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Co-constructing an understanding of creativity in drama education that draws on neuropsychological concepts

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Background: Neuroscience is unlikely to produce findings for immediate application in the classroom. The educational significance and practical implications of knowledge about mind and brain inevitably require some level of interpretation, yet the multiplying examples of unscientific 'brain-based' educational concepts suggest this process of interpretation is potentially problematic. Research is needed into the most appropriate ways of developing such concepts.
Purpose: This paper reports on an attempt to develop a process of 'co-construction' of pedagogical concepts, enriched by insights about the brain and the mind, with a group of trainee teachers led by a team with both educational and scientific expertise.
Sample, design and methods: A research team consisting of two teacher trainers and a psychologist followed an action research spiral involving 16 trainee teachers who explored their own creativity, and the psychology and cognitive neuroscience of creativity in seminars, discussions and practical workshops, with the pedagogical aim of developing their own reflective capability.
Results: Outcomes illustrated both dangers and opportunities associated with developing concepts bridging neuroscience and education. Trainees' understanding developed in stages that might broadly be described as initial enchantment, mythologising, disenchantment, an increased focus on metacognition and, finally, a demonstrable ability to reflect on their own classroom practice with a heightened sensitivity to issues of underlying cognitive processes.
Conclusions: The type of 'co-construction' process reported here may help reduce some of the more popular and problematic misconceptions that arise when developing pedagogical concepts involving the brain and mind. Further research is needed to assess impact of such concepts upon practice.

Keywords: creativity; drama; cognition; neuroscience

Introduction

An important area of challenge for the new interdisciplinary area of neuroscience and education is the culturing of pedagogical ideas that appropriately combine educational knowledge with concepts about the brain and the mind. History has already demonstrated how this can happen in a variety of unsatisfactory and often unscientific ways (see Geake, in this issue). As well as the practical usefulness of a pedagogic concept, the validity of any purported scientific basis for its validity is also an important issue, not least because many teachers would like to know not just what works, but why and how (Pickering and

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Howard-Jones 2007). This understanding of underlying processes may also contribute to more effective implementation and evaluation. However, the production of credible concepts that span neuroscience and education may rely upon the development of improved communication and language, and the emergence of a two-way dialogue rather than a one-way transfer (Geake 2004). In the project described here, a process of co-construction is pursued by two educators (teacher trainers) and a psychologist with some educational and neuroscientific experience. We report upon efforts to collaborate within one particular context of teacher training, but it is hoped that the insights regarding the process of co-construction may be helpful in developing similar projects in other areas of education.

The chosen context for this study was the fostering of creativity in drama education. The potential complexity and diversity of creative processes made this a somewhat daunting context to work in. However, there is an increasing interest in creativity in the curriculum and a surprising lack of guidance available for trainee teachers in the fostering of creativity, especially in the field of drama education. It was this paucity of current research and understanding that provided the chief motivation for the project reported here which, in pedagogical terms, aimed to develop the reflective capability of trainee drama teachers in regard to the fostering of creativity, through a better awareness of the underlying cognitive and neurocognitive processes involved. Such an aim attends to the calls of those such as Chappell (2007), who has also highlighted the need within teacher training for an increased emphasis upon reflective practice in teaching for creativity. It should be noted, however, that the team did not intend to produce a pedagogical approach based solely upon scientific findings. The inadequacy of neuroscience (including cognitive neuroscience) to provide specific instructions for improving learning has been explored by a number of writers (e.g., Schumacher 2007; Davis 2004) and the team made several excursions during seminars to illustrate the limitations of scientific knowledge within education, when such knowledge is isolated from insights arising from other perspectives. Rather, the approach was to encourage trainees to broaden their reflections upon learning by *including* psycho-biological perspectives, and to provide them with a set of theoretical tools drawing on scientific insights that could be judiciously integrated with their own experience and those educational concepts they had already developed as part of their training.

Questions about the processes by which teachers and trainee teachers might successfully integrate their existing pedagogical knowledge and experience arose during efforts to pursue a wider multi-perspective cycle of research activity involving biological, social and experiential approaches to investigate creativity. This paper focuses only on this issue of developing practical and credible pedagogical concepts, but the wider cycle is reproduced in Figure 1, in order to illustrate the broader research contexts in which the study was undertaken. As part of the wider investigative effort, students attending the same BA course in Drama Education as our present participants had already been involved with a functional magnetic resonance imaging (fMRI) study of a strategy intended to foster creativity (Howard-Jones et al. 2005). (However, none of the trainees participating here had participated themselves in the fMRI study, or received any specialist knowledge of psychology or cognitive neuroscience as part of their undergraduate experience.) This fMRI study had focused upon ‘random strategies’ – i.e., strategies that require the incorporation of items into a creative outcome that are unrelated to each other and/or any context of the brief. As confirmed by the study, such strategies generally improve the perceived creativity of outcomes, but the fMRI results also showed increases in activity associated with creative effort. This supported the notion

