled (see also Section 2.1 on multimodal processing). Multimodal processing is not necessarily implicated in multiple representations, because the latter processing is usually restricted to the visual domain (albeit that visual information, particularly words, may to some extent illicit processing related to the auditory domain, e.g., inner speech). Sometimes, however, multimodality is not implemented with respect to the different primary sensory domains (e.g., visual or auditory), but as instances of different representations of the same cognitive concept within a single sensory modality. For example, in studying semantics and its neurophysiological representation in the brain, words and pictures presented in the visual domain have been shown to partially share a neuronal substrate. The anterior part of the fusiform gyrus was implicated in the representation of conceptual knowledge, irrespective of the modality of the visual input (visual word or picture), meaning that there is a single semantic representation, which also commonly recruited the left parahippocampal and perirhinal cortex and the left inferior frontal gyrus, but word-specific activations were found in the anterior temporal cortex and picture-specific activations in the occipitotemporal cortex (Bright, Moss, & Tyler, 2004; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996).

Similarly, with respect to the concept of numeracy, the single cognitive concept of the number 2, can be activated by an auditory representation (the spoken word ‘two’) or visual representations of the word ‘two’ or the Arabic digit ‘2’ or maybe by presenting two instances of some arbitrary visual or auditory stimulus. Domain specific brain correlates have been found in the horizontal segment of the intraparietal sulcus, a bilateral region in the posterior superior parietal lobule involved in visuospatial and attentional processes. In addition, activation was observed in the left angular gyrus (also known as the visual word form area) and left-hemispheric perisylvian areas, which are not specific to the number domain but relate to aspects of language, including verbal coding (Dehaene, Piazza, Pinel, & Cohen, 2003) (see also Chapter 5).

These two examples of multiple representations are relevant to the question of the effect of multiple representations in the learning environment, in the sense that they illustrate single concepts (semantics, number), comparable to the single conceptual message or information that has to be communicated in the multi-representational learning environment. However, there are also (fundamental) differences, because in the former examples stimuli are usually statically and successively presented,

whereas in the multi representational learning situations, stimulation can be either static or dynamic and multiple representations of the information are usually simultaneously presented.

### 2.2.3 *Future Directions*

There are several relevant issues in cognitive neuroscience that may help to clarify the neurophysiological underpinnings of learning with multiple representations and may help to explain how these representations are cognitively processed and how they lead to deeper understanding.

One of these topics relates to selective attention. The different representations (assuming that they are simultaneously present) cannot be simultaneously processed in a conscious way. It would therefore be advantageous to know what determines the order in which they are processed and to find out whether this order determines the quality of processing. One relevant question in this respect concerns, for example, whether (initial or subsequent) selection of different representations relates to the amount of redundancy of the information that is conveyed by them ('complementary functions', Ainsworth, 1999).

Another relevant aspect related to the processing of multiple representations concerns memory load and attentional resources (see e.g., Bunge, Klingberg, Jacobsen, & Gabrieli, 2000). Neurophysiological research could clarify how simultaneously presented multiple representations share such resources, how they impose memory load, and how this relates to task demands. Issues from the dual task literature may be relevant here, although in such paradigms subjects explicitly have to ignore one (secondary) task in favour of another (primary) task, while in the case of multiple representations, subjects are free to divide their (limited capacity) attentional resources.

Research could also aim toward unravelling the contribution of separate representations underlying the simultaneous representation. Does processing a graph differ from that of a concrete instance or animation of the same topic (when controlled for differences in, for example, dynamics and physical visual features)? Insight into this matter could be obtained by studying synchronized networks in the brain, as manifested in patterns of cortical coherence (see e.g., Tallon-Baudry & Bertrand, 1999). Relevant questions include: Are these patterns stable over time or do their dynamics reveal aspects of learning? Do separate coherence patterns, for separate representations, sum up to the coherence pattern of the multiple representations?

In addition, future research should also aim at disentangling maintenance of longer term goal directed processing from that of separate (transient) processing of the multiple representations that have to be inspected to achieve a goal (cf. Dosenbach et al., 2007).

Further, simultaneously presenting different representations of the same (or highly similar) information may lead to redundancy and possibly to competition

with respect to access to the neural substrate for elaborate processing, especially when there is an overlap in the brain areas involved, as has been shown in multi-modal processing (see Section 2.1). Future research should shed light on this issue.

