# Explorations in Learning and the Brain: A *Quick Scan* of the Potential of Neuroscience for Education


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Netherlands Organisation for Scientific Research; Grant no. 411-07-991

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## Preface

This paper presents a short review study of the potential relationships between cognitive neuroscience and educational science. This review study was conducted by order of the Dutch Programme Council for Educational Research of the Netherlands Organization for Scientific Research (NWO; cf. the American NSF). Through an examination of the literature this review aims to identify: 1) which neuroscience principles, mechanisms, or theories may have implications for educational research and could lead to new interdisciplinary research ventures, and 2) how educational principles, mechanisms, and theories could be extended or refined based on findings from neuroscience. The current report should be seen as the first preliminary outcome of the “Explorations in Learning and the Brain” project. The project will continue with a web-based discussion and an expert workshop, which will lead to a more comprehensive report. Authors of this report are listed in alphabetical order.

## 1 Introduction

The past decade has seen a few efforts on the part of research, education and policy communities to create a dialogue about the potential relationship between cognitive neuroscience and both the science and practice of education. Notable examples include the publications from the Centre for Educational Research and Innovation (CERI) of the OECD. Their 2002 report on learning sciences and the brain was recently followed by a report entitled ‘Understanding the brain: The birth of a learning science’ (2007). This book evaluated state of the art knowledge and insights from the cognitive sciences and neurosciences which are pertinent to education. It gives an agenda for the future development of this field and encourages collaboration between the learning sciences, brain research, and policy organizations (p. 3). Likewise, the report ‘Brain Lessons’ (Jolles et al., 2006) and its earlier version ‘Learning to know the Brain (Jolles et al., 2005) published under auspices of the Netherlands Organisation for Scientific Research stated that “the time is ripe for an active exchange between scientists from neuroscience, cognitive science, educational science and the practice of education.” Berninger and Richard’s (Berninger & Richards, 2002) book on Brain Literacy reaches out to educators and psychologists about what we know of the brain and how it might be relevant to teaching and learning. Another example is a recent report of the German Ministry of Education that after reviewing relevant neuroscientific research concluded with ten research questions that link neuroscience and educational science (Stern, Grabner, & Schumacher, 2006). In the Netherlands, the Netherlands Organisation for Scientific Research in collaboration with the Ministry of Education, Culture and Science installed the ‘Brain & Learning committee’ in 2003, which organized an invitation conference on the multi-dimensional research domain in 2004, which led to the above mentioned report. A further Dutch initiative is currently being undertaken by the “Study Centre for Technology Trends” (Rispens, in preparation). Review articles such as Byrnes and Fox (1998), Goswami (2004), Posner and Rothbard (2005), and Katzir and Paré-Blagoev (2006) furthered this dialogue by asking critical questions about the educational implications of cognitive neuroscience research. New initiatives are bibliometric analyses to explore whether there already are overlaps between the fields in the research literature (Merkx & van Koten, in preparation). This paper presents a review study, conducted by order of the Dutch Programme Council for Educational Research of the Netherlands Organization for Scientific Research, that also seeks to contribute to the afore mentioned dialogue. It provides a review of the present state of potential relationships that exist between cognitive neurosciences and educational sciences.

The present study takes a somewhat different stance than the studies mentioned in the first paragraph in the sense that it does not take developments within neuroscience as the first starting point but rather sets off from major questions that are dominant in educational research, notably instructional systems design and related fields within the educational sciences. The goals of this study are to identify interesting interfaces between neuroscientific and educational research, as well as to inform the program council on potentially interesting additions to educational research programs of the Netherlands Organisation for Scientific Research and viable interdisciplinary ventures. By drawing on empirical findings from both disciplines, the following general questions will be addressed:

1 Which principles, mechanisms and theories studied in educational research could be further extended or refined based on findings from cognitive neuroscience?
2 Which principles, mechanisms and theories studied in cognitive neuroscience may have implications for educational research?
3 What are these implications and which (interdisciplinary or transdisciplinary) research questions can be drawn from them?
4 What form could an interdisciplinary or transdisciplinary research program take based on research questions generated from the above questions?

The approach taken is that of a ‘quick scan’, i.e. a literature review which does not pretend to provide a complete coverage of the pertinent domain and does not give an in-depth evaluation of all the relevant issues. Rather, it gives a lead to some of the most important trends as can be observed in the recent literature. The aim is to enable other researchers who are interested in this interdisciplinary/transdisciplinary domain a quick access to the literature and enable them to participate in research development. It is a major aim of the quick scan to aid in the web-discussion which will be the second step in a three phase process initiated by the committee Learning & the Brain from the Educational Research Program Council (PROO). The third phase of this process will be an international workshop (March 2008) which will yield a more elaborate report on the same topic as the present quick scan.

The literature utilized to answer the questions mentioned above developed as follows. First, a short list of educational topics was developed to begin an initial scan of the literature. This scan resulted in the creation of a more constrained list of relevant articles and journals such as the Journal of Cognitive Neuroscience, Trends in Cognitive Sciences, Neuropsychologia, Experimental Brain Research, and Review of Educational Research. This list was reviewed by cognitive neuroscience and learning science experts prior to the actual literature review to ensure accuracy. A review was then conducted to gather relevant empirical findings from both fields. In view of the purpose of the quick scan, there was a focus upon research papers published in recent years, notably those which are relevant for the major topics investigated in present-day educational research. A number of common topics evolved. Within topic areas, issues also became apparent that may prove fruitful for identifying interesting interfaces between (cognitive) neuroscience and educational research. As such, this quick scan is organized around these common topics and issues:

1. Learning principles, including effects of multimodal processing and cognitive load.
2. Learning of practical skills, including observation/imitation learning of those tasks
3. Learning specific domains, such as (second) language learning & mathematics,
4. Higher-order skills, including the role of self-regulation, reflection, planning, and creativity in learning
5. The role of social/emotional processes in learning
6. Learning problems, including dyslexia and dyscalculia

As mentioned, this list is not at all meant to be exhaustive but rather provides a focus upon areas commonly addressed in the literature and which have potential for fruitful collaboration between the fields of educational research and cognitive neuroscience. One difficulty with this approach was the placement of the topics development and plasticity (Bach-y-Rita, Danilov, Tyler, & Grimm, 2005; Merzenich et al., 1996; Taub, 2004). Though these are important areas of research in their own right, they are interwoven with learning processes. Thus it was deemed fruitful to consolidate developmental and plasticity issues within the six topics described above, and give some consideration on issues in cognitive neuroscience research which are pertinent to the impact of developmental and plasticity issues on these topics.

The following sections detail the above topic definitions, describe relevant cognitive neuroscientific research and discuss how these findings contribute to learning science research or theory. Where applicable, future directions are presented to advance potential research avenues between cognitive neuroscience and learning science communities.

## 2 Learning principles

In past decades, educational research has put major efforts in the development and evaluation of 'modern' learning environments which are characterized by an emphasis on (structured) self-directed learning and collaborative learning. They also embed the content in a (multimodal and multi-representational) realistic context (Mayer, 2001). Such rich learning environments are assumed to contribute to development of the brain (Diamond & Hopson, 1989). Processing of rich material, on the other hand, also requires specific brain activities. The current section focuses on the latter aspect, the representation of material in relation to functioning of the brain. Research on self-directed learning is further discussed in Section 6. To our knowledge, collaborative learning is an aspect that has not yet been addressed by neuroscientific research.

### *2.1 Multimodal processing*

#### 2.1.1 Education

The dual coding theory proposed by (Paivio, 1979, 1986) states that recall/ recognition 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 nonverbal 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 (in order, the phonological loop and the visuo-spatial sketchpad, (Baddeley & Hitch, 1974). Later, another component was added: the episodic buffer (Baddeley, 2000). Despite later 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. More specifically, 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 there is a grey area (e.g., are visual stimuli that can be named verbal or non-verbal)? In recent years there has been a tremendous amount of research in which aspects of working memory, verbal learning, the use of strategies and/or the organization of memory performance are related to brain function by the use of functional brain imaging (f-MRI or PET). 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 response 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 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 (unconstrained) 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 their memory performance and that these strategies engage distinct brain regions that may separately influence memory performance.

#### 2.1.3 Future directions

The findings by Beauchamps 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 Cognitive load*

#### 2.2.1 Education

Cognitive load theory (Sweller, 1988; Sweller, Van Merriënboer, & Paas, 1998; Van Merriënboer & Sweller, 2005) hypothesizes that in order to be effective, learning materials should be designed in a way that takes human cognitive architecture into account. Our cognitive architecture 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 +/- 2 information elements can be held in working memory, and the number decreases (Cowan, 2001) when information is not auditory (i.e. unpronounceable), or when it 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. 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.