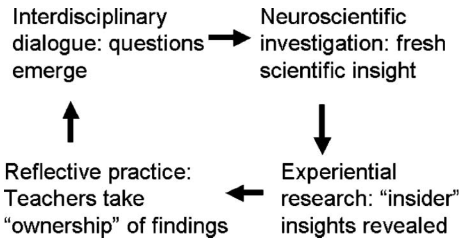

Figure 1. The work reported here is a part of a wider cycle of research activity aimed at increasing understanding about creativity, involving experimentation and more interpretative approaches. The cycle began by consulting with teachers and teacher trainers (top left) to help formulate hypotheses that might be tested using neuroscientific techniques such as functional magnetic resonance imaging (fMRI) (top right). Experiential investigations (bottom right) then examined issues from an 'insider' viewpoint, using theatrical workshops to explore aspects that scientific investigations find typically problematic, such as those associated with free-will and autonomy. Finally (bottom left), the findings from both the 'outsider' scientific studies and the 'insider' experiential investigations were taken forward to the present study, allowing practitioners, with expert support, to take ownership over findings in terms of their educational significance, using these and other findings to co-construct concepts that can support improved reflective practice. Such interdisciplinary dialogue may give rise to further potential research questions.

that the strategies encourage increased processing of a type associated with creative thought, rather than providing an effortless cognitive short-cut to improved ratings. By suggesting they encourage rehearsal of cognitive processes that we might call creative, the results support the likelihood of their being longer-term benefits to the learner. So, this fMRI study produced a finding that might be relevant to practice, but issues quickly arose when we considered how such a finding should be communicated back to educators. First, any individual scientific finding about creativity resides in the context of a larger body of knowledge from psychology and cognitive neuroscience and needs to be understood within that context. For example, without reference to related cognitive models, isolated biological images of blood flow in the brain may be distracting but have little to offer education (Bruer 1997). It was clear that the 'translation' of neuroscientific understanding to the classroom would be fraught with dangers of unscientific interpretation and/or departure from a grounded educational understanding. Building any useful conceptual bridge that spans neuroscience and education would require communication of broader issues and concepts, and co-construction of understanding by those with expertise on both sides. Therefore, in addition to the pedagogical aim identified above, the research aim of the project was to provide an improved understanding of this process of co-construction, since this might be helpful to any future ventures integrating neuroscience and education.

Method

The research team consisted of two teacher trainers and the neuroeducational researcher who directed the original fMRI study. The methods used to communicate concepts and the details of the content covered in sessions was negotiated between members of the research team and informed by the responses of the trainees as the project progressed. In terms of content, note was made of what trainees found useful in terms of understanding their own and their pupils' experiences and learning. In terms of developing communication methods, the research team took particular note of the appropriateness, relevance and validity of the ideas expressed by trainees during sessions.

Sixteen trainee teachers, in the second year of their training, voluntarily took part in what was advertised as a short program of seminars and activity-based workshops exploring concepts about creativity. An action research spiral (Elliot 1991) was followed by the researchers (Figure 2) consisting of an initial meeting of the research team and initial discussion with the trainee teachers, followed by three cycles of research meeting, seminar, workshop and student discussion, ending in a final meeting of the team to reflect upon the project as a whole. Workshops, seminars and trainee discussions were video taped, with informed written permission from the participants. After each of these events, an analysis of the video data was used as a basis for discussions during subsequent research team meetings that deliberated upon progress and revised future plans (see Figure 2). An audio recording was made of these research team meetings and this was transcribed to help track the issues raised and decisions made.

Results and analysis

The processes by which pedagogical concepts were constructed are now reported upon in the chronological order in which they occurred, beginning with data arising from the preliminary discussion with the students, followed by each of the three cycles of activity in turn.

Initial discussion with trainees about how to foster their pupils' creativity

Before introducing any new concepts, we had an initial discussion with the trainees that provided some sense of baseline regarding existing ideas about creativity. As observed by Hayes (2004), although the term 'creativity' is frequently used, its direct definition remains problematic, with recent attempts emphasising the role of factors beyond the level of the individual, and issues of ethics and morality (e.g., Craft 2000, 2006). In the initial discussions, the team drew on a simple definition of creativity as the type of imaginative thinking that produces an outcome possessing some level of originality, as well as some

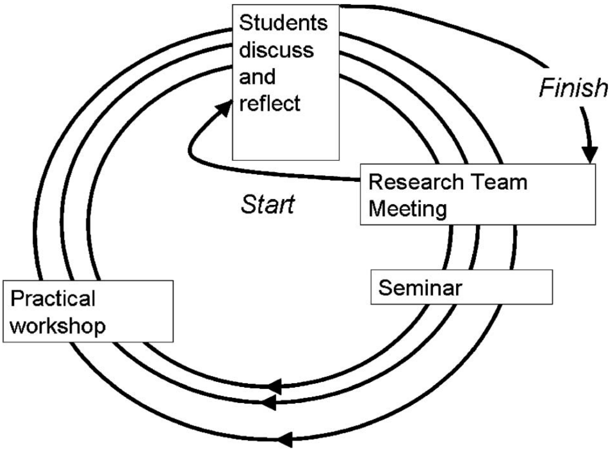

Figure 2. The action research spiral followed by the researchers. After an initial meeting of the research team and discussion with the student participants (trainee teachers), there were three cycles of research meeting, seminar, workshop and discussion with participants, ending with a final meeting of the research team to reflect upon the project as a whole.

