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Position paper

Cognitive neuroscience meets mathematics education: It takes two to Tango

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1. Introduction

Against the background of the organization of an EARLI Advanced Study Colloquium on *Cognitive Neuroscience Meets Mathematics Education*, we argued that the interdisciplinary field of neuroscience and education should be conceived as a two-way street with multiple bi-directional interactions between educational research and cognitive neuroscience (De Smedt et al., 2010a).

In his response to our paper, Turner (2011) provided a critical examination of the possible connections between educational research and neuroscience and argued that there is currently a very unbalanced one-way exchange and dominance of cognitive neuroscience rather than a two-way street between neuroscience and education, if, at all, such a two-way street can be possible. This unbalanced exchange arises because the limitations of neuroimaging research are not always clearly articulated and because the findings that it generates are often taken for granted and not open to critical evaluation, particularly not by educational researchers. In the enthusiasm for promoting connections between neuroscience and education, behavioral studies are undervalued and neuroscience is often credited for data that are actually obtained by means of behavioral studies.

We appreciate Turner's (2011) efforts to undertake this critical examination, especially because, as also highlighted by the author, a critical interrogation of cognitive neuroscience from within the field of education is currently missing. Without doubt, neuroimaging research has its limitations, most of which are highly similar to any quantitative research method, as we will discuss further below. The important role of behavioral studies needs to be emphasized and it is inappropriate to assume that the results of one approach, such as cognitive neuroscience, are more informative or valued than the results of any other studies of that behavior.

The author proposes that if the field of neuroscience and education wants to move forward, a critical acknowledgement of the strengths and weaknesses of each subfield and mutual respect for both research traditions, that (might) have distinct philosophical backgrounds, are crucial. This aim for a balanced and complementary relationship represents exactly what we wanted to highlight with the idea of a two-way street scenario between neuroscience and education (De Smedt et al., 2010a). The connection between both disciplines should not be limited to a one-way street view in which findings from cognitive neuroscience are applied to educational theory. This would be the imbalance that Turner's (2011) is pointing to, where one of both partners is dominant. Clearly, the two-way street scenario is not something that has been achieved so far. Educational researchers and cognitive neuroscientists should understand each other more fully than is currently the case, a challenge for the future in which the role of education of researchers both in education and in cognitive neuroscience will be fundamental.

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2. Background of De Smedt et al. (2010a)

It is important to re-iterate the background that constituted the writing of the De Smedt et al. (2010a) paper. In 2009, we organized an EARLI Advanced Study Colloquium (ASC), i.e. a small group of educational researchers who gather for an in-depth discussion on current developments and future research questions in a specific domain of learning and instruction, on *Cognitive Neuroscience Meets Mathematics Education* in Bruges, Belgium (De Smedt & Verschaffel, 2009). The aim of this colloquium was to reflect on the position of cognitive neuroscience in research on learning and instruction. This created a focus on research projects aimed at understanding mathematical learning that involved an interdisciplinary collaboration between educational researchers and cognitive neuroscientists. The discussions at this colloquium, highlighting the promises and pitfalls of research at this intersection between cognitive neuroscience and education, served as a background for De Smedt et al. (2010a). For this reason, the paper of De Smedt et al. (2010a) was restricted to the field of mathematics learning, and may not be readily generalized to other fields of education. More progress, for example, has already been made in the field of reading development, where successful interdisciplinary interactions between cognitive neuroscience and education have addressed questions that go beyond what cognitive neuroscience and education research alone can investigate (McCandliss, 2010).

3. Limitations of neuroimaging methods

Without doubt, neuroimaging methods have some important methodological limitations and, true enough, as highlighted by the author, these limitations are not always clearly articulated in neuroimaging research papers compared to educational research. There are important concerns with regard to specific statistical analyses of fMRI data (e.g., Vul, Harris, Winkielman, & Pashler, 2009) and there is a universal awareness of those issues among neuroscientists. The author lists a number of methodological caveats, including group averaging, ignoring individual and strategic variability, absence of longitudinal research, limited generalizability to real-life situations, which might prevent a connection between cognitive neuroscience and educational research. While these methodological issues are undoubtedly very important to consider when designing and evaluating educational research, these issues are not specific to fMRI and apply to any quantitative research method that is used in educational research, such as experimental or correlational studies.