### 2.2.2 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 was 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 in terms 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 because of the activation of a larger knowledge base, more deliberate strategies, or both, but indicate that it remains unclear whether this can be regarded as an indicator of neural efficiency.

### 2.2.3 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 a similar drawback as the cognitive load measures 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. New experimental paradigms to combine neurocognitive measures and measures of learning processes and educational performance should be developed.

Future studies can help us understand the brain basis of working memory processes (e.g., corroborate or refine theories about controlled vs. automatic processing), might provide neuroscientific methods to measure cognitive load, and explain how individual characteristics such as expertise or intelligence affect memory mechanisms.

## 3 Learning of practical skills

Vocational training is an important part of our educational system. Much of the training here is performed “in situ”. Students learn in a (cognitive) apprenticeship mode in which part of the learning takes place by observation of experts.

### *3.1 Education*

Learning by observing and imitating others has long been recognised as constituting a powerful learning strategy for humans (see Bandura, 1986). In evolutionary psychology, it is argued that we may have evolved to observe and imitate other people (see Sweller & Sweller, 2006). The terms observational learning and imitation learning are often used interchangeably. However, they can be differentiated as learning can occur without imitation (Bandura, 1986). We may learn by observing and generating inferences beyond the observation without imitation.

Learning from expert models (“live” or video-based) or worked-out examples that make the solution steps an expert performs explicit (e.g., in solving a mathematics problem), are instructional strategies that rely in part on observation/imitation learning, and are used for teaching both motor tasks and cognitive tasks.

### *3.2 Cognitive neuroscience*

An interesting finding from cognitive neuroscience for observation and imitation 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 may be responsible for our ability to learn by imitating others.

It has been shown that observing object-oriented actions made by others activates the mirror-neuron system (Iacoboni et al., 1999; Meltzoff & Prinz, 2002). The same cortical circuits that are involved in executing an action also respond to observing someone execute that action. 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).

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). The findings on the mirror neuron system first of all begin to provide us with an understanding of the neural basis of the well known educational principle of observational learning. We deliberately use the words “begin to”, because these findings regarding the mirror neuron system concern human-movement tasks, whereas observational learning is known to be effective for cognitive and linguistic tasks as well. Moreover, these findings may be used in instructional design. For example, Paas, Van Gog, and Sweller (submitted) 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. They 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 case they are equally or even less effective than static visualizations (for a review see Tversky, Morrison, & Betrancourt, 2002).

### *3.3 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, 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 tasks, as well as on instructional design implications, for example regarding the design of instructional visualizations. Future research should make careful comparisons of activations of the mirror neuron system between dynamic and static visualizations of human movement related and other types of instructional animations.

## 4 Language learning and literacy

Literacy is incredibly complex, and a full report on the links between neuroscience and language instruction would be an undertaking all on its own. Therefore, some constraints were needed for this review. According to the OECD (2007) report, “Neuroscientists are only beginning to investigate reading at the level of whole sentences” (p. 88), therefore the learning science review found here focuses primarily on issues with regard to early language instruction and development. Where possible, something is said with regard to adult learners and literacy however. In this search for the right experience trends in language instruction and research have focused on a) developmental trajectories for literacy experience, b) instructional approaches to literacy development, and c) influencing factors to literacy (i.e. 2$^{nd}$ language versus native language learning, and linguistic structure)

### *4.1. Education*

#### 4.1.1 Developmental trajectories

According to the 2000 National Reading Panel Report: Teaching Children to Read, reading development is comprised of five essential component skills which build on each other successively; the alphabetic principle, phonemic awareness, oral reading fluency, vocabulary and comprehension (Paris, 2005). The alphabetic principle pertains to ability to associate phonemes (sounds) to letters and to use these phonemes to read words. Phonemic awareness is the learning of specific phonic units of language including vowels, consonants, and consonant digraphs for example and their corresponding sounds (Ehri, Nunes, Stahl, & Willows, 2001). Oral reading fluency is considered to follow these prior component skills. In the oral fluency stage the practice of reading becomes automatized which frees up working memory for the final two component skills of vocabulary development and comprehension.
Although general consensus exists with regard to this developmental trajectory, as evidenced by national policies formed by reports such as the 2000 National reading panel, there is controversy with regard to developmental order and the importance of decoding skills (alphabetic principle and phoneme awareness) over comprehension (Calfee & Norman, 1998). This controversy is mainly found in instructional design approaches to reading such as exemplified in the phonics over whole language debates. Details with regard to these approaches are discussed in Section 4.1.2. In the literature on visual word recognition (i.e., reading a single word), two types of models are prominent: dual-route models (e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Zeigler, 2001) and models emphasizing the importance of phonological processing (e.g., Frost, 1998; Stone, Vanhoy, & Van Orden, 1997). In short, dual-route models propose two distinct routes for reading. One route can be described as direct access from the written word to the mental lexicon which contains the word’s meaning and pronunciation. The second route is indirect, in the sense that it requires converting letters to sounds (i.e., graphemes to phonemes) in order to access the word in the mental lexicon. Dual route models propose that beginning readers use the indirect route, in which they (slowly) sound out words. As reading ability progresses, however, dual route models assume that the direct route will be used more and more frequently. Such models propose that experienced readers would only use the indirect route for reading infrequent words or non-words because

the direct route is seen as quicker and more efficient. An increasing number of researchers dispute dual route models in favour of a strong phonological theory of reading, in which phonological processing is mandatory, early, and rapid.

When thinking about language learning and literacy it is important to keep in mind that the world's language system is rapidly changing because of demographic trends, new technologies, and international communication (Graddol, 2004). One of the consequences is that the majority of present and future generations of children attain literacy in more than one language. This is certainly true for the Netherlands, where an increasing number of children are exposed to two (or more) languages at an early age. Furthermore, the Dutch curriculum emphasizes the learning of foreign languages, and English, for example, is taught from 5$^{th}$ grade primary school onwards. Behavioral and neurocognitive research shows that the language systems in bilinguals and multilinguals are highly interactive, at all linguistic levels (for an overview, see Kroll & de Groot, 2005). This implies that language processing and the attainment of literacy in one language are affected by knowledge of the other language(s).

#### 4.1.2 Instructional approaches

The controversies with regard to the developmental order in which the component skills should be taught, and the importance of comprehension are referred to as "the reading wars" within the literature on instructional designs that promote literacy. They centre on debates about the phonemic awareness perspective over a whole language comprehension oriented perspective.

Two meta-analysis studies are known to have compared these two approaches: Ehri et al. (2001) and Jeynes and Littell (2000). Phonemic awareness instruction, also known as the phonics approach, emphasizes teaching the alphabetic code needed for literacy of written language. Ehri et al. (2001) define this approach as one which incorporates a planned set of phonic elements including correspondence between consonant letters and sounds, vowel and consonant diagraphs (oi, ea, sh, th), and blends of larger sub units in words, such as "op" in the word stop (p. 394). In contrast, whole language emphasizes "(1) whole pieces of literature and functional language as opposed to abridgments, adaptations, or segmented texts; (2) individual students' choice as opposed to teacher-sponsored, whole-class assignments; and (3) integrated language experiences as opposed to direct instruction in isolated skill sequences" (Jeynes & Littell, 2000, p. 21). These two meta-analysis studies (Ehri et al., 2001;

Jeynes & Littell, 2000), one investigating phonics research, and the other looking at the effectiveness of whole language approaches are suggestive of the dichotomy which is apparent in the literature. Calfee and Norman (1998) sum up attempts to resolve the question of which approach is better and conclude that “The outcome of these investigations seemed clear-cut: (1) Teacher-led direct phonic programs produce (slightly) higher scores on decoding measures at the end of the first grade but (2) variability between teachers within programs was substantial, (3) many students did poorly under all programs, and (4) the initial advantages washed out by the end of third grade” (Calfee & Norman, 1998. p. 243).

Results from both Ehri et al’s (2001) and Jeynes and Littell’s (2000) meta-analyses suggest that phonics instruction has particularly strong effects on low and middle socio-economic status (SES) readers. Ehri et al.’s 2001 meta-analysis also found that phonics instruction was particularly beneficial to early readers and readers with reading disabilities, in addition to being more effective than whole-language or other (control group) forms of instruction. They conclude, however, with the speculation that larger effect sizes could be achieved if whole language instruction is “enriched” with systematic phonics.