## 2.3 Cognitive Load

### 2.3.1 *Education*

Cognitive load theory (CLT, Sweller, 1988; Sweller, van Merriënboer, & Paas, 1998; van Merriënboer & Sweller, 2005) proposes that in order to be effective, learning materials should be designed in a way that takes human cognitive architecture into account. The model of cognitive architecture used in CLT consists of a working memory that is limited in capacity and time when it comes to holding or processing novel information (see Cowan, 2001; Miller, 1956), and a long-term memory with virtually unlimited capacity. Working memory limitations regarding novel information are a bottleneck when it comes to learning. Only  $7 \pm 2$  information elements can be held in working memory, and the number decreases (Cowan, 2001) when information not only has to be remembered (e.g., word lists), but also processed (i.e., when elements inter-relate and have to be combined, as in solving a math problem). However, information that has already been stored in long-term memory (in the form of cognitive schemata) can be handled in working memory as a single information element. Therefore, having prior knowledge (or expertise) of a certain task lowers the cognitive load imposed by that task, leaving more capacity available for other processes (e.g., deeper elaboration). Moreover, when a task or aspects of a task are repeatedly practiced (i.e., with increasing expertise), cognitive schemata become automated, and no longer require controlled processing (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), which further frees up working memory resources. In sum, prior domain knowledge or expertise leads to more efficient processing.

### 2.3.2 *Cognitive Neuroscience*

Neuroscience research into the mechanisms underlying cognitive load has been done in the past decade using PET, fMRI, and EEG. Using PET, Jonides et al. (1997) found that increases in task difficulty on a verbal task were associated with decreases in performance and increases in activation patterns in verbal working memory regions. Using fMRI, Jansma, Ramsey, Slagter, and Kahn (2001) showed that automatic processing that occurs due to repeated practice of a task is visible on a behavioural level in faster, less variable, and more accurate responses. At a neural level, such automatic processing results in a decrease in activation in the regions related to working memory. It should be noted, however, that these authors found no evidence for a shift of foci within or across regions of the brain. In addition to domain expertise, a higher level of intelligence also seems to be associated with

higher efficiency of processing (neural efficiency). Using EEG, Grabner, Neubauer, and Stern (2006) studied the effects of chess players' intelligence and expertise on tasks related to mental speed, memory and reasoning (half the tasks were chess related, the other half were not). They concluded that intelligence and expertise influenced the efficiency of brain processing independently of each other. Participants with higher (figural) intelligence displayed a lower amount of cortical activation (interpreted as an indication of higher efficiency) than less intelligent participants, and (figural) intelligence did not lose its impact on neural efficiency when expertise is involved. Interestingly, expertise did have effects (more focused activation patterns) on the speed and reasoning tasks, but not on the memory tasks. The authors speculated that this might be due to the activation of a larger knowledge base, the use of more deliberate strategies, or both. They also indicate that it remains unclear whether this can be regarded as an indicator of neural efficiency.

### ***2.3.3 Future Directions***

The finding that higher intelligence is associated with higher neural efficiency is very interesting, but raises a causality question. Grabner et al.'s (2006) findings on the memory task show that neuroscientific methods might have the same drawback as the cognitive load measures do when used in educational research: the fact that certain regions are activated to a certain extent (or that a certain amount of load is imposed) does not always reveal which cognitive processes are occurring (or impose the load), and uncovering these processes is crucial for understanding learning or performance outcomes. Thus, an important route for future research is to deepen our understanding of brain activation patterns in relation to particular cognitive and learning processes, for instance, through the combined use of measurements from neuroscience and quantitative and qualitative (but potentially subjective) process measures such as eye movement data or thinking aloud protocols and retrospective reports (cf. van Gog, Paas, & van Merriënboer, 2005; van Gog, Paas, van Merriënboer, & Witte, 2005). New experimental paradigms to combine neurocognitive measures and measures of learning processes and educational performance should be developed.

## **2.4 Insightful Problem Solving**

### ***2.4.1 Education***

In education there is a shift of attention from problems that can be solved in an algorithmic way to problems that require insight and conceptual knowledge (Bransford, Brown, & Cocking, 1999). According to Bowden, Jung-Beeman, Fleck, and Kounios (2005), 'insight solutions differ from non-insight solutions in a number of ways: (i) solvers experience these solutions as sudden and obviously correct

(the Aha!), (ii) prior to producing an insight solution, solvers sometimes come to an impasse, no longer progressing towards a solution, and (iii) solvers usually cannot report the processing that enables them to overcome an impasse and reach a solution' (pp. 322–323). According to Ohlsson (1992) 'insight occurs in the context of an impasse, which is unmerited in the sense that the thinker is, in fact, competent to solve the problem' (p. 4). In other words, if you do not have the prerequisite knowledge you can never have insight. However, insights can also be wrong. Moreover, insight also has a subjective component: one can have insight experiences (Aha Erlebnisse) on non-insight, (incremental) problems (e.g., some algebra problems).

Insight occurs usually due to a shift in problem representation, or re-representation. Often problems are not adequately represented, because not all relevant information is available. Another important consideration is the extent to which the representation enables inferences to be drawn: it may be unknown what relevant inferences are, or the representation may not enable any inferences at all. A well-known insight problem is Maier's (1931) two strings problem. His experiment also showed that small hints (the experimenter 'accidentally' brushing against the strings) can lead to a re-representation, without the learners even realizing they had got a hint.