For example, the author argued that brain imaging studies are problematic for educational research because fMRI data are always averaged over several scans and averaged over several individuals. Yet, many quantitative studies in educational research adopt measures that contain multiple items to investigate a particular skill or trait. It is even recommended to use multiple measures of the same skill in order to increase the reliability of the data (e.g., Schneider & Stern, 2010). Educational studies that examine the effect of a particular intervention by means of the standard pre-test posttest design, typically aggregate data over individuals that are assigned to different instructional conditions, rather than looking at the effects of interventions at the level of the individual.

We agree with the author that for a long time neuroimaging studies have disregarded the issues of individual differences and strategic variability as well as the effects of environmental factors on performance, issues that educational researchers largely have been focusing on. We are happy to note that these issues are being increasingly taken up in neuroimaging research, as evidenced by the increasing number of studies that look at individual differences, where the level of brain activity is correlated with individual differences in mathematical competence (Grabner et al., 2007; see also Adolphs, 2010 for examples of neuroscientific studies of individual differences in social behavior). There are also more and more studies that take into account differences in contextual variables on brain activity and structure. For example, recent work investigated the effect of abacus-based mental calculation training on children's brain structure, by comparing children who received 3 years of abacus training with those who had no experience in abacus calculation (Hu et al., 2011). This study revealed that children who received abacus training showed an enhanced quality of the white matter tracts that are related with motor and visuospatial processes. There is also an increasing number of neuroimaging studies that investigate the effects of strategic variability on brain activity, both in the field of mathematics learning (Grabner et al., 2009) and beyond (e.g., Voss et al., in press, for an example on game-based learning). This being said, the number of studies that focus on these variables is limited, but we hope this to become a priority on the research agenda of future neuroimaging research. The design of these studies will require a careful consideration of the different factors that influence learning behavior, and this is where we think the input of educational (and psychological) researchers will be crucial. If researchers are to unravel the effects of these variables on brain activity, there is no doubt that educational researchers should be considered as equal partners. Otherwise the outcome of this neuroimaging research will be meaningless, both to neuroscience and to education.

It is also true that most of the existing neuroimaging studies are cross-sectional and that the number of longitudinal studies is currently limited. Yet, there are several examples of longitudinal fMRI studies (e.g., Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011; Finn, Sheridan, Kam, Hinshaw, & D'Esposito, 2010), although no longitudinal studies on mathematics learning have been published so far. Longitudinal studies are much more difficult to conduct than cross-sectional studies, as is the case in educational research, but this does not mean that fMRI is not well suited for performing longitudinal research, as Turner's (2011) incorrectly states.

fMRI data are collected in a very specific environment, the magnet bore, and this surely cast doubts on the external validity of these measurements. But again, these limits on the generalizability of findings in brain imaging research also apply to other laboratory or experimental situations in which data are collected, as every study is limited in its external validity to some degree. This issue might be addressed by correlating measures inside and outside the scanner (De Smedt et al., 2010a). In other words, measures from the laboratory can be used to predict real-world behavior in the classroom (or vice versa).

We would like to emphasize here that the author targeted only one neuroimaging technique, i.e. fMRI. Although this technique is non-invasive and its development probably provided the growth of cognitive neuroscience and, consequently the interest in cognitive neuroscience and education, there exist other brain imaging techniques, such as ElectroEncephalography (EEG) or Near InfraRed Spectroscopy (NIRS). The abovementioned methodological issues also apply to EEG and NIRS, but, different from fMRI, the collection of NIRS and EEG data takes place in less restricted and unnatural environments as they only require sensors within a helmet or cap to detect brain activity. These technologies can be portable and offer opportunities for data collection in real-world settings, such as classrooms (see Obersteiner et al., 2010, for an example).