#### 4.1.3 Influencing factors

Children’s SES is one of the many factors to consider in the development of literacy and instructional approaches to literacy. Two of these other factors are discussed here: second language learning and orthographic complexity of the language. Second language learning or bilingual literacy is the acquisition of a language other than one’s native tongue. Orthographic complexity is the extent to which the language utilizes single or more complex phoneme structures.

With regard to the first, there seems to be considerable overlap in reading skills in the first and second language (Bernhardt, 2000). Bernhardt’s (1991) extensive review of the literature indicates that skills relevant to learning to read in the first and in the second language are similar. For example, fluency is related to speed of processing, and phonological processing is key to word recognition in all languages, “even in languages that are non-alphabetic and considered more conceptual in nature” (p. 797, Bernhardt, 2000). Another relevant issue to second-language instruction is the issue of timing. Although children are well known to acquire fluency in languages easily, a paradox exists with regard to the suspicion that some educational systems hold that exposure to bilingual education too early will impede progress in a first language. Petitto and Dunbar (in press) refer to this as the “hold-back” position. These authors cite two classes of hypotheses with regard to this bilingual paradox; the unitary and differentiated. In the unitary hypothesis children exposed to two languages are thought to have a fused view of linguistic representation which are differentiated only after the age of 3 (Redlinger & Park, 1980). In the differentiated position, researchers claim that bilingual children do differentiate between their two languages (Genesee, Nicoladis, & Paradis, 1995).

The extent to which a language is orthographically complex relates to how a language is structured at a “grain-size” (OECD, 2007) from decoding single sounds (t), to mixed sounds (th), to whole syllables and whole words (Kanji). Apparently, orthographic complexity impacts the reading strategies which are employed and how quickly or easily literacy develops, and how literacy in a second language is attained. Zeigler and Goswami (2006) argue that inconsistency in the symbol-to-sound mapping impacts literacy development. If a language is inconsistent in its pronunciations or has multiple pronunciations it may be more challenging to learn. Zeigler and Goswami (2006) cite cross-language reading comparison research conducted by the European Concerted Action on Learning Disorders as a ‘Barrier to Human Development’. Fourteen European Union countries participated in assessments of children’s reading with word and non-word tests. A striking finding was that children who were acquiring reading in orthographically consistent languages (Greek, Finnish, German, Italian, Spanish) were close to ceiling in both word and nonword reading by the middle of the first grade. In contrast, English speaking children performed extremely poorly (34% correct). Danish (71% correct), Portuguese (73% correct) and French (79% correct) children showed somewhat reduced levels of recoding accuracy, which is in line with a lower orthographic consistency of these languages. This characteristic of language’s impact on literacy development is related, according to Zeigler and Goswami (2006) to a cross-language theory of reading – the orthographic depth hypothesis (ODH) (Frost, Katz, & Bentin, 1987; Katz & Frost, 1992). This hypothesis states that “different psycholinguistic units develop in response to differences in orthography. Rather, the ODH suggests that readers adapt their reliance on the ‘orthographic’ (whole word recognition) or ‘phonological’ (recoding) route, depending on the demands of the orthography. In a consistent orthography, readers rely more on the ‘phonological’ or nonlexical route, because mapping between two letters and sounds is relatively direct and unambiguous. In an inconsistent orthography, readers rely less on the phonological route and to a greater extent on the lexical or ‘orthographic’ route” (Zeigler & Goswami, 2006, p. 434). The ODH is based on a model of reading called “dual route” theory (Colheart, Rastle, Perry, Langdon, & Zeigler, 2001). This theory of reading is cited by cognitive neuroscience research as holding promise as a neurologically verifiable theory of reading (OECD, 2007), but, as discussed above, an increasing number of researchers dispute dual route models in favour of a strong phonological theory of reading.

## *4.2 Cognitive neuroscience*

### 4.2.1 Developmental trajectories

Comparisons between children and adults on reading tasks has shown some differences (Booth et al., 2000; Gaillard et al., 2000). For example, Booth et al. (2000) showed that both children and adults utilize the left frontal cortex when engaged in silent reading, but that children’s fMRI scans showed increased activation patterns during the task in comparison to adults. The study of Gaillard et al. (2000) examined comprehension and found children to have similar activation patterns to adults with regard to temporal and frontal regions of the brain, but increased activation in the inferior occipital and anterior superior temporal areas. Turkeltaub et al. (2003) furthered these lines by investigating neural changes during periods of reading acquisition with fMRI analysis of children whose ages spanned the formal schooling years. They found that the temporoparietal cortex and left superior temporal sulcus matures early in learning and continues to be involved in adult readers. Furthermore, this research shows that “…posterior language areas mature earlier than anterior ones” (p. 771). Turkeltaub et al. also cite correlations between activity in the left superior temporal sulcus and phonological awareness. Phonological awareness has a long history of being associated in psycholinguistic and Behavioral research with success in reading. Studies such as these will continue to play an important role in understanding how literacy develops and to serve as a reminder that “brain activation for adults does not necessarily generalize to children” (Berninger & Richards, 2002, p. 145).

### 4.2.2 Instructional approaches

With regard to theories of literacy related to whether or not whole language and/or phonic instruction might be better, evidence exists for a balance between the two approaches in cognitive neuroscience as is expressed in literacy research. Most of the evidence comes from attempts in cognitive neuroscience to verify theories of literacy (see the OECD report for an extensive review). The OECD report claims that the "The most comprehensive and well-supported model of reading to date is the "dual route" theory" (p. 87). Jobard, Crivello and Tzourio-Mazoyer (2003) describes this theory as one in which word reading is achieved through a "graph-phonological route" where readers translate words into auditory forms or a "direct route" in which readers translate words from visual symbols (p. 693-694). Pertinent to this theory is the question of "…whether there exists a system dedicated to the processing of visual word form as postulated by the dual route models, and whether neuro imaging results support the possibility of two distinct routes for accessing words." (p. 695). On the basis of a meta-analysis, Jobard et al. conclude that this theory is a suitable framework to account for observed reading activations in the brain.

Researchers in cognitive neuroscience research also addressed the question of what effect orthographic complexity has on language learning and development. Paulesu et al. (2000), for example, compared adult readers of Italian and English. Italian has a consistent orthography, so that readers can consistently converse graphemes into phonemes, whereas English has an inconsistent orthography. Paulesu et al. observed that Italian readers were faster in reading words and nonwords than English readers, and different regions in the brain were activate during reading. Italian readers showed greater activation in areas associated with phoneme processing, left superior temporal regions. English readers showed greater activations in areas associated with word retrieval during reading, the posterior inferior temporal gyrus and anterior inferior frontal gyrus.

### 4.2.3 Influencing factors

Attempts have been made to take a neuroscience perspective on factors which impact literacy. Noble, Tottenham, and Casey (2005) examined neuroscientific evidence for language and reading and attempt to relate it to racial and SES disparities in neurocognitive performance. The authors cite the work of Messacappa (2004) which showed that children from higher SES backgrounds generally outperformed lower

SES status students with regard to cognitive control (the ability to ignore distraction, allocate attention and hold items in working memory). Noble, Norman and Farah (2005) examined neurocognitive functioning of African American kindergartners from different SES backgrounds using cognitive neuroscience tasks. The authors found that while SES correlated with performance on the tests battery as whole, the effects on language and cognitive control systems in particular were quite large. In a replication of their research, these authors confirmed their original findings. As cited in the above educational definitions, learning science research has found SES to impact the success of literacy instructional approaches such as phonics or whole-language.

Learning a second language

One of the research lines in the cognitive neuroscience of second language learning is to examine how first language learning impacts second-language learning. Nakada, Fujii, and Kwee (2001) conducted fMRI research with ten Japanese volunteers, five of which were literate in English, and ten American native English speakers five of which were literate to the same degree as their Japanese speaking counterparts in Japanese. The results showed that cognitive processes for reading in a second language are neurologically similar to those employed by the first language. They regard this as evidence for the hypothesis that the second language represents a cognitive extension of the first language. Further research with Chinese has shown that similar areas in are recruited when Chinese speakers Kanji and when they read English, leading (Tan et al., 2003) to suggest that the neural systems of second language reading are shaped by the native language.