Metcalf (1986) and Metcalfe and Wiebe (1987) have shown that for non-insight problems, students were able to give warmth ratings that increased every few seconds, indicating they were coming closer to a solution. For insight problems however, these ratings did not increase until just before the solution was found, suggesting that insight occurs suddenly. This was further corroborated by Jausovec and Bakracevic (1995) who demonstrated that heart rate during problem solving is also dependent on the kind of problem solved. Incremental problems are accompanied by a steadily increasing heart rate, while insight problems can be recognized by a steady heart rate that suddenly increases at the end (supposedly when the insight occurs). This seems strong evidence for a difference between finding solutions in incremental non-insight problems and genuine insight problems.

### **2.4.2 Cognitive Neuroscience**

Jung-Beeman et al. (2004) conducted a study on neural activity during insight and non-insight problem solving. They note that some questions about insight persist: whether unconscious processing precedes reinterpretation and solution, whether distinct cognitive and neural mechanisms beyond a common problem-solving network are involved in insight, and whether the apparent suddenness of insight solutions reflects truly sudden changes in cognitive processing and neural activity.

Jung-Beeman et al. (2004) hypothesize that the anterior superior temporal gyrus of the right hemisphere (RH), which is important for recognizing distant semantic relations, might play an important role in insight on verbal remote association problems. This hypothesis is based on previous studies by two of the authors (Bowden & Beeman, 1998). In that study, they found that when people were presented with

potential solution words for the association task (actual solution and unrelated words), while working on a verbal problem they had yet to solve, the actual solution words were read faster than the unrelated words, and that this effect was larger when words were presented in the left visual hemifield, meaning they were projected into the RH. This RH advantage occurred only when solvers experienced insight. Trials consisted of verbal association problems in which three words were presented and the task was to find a single word that could combine with each of the three words to form new words (e.g., pine, crab, sauce → apple). Participants were asked whether they experienced insight or not, and differences in processing of insight and non-insight solutions were investigated. In their first experiment, fMRI was used. Participants solved 59% of the problems. Of the solved problems, they indicated (by a bimanual button press and subsequent verbalization of the solution word) solving 56% with insight, 41% without insight (and 2% other). As predicted, insight solutions were associated with greater neural activity in the RH anterior superior temporal gyrus (aSTG) than non-insight solutions. Although insight solutions may sometimes produce a strong emotional response, this is not likely to be due to the insight itself, as the area also showed increased activation when participants first encountered each problem. No insight effects occurred in the temporal cortex of the LH, and involvement of the RH did not appear to be due to greater difficulty in producing insight solutions given that solution times did not differ for insight and non-insight solutions.

In a second experiment, Jung-Beeman et al. (2004) investigated whether insight really occurs suddenly as studies by Metcalfe (1986), for example, suggest. They used EEG because of its greater temporal resolution. They expected to see a sudden increase in high-frequency gamma band oscillations in electrodes over the RH aSTG just before insight. In this experiment, 46% of problems were solved correctly, 56% of those reportedly with insight. A burst of high-frequency gamma band activity was associated with correct insight solutions, but not with non-insight solutions, approximately 0.3 seconds before the button was pressed to indicate the solution. Again, there was no difference between insight and non insight solutions in LH. The gamma burst could not be related to the motor response, because the button press was done bimanually (i.e., should have increased activation in both hemispheres) and both insight and non-insight problems required button presses. This study suggests that semantic integration (occurring in the RH aSTG) is important for connecting various problem elements together and for connecting the problem to the solution, leading to insight, at least for verbal problems.

In a recent attempt to further unravel the neurobiological underpinnings of insight problem solving, Sandkuhler and Bhattacharya (2008) extended their search to four different aspects of insightful problem solving: mental impasse, restructuring of the problem, deeper understanding of the problem, and the suddenness of the solution, all during performance in a compound remote association task. They found neural correlates for mental impasse in parieto-occipital brain regions in the gamma frequency band (selective attention) and theta frequency band (working memory) which, according to the authors, suggested increased top-down control and increased memory search leading to attentional overload. Moreover, functional

fixedness of the mental impasse was associated with increased gamma frequency band activity in right parieto-occipital regions. Parieto-occipital gamma band frequencies were also stronger for correct solutions (deep insight) than for incorrect false positive solutions (there was subjective insight but it was incorrect, thus leading to less deep understanding). The right prefrontal brain regions were implicated in the restructuring of the problem, here alpha band frequencies were increased compared to no restructuring conditions, and this result showed consistency with involvement of this brain region in planning open-ended tasks. Suddenness of the solution was likewise related to power in the gamma frequency band (38–44 Hz) at parieto-occipital regions mainly in the right hemisphere, just before resolution response. Again, as was also reported by Jung-Beeman et al. (2004) the right hemisphere appears to be mainly involved in both mental impasse, the restructuring of the problem, and the suddenness of the solution.