To conclude, each of the abovementioned methodological limitations are not specific to fMRI and apply to some extent to any quantitative research method that is used in educational research. We believe that it is crucial to keep these issues in mind, but this does not mean that we have to throw away the baby out with the bath water.

4. The importance of behavior

It is beyond doubt that the crucial role of behavioral studies should be emphasized in any discussion on cognitive neuroscience and educational research. In this context, we would like to point out that measurements in cognitive neuroscience, signals indicating brain activity or structure, can only be interpreted by linking them to behavior (e.g., Cacioppo, Berntson, & Nusbaum, 2008; Phelps & Thomas, 2003). The collection and analysis of behavioral data represents a necessary step in most fMRI experiments (Huettel, Song, & McCarthy, 2004) and studies in cognitive neuroscience are grounded in hypotheses that are derived from behavioral (cognitive) data. In cognitive neuroscience, behavioral and neuroimaging data are considered on a level playing field with each type of data providing information that constrains the insights gleaned from the other, thereby becoming inextricably linked. In other words, there is no knowledge hierarchy, but an appreciation of multiple sources of data at different levels of description is essential to better understand a phenomenon under investigation.

In this context we should also note that we deliberately restricted our focus to the potential interactions between *cognitive* neuroscience and education, rather than neuroscience more broadly construed. Cognitive neuroscience would be unthinkable without behavioral data and is scaffolded on decades of research in cognitive psychology and cognitive science. In the same way a new science of Mind, Brain and Education or Educational Neuroscience will need to be constructed upon and heavily informed by educational research.

We agree with the author that it is inappropriate to assume that neuroscientific data of a given behavior are more informative than behavioral studies. There may be a belief, in the general public as in science, that is rooted in the assumption that a biological explanation of behavior is more informative or valid than a non-biological explanation (Racine, Bar-Ilan, & Illes, 2005). Here, we think that training, more specifically of future educational researchers and teachers, is important (Ansari & Coch, 2006; Szucs & Goswami, 2007) to wipe out this particular prejudice. This training should also be clear on the scope of a biological explanation: Such explanation does not indicate that a behavior is innate, hardwired or unchangeable. On the contrary, the human brain shows remarkable plasticity and is shaped by experience (Jäncke, 2009). Indeed, brain plasticity forms much of the basis for efforts trying to link educational research and cognitive neuroscience, since the goal of education is – at one level of abstraction - to induce plastic changes in the brain, such as the encoding of new information. Consequently one of the goals of forging connections between cognitive neuroscience and education is to find ways to induce plastic changes that most optimally support processes of learning and knowledge acquisition.

5. The need for realistic expectations of what cognitive neuroscience can contribute

Cognitive neuroscience, compared to educational research, is a very young discipline and it is unreasonable to assume that it quickly will resolve key issues and questions in (mathematics) education, which have been there for quite a long time. Even if progress is being made on the short run, it has to be stressed that neuroscience offers no panacea or quick fix. Just as any scientific approach, it is a gradual process that is marked by conjectures and refutations as well as advances in measurement and analysis.

We contend that cognitive neuroscience offers to social scientists a series of tools, methodologies, and theories that allow them to complement and extend the knowledge that has already been accumulated through decades of behavioral research (Cacioppo et al., 2008; De Smedt & Verschaffel, 2009; Lieberman, Schreiber, & Ochsner, 2003). Even if we do not, at this point in time, exactly know how useful neurocognitive methods and theories will be for educational research in the future, it is still good to broaden out theoretical frameworks and methodological repertoires. In cases where cognitive neuroscience can provide value added, it is in the convergence of using different research methods, i.e. methodological triangulation, that progress is being made (Lieberman et al., 2003). So even if neuroscience data only confirm what we already know from educational research, this is still valuable information because convergent findings from different research methodologies provide a more solid empirical ground for a given hypothesis, model or theory, than findings obtained by only one research method. In our view, cognitive neuroscience is not setting out to change all that has become before it in educational theory or research but merely to complement and extend the available knowledge. Furthermore, the fact that cognitive neuroscience is still a very young and developing field makes it possible for perspectives coming from within educational research to constrain this development and to help in the construction of this relatively new field of inquiry.