An other line of studies focus specifically on the time course of achieving fluency in the second language and factors that may influence this (for a review, see Van Hell & Tokowicz, in preparation). An important issue in the acquisition of literacy in a second language is the amount and timing of second language exposure. McLaughlin, Osterhout and Kim (2004) investigated ERPs (Event-Related brain Potentials) during word identification in adult (English-native) learners of French, and observed that these learners discriminated between words and ‘pseudowords’ (i.e., letter strings following orthographic rules in the language) in their second language after only 14 hours of instruction. Interestingly, when measured with traditional behavioural measures, the learners performed at chance level when making overt word-pseudoword judgments. In an ERP-study on syntactic violations, In a grammaticality judgment test using ERPs, Tokowicz and MacWhinney (2005) found that adult (English-native) novice learners of Spanish were sensitive to violations of grammatical constructions in their second language that were similar to those in their native language, and to constructions that were unique in their second language (hence, did not exist in their native language). The second-language learners were not sensitive to violations for grammatical constructions that differed in the second and native language.

Studies on the timing of exposure to L2 provide important insights into the age at which a second language optimally develops (Kovelman & Petitto, 2002; Petitto, Kovelman, & Harasymowycz, 2003). Kovelman and Petitto (2002) found that prior to age 5 exposure to a bilingual language is optimal for the development of both languages. They also found that children exposed to new languages after this critical time can achieve a fundamental grammatical basis in the second language within the first year, but only if second language exposure occurs in multiple contexts beyond formal schooling. In subsequent neurocognitive research, Petitto et al. (2004) investigated visual perception, speech recognition as well as native and non-native phonetic perception in infants with Near Infrared Spectroscopy (NIRS). The authors found activations in classical language areas of both bilingual and mono-lingual babies (Petitto & Dunbar, in press). fMRI research with adults exposed to two languages before the age of five show evidence of differences in activations for the two languages in comparison to adults who are exposed later in life. This research provides some evidence for psycholinguistic findings that state that language processing declines if the language is learned after puberty (Kim, Relkin, Lee, & Hirsch, 1997; Petitto et al., 2004; Petitto & Dunbar, in press; Wartenburger et al., 2003). For an extensive review, see Abutalebi, Stefano and Perani (2005).

### *4.3 Future directions*

This quick scan of the literature from an educational science and cognitive neuroscience perspective sought to find commonalities in three areas: developmental trajectories, instructional approaches, and factors influencing reading development. Currently cognitive neuroscience aims to refine and explain how the human brain decodes words and sentence in the native and in the second languages. Cognitive neuroscience research potentially provides important insights needed to fine tune developmental trajectories in language learning and the acquisition of literacy. Cognitive neuroscience may also give support for the hypothesis that a balanced approach between phonics and reading for meaning (whole-language) is a key instructional strategy. Finally, neurocognitive research will provide crucial insights into the brain processes involved in the learning of foreign languages, which is of particular importance given the emphasis on the attainment of literacy in foreign languages in the Dutch curriculum, and the neurological implications of exposure to multiple languages at an early age.

## 5 Mathematics learning and numeracy

Because numeracy, like literacy, results from the interplay of biology and experience it is the natural domain of both cognitive neuroscience and educational science. Although there is no single agreed upon definition, numeracy implies an understanding of the concept of number and the ability to reason quantitatively. As such, it is considered the basis of both simple and complex mathematics.

### *5.1 Education*

In order to design curricula that help children maximize their innate cognitive capacities, it is necessary to first have a detailed understanding of what those cognitive capacities are. Resent research has shown that even infants possess certain innate numerical abilities. Although studies in the 1980s and 1990s concluded that infants are able to make numerosity discriminations between, for example, two and three dots (Starkey & Cooper, 1980) and to perform simple arithmetic operations, such as 1 + 1 (Wynn, 1992), there has been some criticism citing that these studies did not properly control for continuous variables that covaried with numerosity, such as total filled area. Results of more carefully controlled studies show that although infants possess numerical abilities, these abilities appear to be restricted to large numerosity discrimination between, for example, 8 and 16 sounds or dots (Lipton, 2005; Xu & Spelke, 2000). These studies also demonstrate the imprecision of infants' numerosity discrimination, showing that infants are unable to distinguish 8 from 12 sounds or dots (Lipton, 2005; Xu & Spelke, 2000).

It has been proposed that there are two different cognitive systems to assess numerosity: One system for the exact representation of small numbers of objects and another system for representing approximate numerosity (Carey, 2001; Feigenson, Dehaene, & Spelke, 2004). The second system, sometimes referred to as the analogue magnitude system, is thought to be activated during symbolic numerical and mathematical operations using Arabic digits or number words (Dehaene, 1996; Dehaene, Dupoux, & Mehler, 1990).

In recent decades there has been a shift in many countries from direct instruction, which relies largely on drill and practice, to more realistic mathematics education based on constructionist principles. In the Netherlands, this has taken the form of Realistic Mathematics Education (e.g., Streefland, 1986; Treffers, 1993). However, there is evidence that children with intellectual impairments achieve better results with direct instruction (e.g., Kroesbergen & Van-Luit, 2005). In addition, because realistic mathematics education places more demand on the skills that students with mathematical learning problems may perform more poorly in, such as vocabulary, reading level, and math fact fluency, there is some question as to whether this method is appropriate for these children (Ruijssenaars, van Luit, & van Lieshout, 2004). It should be noted, however, that there are a number of researchers in the Netherlands that advocate the use of realistic mathematics education with children in special education (Boswinkel, Baltussen, Hoogendijk, & Moerlands, 2003).

### *5.2 Cognitive neuroscience*

Some progress has been made in the investigation of the neural substrate of mathematical processes. Evidence from both lesion and brain-imaging studies suggest that areas in the parietal cortex of the brain are involved in number processing (Dehaene, Piazza, Pinel, & Cohen, 2003). Specifically, the horizontal segment of the intraparietal sulcus (HIPS) in both hemispheres is systematically activated during tasks that require access to a semantic representation of magnitude, such as estimation or subtraction. Dehaene and colleagues (2003) suggested that the (bilateral) HIPS might constitute a genetically-defined brain structure for numerical cognition, because of its crucial role in the formation and manipulation of mental magnitude representations and because damage to this area has devastating effects on mathematical abilities. The left angular gyrus (in the parietal lobe), which is part of the language system, is activated during operations such as multiplication that call upon a verbal coding of numbers. In addition, the (bilateral) posterior superior parietal area is associated with visuospatial processing and is thought to be involved in attentional orientation on the mental number line, which implies that this area would be activated during calculations such as subtraction. In addition to these brain areas that appear to be directly involved in numerical cognition, a number of studies have cited the importance of such cognitive processes as executive functions (Mazzocco & Kover, 2007) and working memory (Adams & Hitch, 1997) in mathematics. Whereas executive functions are associated with both prefrontal and posterior (mainly parietal) regions (Collette, Hogge, Salmon, & Van der Linden, 2006), working memory has been associated with a dynamic fronto-parietal network (D'Esposito, Postle, Jonides, & Smith, 1999). An understanding of the neural substrate involved in numerical cognition can contribute to an understanding of the effects of training and instruction. Ischebeck and colleagues (2006) showed that training with either multiplication or subtraction led to decreases in activation in inferior frontal areas, indicating that training reduces demand on working memory and executive control. Training in multiplication also led to a shift in activation to the left angular gyrus, suggesting that training caused a shift in strategy from calculation to more automatic retrieval.

### *5.3 Future directions*

A more thorough understanding of the development of mathematical abilities from a cognitive neuroscience perspective has the potential to facilitate the design of research paradigms in educational research. For example, some children with mathematical learning difficulties seem to make use of immature strategies (Geary, 1994). Such strategies can be considered inferior in the sense that they place greater demands on cognitive processes such as working memory. However, strategy use is commonly determined by verbal or written reports by the children themselves and there is reason to believe that such reports may not accurately reflect strategy use (Kirk & Ashcraft, 2001). The possibility exists that brain imaging could be used as an objective measure that combined with more qualitative data could give indications of strategy use, facilitating research into the effectiveness of strategy and the effects of strategy training.

## 6 Higher order skills

Recent developments in learning environment designs emphasize self-direction on the part of the learners (Hannafin, Land, & Oliver, 1999; Lin & Lehman, 1999). Constructivism is one of the main paradigms which drove these developments. The paradigm shift of constructivism entailed to some degree a shift in research thinking from teacher-centered educational practices which viewed educational designs as how to place knowledge in the heads of students, so to speak, to one in which learners take an active role in the construction of their own learning (Duffy & Jonassen, 1992; Jonassen, 1999). The result of this shift has fueled the development of important learning paradigms like whole-task learning (Van Merrienboer & Kirschner, 2007), where learning is driven by work on rich learning tasks based on real-life tasks, and inquiry learning, where 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). Paradigms like whole-task learning and inquiry learning however place a large emphasis on self-direction and the active role of the student. What is meant by an “active” or “self-directed” role can be encapsulated by processes involved in metacognition and its sub-construct: self-regulation.