### ***2.4.3 Future Directions***

Neurophysiological studies in insight problem solving have almost invariably employed (language related) compound association-like tasks. Sometimes, hints were given to the subjects to improve their performance and thus to elicit ‘insight’. Of course, such highly controlled artificial conditions do not score high on ecological validity. Moreover, (artificial) insight as elicited under such conditions may be different from real-life insight and may also be governed by different underlying cognitive- and neurophysiological mechanisms. Therefore, in order to complement current neurophysiological knowledge on insight, and to approximate real-life insightful problem solving, studies could be designed where more complex concepts rather than words or numbers have to be ‘discovered’, for example the rules or mechanism underlying (simple) physical problems (e.g., gravity, momentum) such as employed in inquiry learning. Further, the role of memory (overload) and the role of attention switching should be explored. Another area of research concerns the precise role of the right hemisphere, which can be explored by selectively presenting visual input to the right (LH) or left (RH) visual field. Future research should also clarify the role of the reported RH gamma just before insight occurs: is it a true manifestation of insight or just an epiphenomenon?

## **2.5 Implicit vs. Explicit Knowledge/Learning**

### ***2.5.1 Education***

In implicit learning, knowledge is acquired without explicit intention of learning, without awareness of the learning process and without knowledge of what has been learned. This type of incidental learning differs from explicit learning, which is conscious and intentional. Up to now, little attention has been given to implicit learning

in the educational literature. Much work has been done on a related topic, informal learning, which basically is the learning that takes place outside the organised, official, schooling institutions (for example in a museum). Though this type of learning can be conscious and intentional, it may also share elements with implicit learning.

There are two major views with respect to implicit learning. One line of thought claims that rules can be abstracted implicitly, as, for example, has been shown in experiments on artificial grammar learning (AGL) where participants are instructed to memorize stimuli structured by a rule, and are later able to classify stimuli into regular and irregular items with above-chance accuracy without being able to verbalize the rule (see e.g., Reber, 1989). A competing vision states that subjects do not learn abstract rules, but that they are sensitive to frequently occurring features, and that they extract probabilistic information about the composition of sequences or procedures (Shanks & StJohn, 1994). In the case of implicit sequence learning, the serial reaction time task (SRTT) is usually adopted, demonstrating implicit learning when subjects respond faster in response to reoccurring sequences than to random sequences, without being aware of these reoccurrences.

Although the role of implicit learning is recognized in several aspects of knowledge acquisition (e.g., native language learning, second language acquisition), its contribution to education is relatively small in comparison to the impact of explicit learning. This was recently demonstrated in a study by Saetrevik, Reber, and Sannum (2006) who employed an implicit learning paradigm for teaching atomic bonding rules in chemistry. Several conditions were tested, among which a simple one consisting of mere exposure to correct bonding models, gradually elaborating on the rule that governed the bonding of the carbon atom through memorization, counting the atoms, counting the bonds and verifying the bonds. Classification was tested and subjects were asked about explicit knowledge, showing above chance performance even for subjects that were not given explicit information about the rule, thus demonstrating implicit learning, but performance was far better for explicitly instructed subjects.

### ***2.5.2 Cognitive Neuroscience***

Quite a few neuroimaging studies, including those conducted with patients (e.g., Amnesia, Huntington), have been conducted on implicit learning. This work shows that separate cortical and subcortical brain regions underlie memory mechanisms in implicit (usually procedural) and explicit (usually declarative) learning. Medial temporal lobe (MTL), the anterior cingulate cortex (ACC) and the medial prefrontal cortex (MPFC) are the brain regions implicated in explicit learning and declarative memory, while striatal (basal ganglia, caudate nucleus) structures have been found to subserve procedural memory and implicit learning (Destrebecqz & Cleeremans, 2001; Reber, Gitelman, Parrish, & Mesulam, 2003). However, it was recently suggested that implicit and explicit learning may share the MTL memory system to some extent (Rose, Haider, Weiller, & Buchel, 2004; Schendan, Searl, Melrose,

& Stern, 2003). In a recent study by Aizenstein and colleagues (Aizenstein et al., 2004), explicit and implicit sequence learning led to learning in both conditions and activation in the prefrontal cortex (PFC), striatal regions, the ACC, and several visual regions. Interestingly, these authors found different activation patterns in the visual cortex in response to the implicit-explicit manipulation, with decreased activation after implicit learning and increased activation in the explicitly learned patterns, but common striatal activity. Reber and colleagues (Reber et al., 2003) also reported differential occipital visual activation for an implicitly learned categorization rule, but found increased activation relative to the implicit learning condition in several brain regions, including the hippocampus, left inferior temporal cortex and posterior cingulate, for explicit intentional learning. In another study, Destrebecqz et al. (2005) found activity in the striatum during recall of an implicitly learned sequence, while ACC/MPFC was recruited for explicit learning. Interestingly, Destrebecqz et al. (2005) report a functional connection between the ACC/MPFC and the striatum (caudate nucleus) during recall after explicit learning, whereas these two systems appear disconnected during recall after implicit learning, thus complementing the reported overlap with respect to implicit and explicit learning in the implicit memory-system dedicated striatum (Aizenstein et al., 2004).