It is important to point out that only some types of research questions within education, but surely not all of them, might benefit from the use of cognitive neuroscience tools and theories. These tools and theories should be selected depending on the research question at hand. Stern and Schneider (2010) described this issue by means of the digital roadmap analogy. In a digital roadmap, the appropriate resolution of a map depends on what the map viewer is looking for, alleys vs. highways, and users can zoom in and out between different levels of resolution. According to this analogy, behavioral educational science corresponds to an intermediate resolution of the roadmap, whereas cognitive neuroscience is on a higher zoom level, allowing researchers to investigate specific cognitive processes in a very detailed way, which is a research goal in some but not all fields of educational science.

For example, cognitive neuroscience research might highlight the cognitive constraints for learning in the individual. Lee et al. (2007) compared the symbolic and schematic method for solving algebraic problems and observed that despite equal behavioral performance the symbolic method was associated with greater activation in brain circuits typically associated with attention than the schematic method. This might have implications for teaching as it might not be appropriate to teach these methods at young ages, when functions of cognitive control and working memory are not fully developed yet, or because teaching these solution methods for solving algebraic problems should involve appropriate scaffolds to reduce cognitive load, for example by increasing awareness to appropriate features of the task and by ignoring inappropriate ones. We appreciate that this is a form of reverse inference, which the author rightly questions and which we discuss in more detail below. However, using reverse inference as a tool for hypothesis generation in the way described above can be a useful starting point for interactions between cognitive neuroscience and education.

Having said that, merely unraveling these cognitive constraints does not directly determine how teaching should take place. Therefore, subsequent educational research is necessary, where this information on cognitive characteristics of learners should be reconciled with principles from theories of instructional design, leading to the construction of learning environments, whose effectiveness should be evaluated by educational research. This might again feed into cognitive neuroscience research, in which the effect of such learning environments on brain activity can be investigated, and which might reveal new insights into brain plasticity or into how brain activity changes as a function of schooling. This all creates new opportunities of iterative loops between educational and cognitive neuroscience research and this would be the way in which we envisaged the two-way street. Such iterative research cycles have not been established so far but it is our hope that this will be the crux of the interdisciplinary field of neuroscience and education.

We would also like to stress here that neuroscience can have indirect effects on educational research, for example by drawing our attention to the importance of specific underlying fine-grained representations (e.g., De Smedt et al., 2010a), thereby setting the stage for further educational research. As correctly pointed out by the author, inferences from neuroimaging data should be treated with great caution and the conclusion by which the engagement of a particular mental process is inferred from the activity of a particular brain region – the so-called reverse inference (Poldrack, 2006) – is indeed troublesome. But, such data can be useful for suggesting novel hypotheses that can be tested in subsequent educational and psychological research (as the example of Lee et al., 2007 discussed above illustrates). This might allow connections to be made between fields of theorizing that have traditionally been distinct, as we have tried to exemplify in De Smedt, Taylor, Archibald, and Ansari (2010b). Even if these studies do not collect measures of brain activity or structure, they rely to some extent on insights gleaned from cognitive neuroscience studies. Used in this way, cognitive neuroscience might set the stage for new educational research and it can, albeit indirectly, enhance our understanding of learning.