### *6.1 Education*

Self-regulation is considered to be an aspect of metacognition, a term first coined by Flavell (1971). Metacognition is the process of thinking about one’s own thoughts (Hacker, 1998) and is generally thought to include both awareness of one’s thinking and regulation or *action* on one’s thinking. Self regulation processes encompass the latter. Three activities are generally thought to be essential for self-regulation: planning, monitoring, and evaluation (Butler & Winne, 1995; Schraw, 1998; Zimmerman, 2000). Where planning involves goal setting and extrapolation of standards and a hierarchy of steps and sub-steps (strategies) for goal attainment, monitoring and evaluation occurs when attention is placed on how well and to what degree a plan is being executed. Monitoring and evaluation are separated from an educational view temporally, i.e. monitoring is considered to occur during the execution of a plan, whereas evaluation is often thought to occur at an end or stopping point (Schön, 1991). Monitoring during learning in particular is thought to include thoughts such as checking understanding and making “feeling-of-knowing” judgments about the state of understanding. If students feel they do not comprehend something they will then seek ways to fix their errors, and ideally evaluate why the error occurred. Critical to the monitoring of comprehension errors is the concept of awareness; students often have problems identifying or even being aware of errors in their understanding, especially if they are not “cued” in some sense by their environments to do so (Butler & Winne, 1995). Cueing or feedback mechanisms for checking understanding during learning are usually supplied by the environment; a teacher tells students their math solution is wrong, or a simulation within a technology-enhanced environment shows data that indicates improper setup. Ideally, once an error is identified students attempt to change their actions to fix mistakes. Sometimes this means adopting an entirely new strategy, or simply adapting steps within an existing one. Viewing these processes from the lens of cognitive neuroscience then, metacognition is higher-order thinking, which can also be referred to as executive control. 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).

### *6.2 Cognitive neuroscience*

As with much research on cognitive neuroscience, gains have been made in locating areas of the brain responsible for executive processes. In particular, the network of frontal areas of the brain such as the anterior cingulated cortex and supplementary motor area, the orbitofrontal cortex, the dorsolateral prefrontal cortex and portions of the basal ganglia and thalamus seem to be related to excecutive control functions (Fernandez-Duque et al., 2000). With regard to specific executive processes, Fernandez-Duque et al. (2000) reviewed cognitive neuroscience research related to conflict resolution, error detection, and developmental trajectories of inhibitory control. For the purposes of this review, performance monitoring is taken as a whole, given questions in cognitive neuroscience as to whether error detection and judgments about competing concepts are housed in one area (Ullsperger & Yves von Cramon, 2001).

#### 6.2.1 Performance monitoring

Conflict resolution might relate to metacognition in the sense of learners trying to fix an incongruence between their plans or comprehension, a current state of an activity and (either internal or external) feedback they receive. fMRI studies with the Stroop task wherein a subject is asked to name a word colour, are often used for imaging studies of conflict resolution (e.g., Bench et al., 1993; Carter, Mintun, & Cohen, 1995;

Carter, Mintun, Nicholas, & Cohen, 1997). In this task, colour words are printed in their corresponding ink colour (congruence) and in different colours (incongruence). When the ink colour and the colour word are incongruent, consistent activation patterns have been found indicating common areas involved in conflict resolution. Pertinent to an understanding of metacognition is the presence and timing of additional patterns of activation in the cingulated cortex during both congruent and incongruent conditions. In the Stroop task participants must inhibit the dominant response of naming the word itself in favour of the less dominant response of naming the colour. The timing of activation of the cingulated cortex indicates the resolution of conflict between an ink colour and the word in the incongruent condition (i.e. between the dominant and non-dominant response), however this activation pattern is also apparent in the congruent condition. “Thus, 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.” (Fernandez-Duque et al., 2000, p. 292). This is a relevant question in metacognitive research which seeks to explain the degree to which metacognition is implicit or explicit in its functioning (Koriat, 2000; Reder & Schunn, 1996).

Petitto and Dunbar (in press) investigated conceptual change issues with regard to neurological patterning in their fMRI study to investigate how students might make changes to their understanding of concepts they find plausible or implausible. Conceptual change is 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 deviations from their ideas, or anomalies (e.g., Baker & Piburn, 1997). Conceptual change has been particularly hard to assess or see as Petitto and Dunbar (in press) state the underlying view is “that when students display a clear understanding of correct concepts a reorganizing of knowledge has occurred. However, while there clearly have been some success stories in teaching scientific concepts through anomalies, it is not clear that restructuring has really occurred” (p. 11). 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 cingulated cortex, and dorsolateral prefrontal cortex (DLPFC) 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 did show evidence of learning network activation.

Physiological research on error-detection has been on-going since the 1960’s. It is well known, for example, that performance slows 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 cingulated, which shows increased activation in tasks meant to provoke errors (Carter et al., 1998; Fernandez-Duque et al., 2000). Event-related potential (ERP) research also indicates error-related negativity after detection of an error (Badgaiyan & Posner, 1998). Taken together, this research appears to signal a beginning understanding of the biological basis for an error detection system. Related to error detection is the idea of feeling-of-knowing (FOK). Theoretically, FOK judgments relate to how people decide if information is readily accessible in memory and if there is “sufficient” reason to try and retrieve it. The FOK paradigm conjectures that such judgments are made based on the relative familiarity of the recall cue (Schnyer, Nicholls, & Verfaellie, 2005). Results of research with healthy participants into the role of brain areas involved in FOK judgments from Schyner, Nicholls, and Verfaellie (2005) show 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. The authors state that the VMPC’s function seemed to have less to do with memory retrieval and more to do with an intuitive assessment or evaluation of “feeling of knowing”, indicating a monitoring role rather memory retrieval.

### 6.2.2 Developmental insights

From a developmental perspective, cognitive neuroscience has begun to elucidate the points at which humans develop the neurological capacity for the executive functions involved in metacognition. Particularly important to metacognitive action is the ability to inhibit incorrect responses or data so proper decisions can be made. Particular aspects of inhibitory control develops neurologically from around 12 months to around five years old and can be seen as being tied to the development of the anterior cingulated cortex (Fernandez-Duque et al., 2000). Other aspects develop up till early adolescence and even late adolescence. Major breakthroughs have been obtained in the last 6 years with respect to our knowledge on the developmental course. Brain maturation takes place up till well in the third decade of life, and structural changes in both white and gray matter can be monitored in parallel to the cognitive and social-emotional development of the child and adolescent (e.g., Giedd, 2004; Gogtay et al., 2004). An evaluation of these findings and their implications for educational research are beyond the scope of this quick scan. Yet it is important to be aware of these findings as they point out that learning and the efficiency of learning might be dependent upon the stage of brain/neurocognitive maturation. This is especially the case since higher order cognitive control appears to develop from middle adolescence onwards and is not developed to such an extent that children or young adolescents can learn completely on their own. In other words, there might be a very important research area here, but a description of its possible merits and implications will be done in the follow-up to this report. As to the ability to incorporate more sophisticated metacognition such as planning and complex error detection over the course of human development, more research is needed.

## *6.3 Future directions*

The theoretical implications of cognitive neuroscience research into metacognitive and self-regulated learning may to some degree facilitate what Byrnes and Fox (1998) describe as fine-tuning the theoretical precision and accuracy of metacognition. Of particular interest may be areas of implicit learning with regard to neurological evidence that metacognition could be shown to be ongoing and implicit when students are faced with congruent information and explicit in the face of incongruent information. The work of Fugelsang and Dunbar (2005) provides an excellent example of how cognitive neuroscience can be used to inform questions about students' causal reasoning and conceptual change, as well as provide an example of the design of research which seeks to bring together educational, cognitive, and neurologically based sciences. In addition, linking metacognition to cognitive neuroscience investigations of executive control shows how terminology between the two fields can be brought together for the furtherance of cooperation. Developmental research with regard to executive control functions will also 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, for example. In addition, models of metacognition can be refined through cognitive neuroscience research. For example, Nelson and Narens' (1994) model of metacognition focuses on how metacognition "… is the interplay between two levels of analysis - an object level and a meta-level. By this view, processes within the object-level are monitored by the meta-level. That is, metacognitive monitoring involves the flow of information from the object level to the meta-level" (Shimamura, 2000, p. 314 ). Cognitive neuroscience could seek to describe from this perspective how the flow of information moves from an executive control point of view, when the flow of information is disrupted, and provide evidence for breakdowns in the metacognitive process given various stimulation.