Neurophysiological differentiations between implicit and explicit learning have also been found when children were compared to adults, as was reported by Thomas et al. (2004), who studied developmental differences in the striatum during implicit learning. Thomas et al. (2004) found that neither adults nor children became explicitly aware of an implicitly learned sequence, but that there were differences between the groups with respect to speed and magnitude of the implicit learning effect, where the adults outperformed the children. Interestingly, adults showed more activity in cortical motor regions whereas children displayed more activity in subcortical motor structures (bilateral putamen). Learning-related developmental differences were reported for the hippocampus and superior parietal cortex, but learning related activity in the (right) caudate did not vary with age.

In the aforementioned studies, SRTTs were employed with concurrent neuroimaging (PET; fMRI), but interesting indicators of implicit learning were also found in the language domain using event-related-potentials (ERPs). In a study on second language learning in native speakers of English who learned Spanish as a second language, Tokowicz and MacWhinney (2005) showed that learners were sensitive to violations (i.e., showed different brain responses to grammatical and ungrammatical sentences; P600) in the second language (L2) for constructions that are formed similarly in the first language (L1), but were not sensitive to violations for constructions that differ in the L1 and the L2. Also, a grammaticality effect was found for the construction that was unique to the L2, suggesting that the learners were implicitly sensitive to these violations. Behavioural data showed that judgment accuracy was near chance for all constructions. These findings suggest that learners are able to implicitly process some aspects of L2 syntax even in early stages of learning, but that this knowledge depends on the similarity between the L1 and the L2. In a similar vein, but now concerned with semantics rather than syntax, Thierry and Wu (2007) used an implicit priming paradigm to assess whether Chinese-English

bilinguals spontaneously access Chinese translations when reading (or listening to) English words. The authors found that implicit priming had no behavioural effect, but that it modulated the N400 ERP component, suggesting implicit access to meaning in the first language, although the bilinguals read words in their second language.

### ***2.5.3 Future Directions***

As was indicated above, under some conditions, implicit and explicit learning and their procedural and declarative memory systems appear to overlap; future research should shed light on this apparent intricate interplay.

Sleep, and particularly slow wave sleep, is important for memory consolidation (Backhaus et al., 2007; Marshall, Helgadottir, Molle, & Born, 2006), but there appear to be differences in the beneficial effects of sleep when implicit learning is compared to explicit learning. Rapid eye movement sleep (REM), rather than slow wave sleep seems to improve implicit learning (Marshall & Born, 2007). Non-REM (NREM) sleep, on the other hand, does not seem to have an advantageous effect on implicit learning (Robertson, Pascual-Leone, & Press, 2004), although others do report positive effects of NREM (stage 2) sleep (Peters, Smith, & Smith, 2007). The issue is even more complicated by the fact that there appear to be developmental differences (Fischer, Wilhelm, & Born, 2007). Clarification, therefore of the precise role of (types of) sleep in memory consolidation of implicitly learned material seems warranted.

Another relevant topic is related to the question of whether or not there is transfer from implicit to explicit knowledge. Lang et al. (2006), for example, showed that several ERP components, including very early ones, differentiated solvers from non-solvers in an implicit sequence paradigm. For some of these solvers, this even led to conscious awareness (insight) and thus explicit knowledge. Future research should further explore the underlying mechanisms and the relation between implicit learning and (precursors of) insight.

Further, the role of prior knowledge and expectations in implicit learning has been acknowledged (see e.g., Sun, Merrill, & Peterson, 2001) and should be further explored, because in usual everyday situations, in contrast to the artificial paradigms employed in the laboratory, such knowledge and expectations may play an important role, not only (for obvious reasons) in explicit learning, but also in implicit learning. Prior knowledge might be a manifestation of earlier experiences with or exposures to the learning material, and might, on the basis of similarity, be associated with the implicit memory of this material (Ziori & Dienes, 2008).

Rather than compare implicit learning with explicit learning, insight into implicit learning mechanisms could also benefit from studying the differences within (more or less successful) implicit learners, see, for example, (Reiss et al., 2005).

A further relevant line of research to be pursued with respect to implicit learning concerns the unconscious detection of errors as reflected in error-related negativity (ERN), a component of the ERP which is seen when errors are made, or feedback

of an error is given (see e.g., Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), and whether and how this contributes to implicit learning (see also Ferdinand, Mecklinger, & Kray, 2008).

## 2.6 Metacognitive and Regulative Skills

An important aspect of recent educational developments is the emphasis on self-regulation and self-direction on the part of the learners (Bransford et al., 1999). It is seen as important that learners develop these skills in order to be able to cope with the huge amounts of information available nowadays and in order to be able to continue their learning after formal schooling (life-long learning). This development marks a shift from teacher-controlled to learner-centred instruction (Duffy & Jonassen, 1992; Jonassen, 1999). The result of this shift has fuelled the development of learning paradigms like whole-task learning (van Merriënboer & Kirschner, 2007), where learning is driven by work on rich learning tasks based on whole tasks with a high degree of authenticity. Similarly, inquiry learning, has students explore a domain, usually in science, develop questions in the process of investigating domain aspects, and then test those questions to develop new understanding (de Jong, 2006). Self-regulated learning implies that more of the planning, monitoring, and evaluating of the learning process is in the hand of the learner. Since learners are not always capable of this, adequate learning environments provide learners with support in this respect (Manlove, Lazonder, & de Jong, 2007).