For example, cognitive neuroscience research on how the brain processes numbers has largely influenced the study of children with dyscalculia - a specific learning disorder in the domain of arithmetic in the presence of otherwise normal cognitive functioning - by pointing to the importance of numerical magnitude representations for successful mathematical development (Price & Ansari, in press). This has fueled behavioral research on numerical magnitude processing in dyscalculia (e.g., Piazza, 2010, for a review). Against this background, cognitive neuroscientists have developed an adaptive computer game "The Number Race" that focuses on numerical magnitude comparison, aiming to improve children's representation of numerical magnitudes (Wilson et al., 2006). Although this computer game had an effect on children's number comparison skills, there was no transfer to other numerical skills, such as counting or arithmetic (Räsänen, Salminen, Wilson, Aunio, & Dehaene, 2009). For the program to work and to induce transfer effects on mathematical learning, it will be crucial for cognitive neuroscientists to collaborate with educational researchers who are more experienced in the design and implementation of such interventions and who typically consider the (math) educational histories of these children as one of the starting points of designing remediation. In other words, the development of effective remediation programs cannot be realized by cognitive neuroscientists alone and will require a synergy of educational researchers' expertise in instructional design and curriculum development and, on the other hand, cognitive neuroscientists' understanding of neurocognitive characteristics of dyscalculia. It takes two to Tango.

6. The role of education

We concur with the author that the two-way street scenario, as we outlined in De Smedt et al. (2010a), is not something that has been achieved so far and that currently, there is an unbalanced exchange rather than a dialogue between cognitive neuroscience and education. There surely is a need for an interested community of educational researchers that critically interrogates cognitive neuroscientists. This is exactly what Turner (2011) did in his reply to De Smedt et al. (2010a) and we appreciate his efforts in doing this. We can only hope that this will be an impetus for educational researchers to challenge cognitive neuroscientists in various forums, including journals and conferences.

We could not agree more with the idea that if the interdisciplinary field of cognitive neuroscience and education wants to move forward, a critical acknowledgement of the strengths and weaknesses of each subfield and mutual respect for both research traditions, which (might) have distinct philosophical backgrounds, is mandatory. This was basically the rationale behind the organization of the EARLI ASC on *Cognitive neuroscience meets mathematics education* in 2009, the founding of the EARLI SIG 22 on Neuroscience and Education and the first SIG 22 meeting in Zürich 2010.

The crucial mechanism, and future challenge, to realize this will be the education of educational researchers and cognitive neuroscientists (Ansari & Coch, 2006; Szucs & Goswami, 2007). We believe that a basic training in cognitive neuroscience for some educational researchers should allow them to critically interrogate cognitive neuroscientists on their work and to evaluate the usefulness of cognitive neuroscience methods and theories for their research questions. Conversely, some cognitive neuroscientists should receive a basic training in educational research on learning and instruction, which should allow them to promote the quality of their research on educational issues (e.g., numerical representations) and to make qualified interpretations and educational implications of their findings (see also Racine et al., 2005).

7. Conclusion

The ultimate aim of the learning sciences is to provide a multilevel analysis to understand how learning takes place and how it can be fostered, with each level of analysis (e.g., behavior, cognition, brain) being compelling in its own right. This calls for researchers who learn to speak each other languages and highlights interdisciplinary training as a crucial mechanism to make headway.

This all should take shape in a climate of interdisciplinary tolerance and respect, since all fields that study learning and instruction will have something to contribute to our understanding of learning and how it can be promoted. Educational research has traditionally incorporated many methodological perspectives and levels of explanation from various other disciplines, such as anthropology, psychology, and neither of these disciplines has taken over or replaced educational research, yet they refined educational theory in some but not all fields of educational research. We believe that the same is true for cognitive neuroscience. It is not as though one field will lead the charge, rather the interaction of fields is poised to generate the most valuable data. We hope that a balanced dialogue will move us into that direction.

The number of research projects, funding calls and master programs at the intersection of neuroscience and education is emerging and there is a new generation of forthcoming researchers who do not belong to either one of these fields but identify themselves as belonging to the interdisciplinary research area of neuroscience and education. This opens new opportunities for broadening our methodological repertoire and for deepening our understanding of learning and instruction.

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