Another research domain which appears to provide findings which are of potential relevance for education lies within cognitive neuropsychology. In brief, the development of higher cognitive functions follows a pattern in which particular processes develop earlier than others. The model provided by Anderson (2002) for example, states that component cognitive processes which are essential for the execution of a complex act develop in a particular order. The formulation of an action plan, attentional control, outcome monitoring and concept shifting/flexibility are some key processes in this regard. New information comes available which suggests that self-evaluation and social monitoring might develop after early adolescence in the majority of normal youth, and that concept formation, abstractional abilities and the ability to prioritize between competing response tendencies also develop late. This might have major implications for application into educational settings and thus suggests that dedicated research is called for.

Cognitive neuroscience is a budding field; as such much of the work that has been done from a metacognitive standpoint has been to map the brain functions which contribute to executive functions. As stated in much of the present quick scan, tasks which cognitive neuroscience has typically used are limited in scope and duration. This makes the results hard to compare to the often complex tasks utilized in educational science. However, there is a rapid development of new paradigms which are already used in cognitive neuroscience and do provide experimental approaches which could be of relevance for educational research. Fuselgang and Dunbar (2005) have provided an example of how cognitive neuroscience can incorporate more complex and educationally relevant tasks. The same applies to approaches such as proposed and used by Blakemore and others (Blakemore, Den Ouden, Choudhury, & Frith, 2007). Paradigms in which strategies can be determined and in which conceptualisation, abstraction and 'thinking' are evaluated bear much promise in this respect. Future research should try to further follow this alley.

# 7 Social and emotional processes in learning

## *7.1 Education*

Educators recognize the importance of social and emotional processes for learning. In the influential theories of Vygotsky (1978) and Bandura (1986), the role of social processes for learning is stressed. 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 also stresses the importance of observing and modelling the behaviours, attitudes, and emotional reactions of others for learning. Emotions affect achievement, by influencing students' interest and attitude towards learning and learning environments, which also affects how information is processed or interpreted (for a discussion of emotion research in education see e.g., Pekrun, 2005; Pekrun, Goetz, Titz, & Perry, 2002)

## *7.2 Cognitive neuroscience*

In basic neuroscience and biological psychology it has been a known fact for decades that the brain areas involved in emotional processing are of prime importance for learning. Already around 1950, insights were obtained on the crucial role of limbic structures for memory consolidation whereas these same structures were also involved in elementary emotional processing. Emotional processing appeared to be necessary for proper memory consolidation to occur, and both animal and human research shows the major importance of emotional and motivational processing and involvement of particular neurotransmitters and neurohormones. These research findings are revitalized by recent brain imaging experiments which are suggestive of the role of limbic areas in temporal lobe and prefrontal (notably anterior cingulate) areas (e.g., Amodio & Frith, 2007) The study of social and affective processes is a rapidly emerging topic in neuroscience, although the cognitive aspects of social/emotional processes were studied in cognitive neuroscience, social and affective neuroscience seems to be emerging as an important sub-field now (e.g., the Journal "*Cognitive, Affective, & Behavioral Neuroscience*" started in 2000, and "*Social, Cognitive, and Affective Neuroscience*" in 2006). The present quick scan can not cover the subject in depth and provides only a first approximation of potentially relevant routes in this fascinating new field which bears promise for educational research and practice given the major importance of motivation and emotion within the learner. Some relevant examples are given in the next paragraphs.

### 7.2.1 Emotional processes

Neuroscientists recognize the important role that social and emotional processes play for learning (Immordino-Yang & Damasio, 2007). Several authors have investigated how materials with different emotional valence are processed. For example, Simpson et al. (2000) investigated effects of emotional valence (negative or neutral) of pictures presented during a cognitive task on task performance. They found that task performance was slower for negatively valenced pictures, and that there were differences in the functional anatomy associated with task performance for negative and neutral pictures. Dolcos and Cabeza (2002) showed that emotional events were remembered better than non-emotional events. They measured ERPs while participants rated the emotional content of pleasant, unpleasant, and neutral pictures. They found differences in the ERPs for emotional and non-emotional (neutral) stimuli and subsequent recall was better for pleasant and unpleasant pictures than for neutral pictures. Results by Fox (2002) suggest that not only the emotional valence of the stimuli is important for how these are processed, but also the emotionality of the individual engaged in the task. She found that participants with high levels of trait anxiety showed an attention bias towards fearful faces.

Another suggestion made by neuroscientists that might be interesting for education, is that made by Immordino-Yang and Damasio (2007). Based on evidence from brain-damaged patients, they suggested that emotion-related processes are also required for transfer of skills and knowledge from school to real-world environments.

#### 7.2.2 Social processes

For social learning processes, the reader is referred to the topic “observational/ imitation learning” (Section 3). As mentioned there, the mirror-neuron system is thought to play an important role in understanding actions made by others. However, it has also been suggested that this system not only plays a role in learning by observation and/or imitation, but also in social cognition more general (e.g., link with theory of mind, see Keysers & Gazzola, 2007). In addition, of major importance are new findings which show 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). It has been hypothesized that it is the ability of the brain to evaluate action programs in terms of emotional consequences and social consequences which are at stake. In other words, the adolescent brain learns to prioritize competing action programs (and parts thereof) in terms of the consequences which these actions have on the short run (e.g. in the next minutes or hours), or on medium term, semi long term (e.g., weeks or months), or long term (e.g. years) and the consequences which these actions have for ‘significant others’ (peers, friends, parents, teacher) and society including social norms.

With regard to the interplay between social and emotional processes, social stimuli function as emotional barometers for the immediate environment and are the catalysts for many emotional reactions (which have inherent value for relationships and survival). Norris, Chen, Zhu, Small, and Cacioppo (2004) conducted a study to test the hypotheses that the neural mechanisms underlying social and emotional information processing could be interconnected. Their study showed that social and emotional processes have both independent and interactive effects on brain activation.

### *7.3 Future directions*

The field of social and affective neuroscience appears to be booming, but with regard to learning and education, the field is still in its infancy. Nevertheless, it is universally accepted that social and emotional factors exert a strong influence on learning, and therefore, future neuroscientific research in this area could provide important contributions to education and educational research. Similar to statements made in earlier paragraphs, effort should be taken to incorporate insights from educational research and practice into social and cognitive neuroscience in order to come to new paradigms which can help develop educational science by providing new experimental models with strong explanatory power.

## 8 Learning problems

### *8.1 Dyslexia*

Many children experience difficulty learning to read although they receive sufficient reading instruction. Reading difficulties that do not result from global intellectual deficits or a chronic problem of motivation are termed dyslexia. Quantifying the (world wide) prevalence of dyslexia would require a universally accepted definition and screening process, both of which are lacking. However, estimates range from 2% to 10% of the population, with higher rates found in languages with a deep orthography. Both within the fields of neuropsychology and cognitive (neuro)science there is considerable knowledge on dyslexia. The present quick scan focuses on some issues which are particularly relevant for education. The reader is referred to recent reviews and reports for more in-depth evaluation (examples are the OECD report 2007 and papers by Goswami in Trends in Neurosciences 2006).

#### 8.1.1 Education

A number of types of dyslexia have been distinguished; including surface dyslexia, phonological dyslexia, and deep dyslexia (Pennington, 1999). Children with surface dyslexia read as beginning readers do; they break even frequent words into their syllabic constituents and have particular difficulty reading irregular words correctly. These children seem to make use of the assembly of phonology without being able to address the word's phonological structure from the mental lexicon (Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Shallice, Warrington, & McCarthy, 1983). Children with phonological dyslexia, however, can read familiar words but their reading of novel words or pseudowords is severely impaired (Funnell, 1983). Deep dyslexic readers make semantic errors consisting of mispronunciations that, rather than being phonologically related to the printed word, are semantically related (e.g., *flower* and *rose).* This seems to suggest that deep dyslexic readers bypass the word's phonological structure and, albeit sometimes inefficiently, access meaning directly from print (Marshall & Newcombe, 1981).