### 2.6.1 Education

An important higher-order skill is self-regulation (Flavell, 1971), that is, the ability to regulate one's own learning process. It includes three essential activities: planning, monitoring, and evaluation (Butler & Winne, 1995; Schraw, 1998; Zimmerman, 2000). Planning involves goal setting and determining strategies for goal attainment. Monitoring and evaluation involve judgements of how well and to what degree a plan is successfully executed, with monitoring occurring *during* the execution of a plan (e.g., task performance), and evaluation occurring at an end or stopping point (e.g., after task performance, Schön, 1991), providing input for the next plan.

For self-regulation to lead to improvements in learning, the accuracy of 'feelings of knowing' and 'judgements of learning' made during monitoring and evaluating is important (Koriat, 2000; Metcalfe, 1986; Thiede, Anderson, & Theriault, 2003). That is, without accurate assessments of comprehension or performance, students cannot decide whether they have to restudy something or engage in new planning to correct their errors. Unfortunately, learners are often not very accurate at assessing the extent to which they learned something (see e.g., Thiede et al., 2003), or at identifying errors when they are not 'cued' in some sense by their environments to do so (e.g., through feedback, Butler & Winne, 1995). An implicit assumption that

seems to be made in educational research is that monitoring and evaluation require conscious reflection to be accurate, and therefore, many attempts have been made to stimulate students' ability to reflect (see e.g., Boud, Keogh, & Walker, 1985; Ertmer & Newby, 1996; van den Boom, Paas, van Merriënboer, & van Gog, 2004). An important question addressed in cognitive psychology, however, is whether certain metacognitive processes are actually implicit or explicit, in other words, whether or not they require awareness (Koriat, 2000; Reder & Schunn, 1996). The answer to this question may have serious implications for the way in which education and instruction can evoke and support metacognitive processes.

### 2.6.2 Cognitive Neuroscience

In neurosciences, higher-order processes including self-regulation are often referred to as executive control processes. Executive control is an umbrella term for a number of component functions, including selective attention, conflict resolution, error detection, and inhibitory control, which is the cognitive ability to suppress a dominant, though task inappropriate, response in favour of a more goal-appropriate response (Fernandez-Duque, Baird, & Posner, 2000; Shimamura, 2000).

*Conflict resolution* might play a role in performance monitoring, for example when learners try to resolve incongruence between plans, comprehension, a current state of an activity and (either internal or external) feedback they receive. fMRI studies with the Stroop task wherein a participant is asked to name a word colour, are often used for imaging studies of conflict (e.g., Bernhardt, 1991; Carter, Mintun, & Cohen, 1995). In this task, colour words are printed in their corresponding ink colour (congruence) and in different colours (incongruence). Participants must inhibit the dominant response of naming the word itself in favour of the less dominant response of naming the colour. When the ink colour and the colour word are incongruent, consistent activation patterns have been found indicating common areas involved in conflict resolution. Fernandez-Duque et al. (2000) indicate that '... in the congruent trials metacognitive knowledge (i.e., awareness) of conflict appears to be absent even though there is evidence of metacognitive regulations (i.e., selection of ink colour and filtering of word meaning). This result, if confirmed, would provide convergent evidence for the existence of implicit metacognitive regulation.' (p. 292). Hence, such findings might contribute to answering the question of the degree to which metacognition is implicit or explicit in its functioning, which has important consequences for the effectiveness of educational measures that seek to enhance metacognitive processes. Conflict resolution also occurs in conceptual change when learners have to decide to change or maintain their current ideas on the basis of conflicting information as may come out of an experiment conducted in, for example an inquiry learning session (Chinn & Brewer, 1993). Petitto and Dunbar (in press) investigated conceptual change issues with regard to neurological patterning in an fMRI study that investigated how students make changes to their understanding of concepts they find plausible or implausible. Conceptual change refers to the idea

that previously held knowledge which is considered naïve or incorrect on the part of students can be changed through instructional interventions such as presentation of anomalies or deviations from these ideas (e.g., Baker & Piburn, 1997). Conceptual change has been particularly hard to assess or observe. Fugelsang and Dunbar (2005) therefore investigated networks in the brain which were activated when students learn scientific knowledge. Fugelsang and Dunbar (2005) hypothesized that data inconsistent with plausible theory would be ignored and not result in changes to concept understanding, whereas data consistent with plausible theory would be integrated with the given concept. They found that people given data consistent with their theories activated networks involved with learning (caudate and parahippocampal gyrus). However when presented with data that were inconsistent with preferred theory, areas involved in conflict resolution, i.e., anterior cingulate cortex, and dorsolateral prefrontal cortex (DLPFC) are activated. This indicates that shallow presentation of anomalies might not promote conceptual change, since learning areas were not activated, and may show that students actually inhibit or ignore this information as the authors hypothesized. In contrast, when students were presented with extensive data inconsistent with theory, fMRI data does show evidence of learning network activation.