Some authors (Coltheart et al., 1993; Coltheart & Rastle, 1994) have interpreted these different types of reading difficulty as support for a dual route model of printed word recognition. Children with surface dyslexia would be seen as having a deficit in the direct route, which implies that they must use the slower indirect route of mapping letters to sounds to read even frequent words. Children with phonological dyslexia, on the other hand, are seen as having a deficit in the indirect route and therefore are able to read familiar words but are unable to sound out novel words or pseudowords. Finally, deep dyslexics are also assumed to have a deficit in the indirect route, impairing their ability to sound out words, along with some impairment of the direct route, resulting in sometimes inaccurate direct access to meaning. Therefore, the double dissociation between surface and phonological dyslexia was seen as reflecting a double dissociation between impairment of the direct and indirect routes, which was interpreted as strong evidence in favour of the dual route model of printed word recognition.

Although at first glance, the evidence of surface and phonological dyslexia may seem like a double disassociation of direct and indirect access to the mental lexicon, there is empirical evidence showing that actual cases of dyslexia are often not so clear cut. In a study by Castles and Coltheart (1993) 60% of dyslexic children were significantly below age level on both pseudoword and irregular word reading. Only about 20% of dyslexic children were selectively impaired on either pseudoword or irregular word reading. Therefore, only 40% of their sample could be considered to have a pure form of either surface or phonological dyslexia, whereas 60% showed evidence of a mix of these two types. From the perspective of dual route models, this would imply that the majority of children with dyslexia have an impairment of both the direct and the indirect route to the mental lexicon. Other researchers emphasized the role of phonology in dyslexia (e.g., Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Pennington, 1999). Manis and colleagues (1996) explain phonological dyslexics as having degraded phonological representations, which has a maximal impact pseudoword reading, somewhat less on irregular word reading and little impact on regular word reading. Depending on the degree of phonological representation degradation, such children would be classified as phonological or mixed dyslexics. These authors found that the performance of surface dyslexics was similar to that of younger typically developing children, suggesting a developmental delay in word recognition. They explain this delay as being due to a reduced number of units in the middle layer of the connectionist network. As a result, such children can learn rule-like regularities (although less efficiently), but are impaired in learning word-specific patterns.

#### 8.1.2 Cognitive neuroscience

There has been considerable progress made in identifying the neurological substrate involved in dyslexia. In a PET (positron emission tomography) study comparing dyslexics Italian, English and French dyslexics, Paulesu and colleagues (2001) found that although the Italian dyslexics (who use a shallow orthography) performed better on reading tasks than the English and French dyslexics, all dyslexics were equally impaired on reading and phonological tasks relative to their controls. PET scans showed that all dyslexics showed evidence of reduced activity during reading in a region of the left hemisphere, with the maximum peak in the middle temporal gyrus and additional peaks in the inferior and superior temporal gyri and middle occipital gyrus. These authors conclude that there is a universal neurocognitive basis for dyslexia and that differences in reading performance among dyslexics of different countries are due to different orthographies.

Shaywitz et al. (2001) report an association between dyslexia and atypical cortical features in the left posterior parieto-temporal region as well as the left posterior occipito-temporal region. The functional consequence of these atypical cortical features is thought to be impairment in processing the sound elements of language. This finding enabled the development of targeted intervention that has been revealed a promising plasticity of these neural circuits. The targeted treatment was shown to enable young dyslexics to develop neural circuitry in posterior portions of the left hemisphere sufficiently to enable them to read accurately and fluently (Shaywitz et al., 2001). Lyytinen and colleagues (2005) report that, even at a very early age, ERPs (event related potentials) to speech sounds can differentiate children with and without risk for dyslexia and are predictive of later language development and reading acquisition. In the same line, Molfese (2000) recorded ARPs (auditory event-related potentials) in response to speech and non-speech syllables from newborns. Results discriminated between newborn infants who 8 years later would be characterized as dyslexic, poor, or normal readers.

#### 8.1.3 Future directions

Cognitive neuroscience has already made important contributions to the understanding of the neurological substrate and the cognitive processes involved in dyslexia, which has already lead to the creation of interventions that show promising results. However, more work remains to be done. Collaborative efforts between educational science and cognitive neuroscience can aim to resolve the debates between, for example, the dual route and connectionist models of word recognition which could, in turn, enable the creation of specific interventions.

Another relevant issue which is provided by cognitive neuroscience has to do with the promising progress in the area of early detection, as detailed above. These efforts could be expanded, with an aim toward establishing early detection protocols. Likewise, major contributions can come from research into the neurocognitive strategies used by children with a reading problem. There are indications that children develop other strategies to cope with the deficient linguistic-visual processing and that these strategies are not always the most efficient form of compensation. Functional brain imaging potentially provides a potent tool to evaluate the efficiency of the reading process and the automatization of an overlearned response. Based upon MRI, the learning process could be adapted in order to be optimally effective for the learner. Research programs into cognitive compensation and reading strategies involving auditory, visual, haptic sensory inputs and various strategies and types of learning materials should be devised and executed.

### *8.2 Mathematical problems*

Although learning difficulties are just as common in mathematics as they are in reading, considerably less research has been done on mathematical learning difficulties (e.g., Rousselle & Noel, 2007; WHO, 1992) both with respect to the underlying causes as to the best educational practices. The term ‘dyscalculia’ is sometimes used to describe mathematical problems but neuropsychologically, it is important to discern problems with the development of skills related to calculation and simple arithmetic from the focal neurocognitive deficits which have been described in terms of ‘dyscalculia’ in the neuropsychological clinic. Mathematical problems were identified later and have not been as well researched as dyslexia and are, therefore, less well understood.

A review of the literature reveals a variety of terms used to describe learning difficulties in the area of mathematics, including mathematical disabilities, mathematics learning difficulties, mathematics learning problems, mathematics learning disorders, mathematics learning disability, and mathematics learning deficiency, among others (Stock, Desoete, & Roeyers, 2006). These terms have often been defined by criteria such as falling below a given percentile on a standardized test of mathematics (Stock et al., 2006), with most authors using a cut-off point between the 25th and 35th percentile. The American Psychiatric Association defines dyscalculia as difficulty in learning arithmetic and failure to achieve adequate proficiency in arithmetic despite normal intelligence, scholastic opportunity, emotional stability, and necessary motivation (APA, 1994). Some authors include a specific reference to neurological deficit in their definition of dyscalculia. For example, Geary and Hoard (2001) define dyscalculia as deficits in the processing of numerical and arithmetical information associated with overt brain injury or presumed neurodevelopmental abnormalities. Mathematical learning problems are estimated to affect as little as 1% to as much as 7% of the school-age population (APA, 1994; Geary & Hoard, 2001), with most authors estimating close to 5%. It should be noted that mathematical learning difficulties that are defined by researchers as performance below the 25th and 35th percentile must necessarily include a larger group of children than the approximately 5% with dyscalculia. Again, the reader should bear in mind that the term ‘dyscalculia’ is used differently by different professionals or research disciplines with the most strict definition stating that dyscalculia should only be used in case of actual or anticipated brain dysfunction, whereas others use the term in a psychometric sense.

### 8.2.1 Education

Although more research is needed to investigate the cognitive characteristics of children with mathematical learning difficulties, children with mathematical learning difficulties who are good readers have been shown to have deficits in the ability to retrieve the answers to simple arithmetic problems, such as 5 + 3, from long term memory, a skill referred to as math fact fluency, whereas children with both mathematical and reading difficulties have not only deficits in math fact fluency, but also in problem solving skills (Geary, Hamson, & Hoard, 2000).

The signs and symptoms of mathematical problems can vary greatly (Geary & Hoard, 2001; Shalev & Gross-Tsur, 2001). Some (younger) children with mathematical problems have difficulties with number sense, the early understandings of numerical quantities and their relations. Many children with mathematical problems may demonstrate difficulty learning number facts (e.g., 2 + 5, 3 x 6) and with the retrieval of such facts from memory. Apparently as a result of these retrieval deficits, children with mathematical problems tend to use inefficient strategies that place a greater demand on, for example, working memory. Children with mathematical problems may make errors resulting from incomplete procedural knowledge necessary for complex problems in addition, subtraction, multiplication, or division. These children may also confuse arithmetic symbols (e.g., +, -, x, ÷) and make procedural errors as a result. The diagnosis of mathematical problems is based on assessment of the child's arithmetic skills and can best be determined by a discrepancy between the intellectual potential of the child and his or her arithmetic achievement (Shalev & Gross-Tsur, 2001). This presupposes the existence of reliable standardized tests that measure all (age appropriate) aspects of numeracy and mathematics.