Regarding *error detection*, research has shown that performance slows down following the detection of an error (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). This strategy adjustment observation lead neuroscientists to propose an error monitoring system located in the medial areas of the frontal lobe, particularly the anterior cingulate, which shows increased activation in response to errors (Carter et al., 1998; Fernandez-Duque et al., 2000). As indicated in Section 2.5.3, event-related potential (ERP) research has identified an ERP component called error-related negativity (ERN, Badgaiyan & Posner, 1998; Ferdinand et al., 2008) which is seen when we make a mistake, or get the feedback that we made a mistake. Interestingly, it also occurs when we observe a mistake being made (see also Section 2.7), and research has shown that this ERN is sensitive to the degree of an error and its subjective meaning. Moreover, it may also occur in response to implicit errors, that is, errors that participants are not explicitly aware of (Ferdinand et al., 2008; Nieuwenhuis et al., 2001). Such neuroscience research might provide us with an understanding of the biological basis of how we detect errors, which plays a crucial role in self-regulation.

It is also important to consider the developmental perspective in this context, because a network of frontal brain areas seems to play a crucial role in executive control (Fernandez-Duque et al., 2000), and the maturation of some of these areas (e.g., prefrontal cortex) continues well into early adulthood. Hence, self-regulated learning, or rather, its effectiveness, might be dependent upon the stage of brain/neurocognitive maturation (see also Section 7.2). That is, children or young adolescents might not be able to engage in self-regulated learning effectively, because the necessary brain areas may not have fully matured. On the other hand, it might also be that younger learners engage different brain areas or use similar brain areas in a different manner (cf., Crone & Huizinga, 2006) especially in the case that explicit awareness is not required (see above).

Metacognition, in the sense of knowing what you know, is related to regulative processes. Schnyer, Nicholls, and Verfaellie (2005) investigated the brain areas involved in feelings of knowing (FOK). Theoretically, the FOK paradigm assumes that FOKs are made based on the relative familiarity of the recall cue (Schnyer et al., 2005). Their results show, however, that the right ventral medial prefrontal cortex (VMPC) was activated during *accurate* retrieval judgments, regardless of actual recall or anticipated recognition of a target item. They go on to conclude that the VMPC's function might be less related to memory retrieval and more to an intuitive assessment of 'feeling of knowing', that is, to monitoring. As we have seen FOK also plays a role in solving insight problems (see Section 2.4).

### **2.6.3 Future Directions**

The research discussed here indicates some areas where neuroscience research may provide important contributions to our theoretical understanding of monitoring and evaluation processes' prerequisites for self-regulation. An important question that neuroscience research might help answer is to what degree metacognitive monitoring is implicit or explicit (cf., Fernandez-Duque et al., 2000). Another important question that neuroscience research might help answer concerns the development of executive control functions, which will provide information with regard to optimal timing of educational endeavours, such as how much regulation we can expect from children in comparison to teenage or adult learners.

## **2.7 Social Cognition and Social Learning by Observation and Imitation**

Educators recognize the importance of social processes for learning. Influential theories in this area are those of Vygotsky (1978) and Bandura (1977; 1986). For example, in Vygotsky's work, social interaction is held to play a fundamental role in (development of) cognition, and Bandura's social learning theory stresses the importance of observing and modelling the behaviours, attitudes, and emotional reactions of others for learning. Especially in vocational training, a large and important part of our educational system, much of the training is performed 'in situ'. Students learn in a (cognitive) apprenticeship mode (Collins, Brown, & Newman, 1989) in which part of the learning takes place by observing experts.

### **2.7.1 Education**

Social learning, that is, learning by observing and imitating others, has long been recognised as a powerful learning strategy for humans (Bandura, 1977, 1986; Collins et al., 1989; Vygotsky, 1978). The terms observational learning and

imitation learning are often used interchangeably. However, they can be differentiated as learning can occur without imitation, that is, we may learn by observing and generating inferences beyond the observation without imitation.

In evolutionary psychology, it is argued that we may have *evolved* to observe and imitate other people (see, Sweller & Sweller, 2006). This seems to apply in particular to what Geary (2007) refers to as biologically primary knowledge, that is, knowledge that we have evolved to acquire almost automatically (e.g., face recognition, first language). However, also in acquiring biologically secondary knowledge, which has to be explicitly taught (e.g., writing, arithmetic), learning from expert models has been shown to be very effective (see, Renkl, 2005; Sweller et al., 1998). Learning from expert models can be done by observing the model directly, either ‘live’, as in a cognitive apprenticeship construction, or on video. But it can also be indirect, through worked-out examples that make the solution steps an expert performs explicit (e.g., in solving a mathematics problem). These instructional strategies rely (in part) on observation/imitation learning, and are used for teaching both motor tasks and cognitive tasks.