### 8.2.2 Cognitive neuroscience

Much cognitive neuroscience research has been done in recent years with the goal of revealing the neural substrate of numerical cognition and a short review of this research can be found in section 5.2 of this report. Evidence suggests that areas in the (bilateral) parietal cortex of the brain, including areas involved in verbal and visuospatial processing, are involved in number processing (Dehaene et al., 2003). Cognitive processes such as executive function and working memory have also been shown to be important for number processing, both of which rely on frontal and parietal areas (Collette et al., 2006; D'Esposito et al., 1999). Neuropsychological tests can be used to help determine the specific cognitive deficits underlying mathematical problems in a particular child. Consequently, it has been suggested that remedial education for children with mathematical problems should employ interventions appropriate for the underlying neuropsychological deficits of the particular child, for example, perceptual and visuospatial or verbal and auditory-perceptual (Rourke & Conway, 1997). There is even evidence that the use of targeted intervention can lead to changes in the brain itself. Learning new number facts or processes is able to alter brain activity (Delazer et al., 2003; Ischebeck et al., 2006). Recent advances in neuropsychological research show that there is a developmental factor involved. Some children might be later than other children in the development of elementary functions which are important for calculation and arithmetical operations. Estimation, mental rotation and spatial processes related to number sense seem to be important. Also clinical neuropsychological research into the implications of focal brain damage also underscore that mathematical abilities require proficiency in quite a number of different neurocognitive functions. More research should be done in order to link these findings to those done in cognitive psychological research, cognitive neuroscience and educational research.

### 8.2.1 Future directions

Although much has been learned about the neural substrate responsible for numerical cognition in recent years, much work remains to be done. In particular, more work is required to examine the precise neurocognitive underpinnings of dyscalculia in the broader sense of mathematical problems as well as the strict sense. An understanding of theses cognitive underpinnings can be used to design neuropsychological tests that can be used to more reliably diagnose dyscalculia and to suggest specific areas to target in interventions. Of major relevance in this respect is the developmental pattern and the complex nature of the skill of mathematical operations, which require the identification of cognitive subprocesses and their interaction and developmental profile. The results of studies that show changes in the brain in response to learning and intervention (Delazer et al., 2003; Ischebeck et al., 2006) are exciting and more of such work needs to be done. Paradigms from cognitive neuroscience offer new ways to judge the effectiveness of one intervention in comparison to another.

# 9 Conclusion

This quick scan has sought to identify promising areas of research in which educational research and neuroscience could come together. This emphasis on identifying research areas also signifies our view on where we currently stand, which is at the edge of an exiting new field of research. We do believe that in many respects it is too early to see direct consequences of neuroscience for educational practice. Many neuroscience reports and studies do present recommendations for education but these recommendations often have a general character that doesn’t directly translate into educational design. In that regard, it is imperative to discern between recommendations which are related to 'learning' on the one hand, and those related to 'education' on the other. This is because the learning process is so diverse, and involves a vast domain of different applications, varying from knowledge learning, via learning psychomotor acts to social-emotional skills and higher cognitive processes including self-regulation and self-initiated learning. In addition, many factors are known to be of major importance for learning, including instruction-related factors, child/learner-related factors (including age, sex, and biological factors) and context related factors (social class, parental education, culture). Accordingly, there is not a simple step from cognitive neuroscience research into the educational setting. Moreover, recommendations are made for different areas of education without considering an integration into a coherent curricular approach. As early as 1991, Caine and Caine (1991) presented 12 recommendations for education based on neuro-scientific research. These recommendations include: "All learning is physiological; the Brain-Mind is social; the search for meaning is innate; the search for meaning occurs through patterning; emotions are critical to patterning; the Brain-Mind processes parts and wholes simultaneously; learning involves both focused attention and peripheral perception; learning always involves conscious and unconscious processes; there are at least two approaches to memory: archiving individual facts or skills or making sense of experience; learning is developmental; complex learning is enhanced by challenge and inhibited by threat associated with helplessness; each brain is uniquely organized" (from http://www.newhorizons.org/neuro/caine%202.htm). Current recommendations often equal Caine and Caine's recommendations in terms of generality and lack of an overall view. Such an approach may lead to the use of what are called "neuromyths" (OECD, 2007).

The time has come to conduct new types of research that will provide us with more detailed and applicable guidelines for educational design based on neuroscientific data. As was indicated in the present quick-scan which is to be regarded as an intermediate report, neuroscience research may prove to be of critical relevance for educational theories or areas of research. In this quick scan, we have identified themes which elaborate on major routes described earlier by Jolles et al. (2005), notable those which are most relevant for further development of educational research. This choice was based upon the direction, given by the Educational Research Program Council (PROO) of the Netherlands Organization for Scientific

Research. Thus, the present report elaborates upon : (a) multimedia learning (Mayer, 2001) for which findings regarding multimodal processing could be relevant; (b) cognitive load (Sweller et al., 1998), for which findings on neurological correlates of cognitive load and attention would be relevant; (c) social-observational learning (Bandura, 1986) and social-emotional learning for which the research on the mirror-neuron system seems relevant; (d) language learning (Evans & Carr, 1985) for which a “dual path” approach combining bottom-up and top down processes in reading finds support in the neuroscience literature; (e) mathematics learning, including work on mathematics learning difficulties (Rousselle & Noel, 2007) could profit from neuroscience research efforts to locate specific mathematical processes (e.g., number processing and semantic activities) and the involvement of executive processes; (f) higher order, metacognitive skills for which neuroscientific identification of processes of conflict resolution, error detection, causal thinking, and planning seems relevant; (g) learning disabilities (Lerner & Kline, 2006) and severe learning problems, such as dyslexia and dyscalculia, for which neuroscientific methods for early detection and the effects of intervention are central, as well research on the plasticity of the brain.

Depending on the nature of the findings which have been collected in preceding years, and will be gathered in the next future, several interpretative steps are required to identify what interesting interfaces for interdisciplinary research could be, or what findings from neuroscience in these areas could contribute to educational research. Examples are: ‘does this provide implications for designing instruction, that is, to shape and support learning?’, ‘does this deepen our insight into neurocognitive processes and skills involved in self-initiated learning?’, ‘does this provide mechanisms to understand the efficient development of an elementary skills and the subsequent application in a more complex educational performance?’. Thus, findings from neuroscience in terms of activation patterns or neural changes show that types of learning (tasks) are correlated with activation or growth of specific brain areas. Although this is highly informative, additional interpretation is necessary to link brain area activation or growth to cognitive processes (e.g., Henson, 2006; Poldrack, 2006). A further step is to translate these findings into practical considerations for use in the classroom. Besides cognitive processes, also interactional skills, motivational processes, social and emotional monitoring and self-evaluation of the learner (to name but a few) are needed. Byrnes and Fox (1998) provide two directions with which to interpret these types of results. First, that research in cognitive neuroscience (including social and affective neuroscience) can aid educational insights as to the nature of cognitive processes while students are engaged in learning tasks, and secondly, cognitive neuroscience may aid educational researchers in their search to resolve conflicts in existing educational theories. In addition, findings from neuroscience research also involve Behavioral measures or measures of learning outcomes. These measures might confirm or corroborate findings from educational research, thereby strengthening educational theories with knowledge of underlying cognitive and brain mechanisms of observed effects on learning as well as cognitive neuropsychological insights into learning and educational performance of individual learners, given their developmental stage, psychosocial context, biopsychological variables and other aspects.

To bring the complex fields of educational and neuroscientific research together we would need to also bridge the methodological approaches as used in both scientific fields. It should also be borne in mind that the fields as such are multidimensional in themselves with researchers focussing on instruction, on knowledge transfer, on attentional, motivational or psychological processes in individual learners or on various aspects of educational performance and/or age or intellectual level. One interesting aspect concerns the granularity of research. Tasks used in neuroscience are often short, decontextualized, and isolated, whereas in educational research interesting tasks are long (ranging from one lesson to a series of lessons), content rich and diverse, and embedded in a complex (social) environment (the classroom). This not only hampers the translation of results from neuroscientific research into educational practice, but also calls for new methodological approaches.

The present quick scan may provide some routes to follow in the search for potent paradigms and good scientific models which can guide a science-based educational innovation which our society calls for. We think it reflects some of the most important trends as can be observed in the literature, whereas it does not pretend to provide a complete coverage of the domain or to give an in-depth evaluation of all relevant issues. This report will primarily act as a starting point for a web discussion and an international workshop, which will then provide the input for a more elaborate report on the potential of cognitive neuroscience for education.

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