### 2.7.2 Cognitive Neuroscience

An interesting finding from cognitive neuroscience for social learning is the discovery of the mirror-neuron system (for a review, see Rizzolatti & Craighero, 2004), which is thought to play an important role in the understanding of actions made by others, and, hence, in our ability to learn by observing and/or imitating others.

It has been shown that observing (object-oriented) actions made by others activates the mirror-neuron system, which is also active when one performs that action oneself (Iacoboni et al., 1999; Meltzoff & Prinz, 2002). Several authors (Buccino et al., 2004; Craighero, Bello, Fadiga, & Rizzolatti, 2002; Vogt, Taylor, & Hopkins, 2003) found that the mirror-neuron system, which is active during mere action observation, primes the execution of similar actions, and thereby mediates imitation-based learning. For a while, it was thought that the mirror neuron system was only activated when the parts of the human body that executed the action were visible, and not when the action was conducted by some other agent such as a robot arm (Tai, Scherfler, Brooks, Sawamoto, & Castiello, 2004). However, recent evidence suggests that the goal of the observed action is more important for activation than, for example, the presence of a human or robotic hand (Gazzola, Rizzolatti, Wicker, & Keysers, 2007).

These findings may help educational researchers understand the biological bases of observational learning, and provide some insights into why certain instructional designs are more effective than others. For example, van Gog, Paas, Marcus, Ayres, and Sweller (2009) have noted that the mirror neuron system may also contribute to our understanding of an unresolved issue in educational research, specifically, why sometimes dynamic visualizations are more effective than static ones, but sometimes static ones are more effective than dynamic ones (for reviews, see Höffler & Leutner,

2007; Tversky, Morrison, & Betrancourt, 2002). van Gog et al. argue that dynamic visualizations involving human movement may have benefits over static visualizations, because they activate the mirror neuron system. Other types of dynamic visualizations that depict natural, mechanical, or abstract processes do not have this benefit, which may explain why in these cases they are equally or even less effective than static visualizations. Of course, joint research ventures would be necessary to investigate this hypothesis.

However, it should be noted that the above applies to learning (psycho)motor skills, that is, skills that involve human movement. An important open question is whether the mirror neuron system can also explain why instructional formats such as worked examples are effective for teaching cognitive skills. Interestingly, there are indications that the mirror neuron system also becomes active when people listen to sentences that describe the performance of actions by humans, with, for example, hand, mouth, or leg (Tettamanti et al., 2005). An interesting question for – joint – future research would be to investigate whether this would also apply to hearing or reading sentences regarding purely cognitive actions.

It has also been suggested that the mirror neuron system may play a broader role in social cognition by enabling understanding of actions made by others, i.e., there might be a link with empathy and development of theory of mind (see e.g., Keyser & Gazzola, 2007). However, it is questionable whether the mirror neuron system alone is involved here (this, by the way, can also be asked regarding the findings on imitation described above). That is, there may be a complex interplay between neural circuits involved in motor control, mental simulation, and mirroring that enable imitation and empathy (see e.g., article by Hurley, 2008, and commentaries). Recent findings indicating that the development of self-evaluation and social monitoring may not take place before middle adolescence in the majority of youth (e.g., Amodio & Frith, 2007; Paus, 2005; Steinberg, 2005) are of major importance in this regard. It has been hypothesized that the ability to cognitively evaluate (i.e., mentally simulate) action programs in terms of emotional consequences and social consequences is dependent upon the development of self-evaluation and social monitoring. In other words, the adolescent brain learns to prioritize competing action programs (and parts thereof) in terms of the consequences which these actions have in the short term (e.g., in the next minutes or hours), or medium term, semi long term (e.g., weeks or months), or long term (e.g., years) and the consequences these actions have for ‘significant others’ (peers, friends, parents, teacher) and society, including social norms (see also Section 7.2 where more general aspects of maturation are discussed).

### ***2.7.3 Future Directions***

It should be noted that although the findings regarding the mirror neuron system are promising, the types of tasks used are often very simple, for example, playing a guitar chord (Buccino et al., 2004) or grasping an object (Gazzola et al., 2007). The

question remains whether these findings also hold for more complex motor tasks. In addition, as mentioned above, it is unclear what these results can tell us about observational and imitation learning of cognitive and linguistic tasks, although the findings of Tettamanti et al. (2005) seem promising in this regard. Joint research ventures are necessary on educationally relevant motor tasks, cognitive tasks with or without motor components, and instructional design implications. For example, regarding the design of instructional visualizations, future research should make careful comparisons between dynamic and static visualizations of human movement and other types of instructional animations on activations of the mirror neuron system (van Gog et al., 2009). In addition, educational implications of (the development of) social cognition in general should be addressed.

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