sense of value (NACCCE 1999). Trainees felt comfortable with this definition and expressed strong personal convictions about the importance of creativity, a capability that enriched many parts of their lives and was especially appreciated in drama education. Many had chosen to become drama teachers because, as pupils themselves, they had discovered drama was a subject area that embraced creativity. However, creativity was generally seen as a spontaneous process mostly beyond influence and that should simply be allowed to flourish:

> Kids they just – they draw so many things from so many places, and they can bring it all together and they can – and there's your creativity – you can't teach it.

Trainees generally emphasised a 'hands-off' notion of creativity as a type of thinking that appeared in the absence of poor teaching rather than resulting from good teaching. This was evident in the frequent use of phrases such as 'you're allowing them to be creative'.

First cycle

The team agreed that the first priority would be to present a simple cognitive model of creativity. The model used was originally developed to support the teaching of design (Howard-Jones 2002) and describes creative cognition as involving two modes of thinking: generative (G) and analytical (A). The model emphasises the difference between thought processes we use to critically evaluate an outcome and those we use to generate it in the first place, the latter requiring access to concepts that are more remotely associated with the matter at hand. When engaged in analytical thinking, an individual is expected to be focused and to constrain their attention upon the analysis. However, when accessing remote associates, there is benefit from being less focused and allowing attention to drift towards concepts that have not previously been directly associated with the problem. Analytical thinking can also be useful elsewhere in the creative process, such as when researching a topic or context before generating any ideas. Creativity, then, may be characterised by an ability to move from one mode of thought to the other without difficulty. The existence of two distinct modes of thinking is not a new one, but builds on the ideas of Ernst Kris (1952), Wundt (1896) and Werner (1948).

After being introduced to this model of creative cognition, trainees were presented with research illustrating how the conditions for supporting analytical and generative thinking can be quite different. They were reminded how our analytic abilities can often be supported by being encouraged to remain focused, being offered some monetary reward for our performance or by the mild stress of knowing we may be evaluated and assessed. Generative ability, on the other hand, can benefit from changes in context (Howard-Jones and Murray 2003), tasks that require divergent semantic association (Howard-Jones et al. 2005), intrinsic motivations such as fascination and curiosity (Cooper and Jayatilaka 2006) and relaxation (Forgays and Forgays 1992). Production of a single creative idea can require alternation between a focused analytical state when exploring what is known about an issue, a generative state when finding associations beyond the context of the issue itself and a return to the analytical state to assess the value of what has been generated. However, even in the production of a very short story, more complex trajectories between these two modes of thinking can be assumed.

To understand how the creativity of pupils can be directly influenced by a teacher, trainees were introduced to 'random strategies' that require the making of links between elements chosen with some degree of randomness. In the fMRI study discussed in the Introduction to this paper, the neural correlates of creativity in a storytelling task were identified by comparing brain activity when trainees were trying to be creative and to be uncreative as they produced their story (Howard-Jones et al. 2005). Participants had to include a different set of three words for each story. The activity in some areas associated with this creative effort increased further when the words were chosen with some degree of randomness and thus were unrelated to one another. (The creativity of such stories, as assessed by an independent panel of judges, also increased as expected.) The chief area in which correlates of creative effort increased when using this strategy was the right medial gyrus – an area associated with higher-level conscious control, presumably due to increased amounts of filtering out of inappropriate combinations of ideas. So, although the strategy encouraged greater generation of ideas, it may also have required increased amounts of conscious analysis and effort.

In the discussion that followed the seminar, considerable enthusiasm was expressed for using what we know about the brain and mind to enrich pedagogy. Much of the dialogue focused on the fMRI study. The power of brain-imaging to engage interest is well known and research has shown that it stimulates a sense of objective evidence and a 'physicalisation' of concepts of the mind (Cohn 2004). There are attendant dangers in this interest, such as it encouraging notions of static brain states characterised by activity that is restricted to a few limited areas. However, as observed here, it can help 'concretise' psychological concepts that might otherwise remain too abstract to be taken up by non-specialists. Trainees were keen to find real-world analogies with the fMRI experimental task and resonances with their own experience. A trainee reported how she had recently asked every pupil in her class to construct a story around any two of four items: a map, a set of car keys, a ballet shoe and a bottle. Two of these items – i.e., the map and car keys – seemed more obviously related and she noticed the effect on the pupils' creativity:

> the majority of people in the class chose the map and the keys and there were just different variations of car crashes and that was pretty much all they came up with, and the bottle and the ballet shoe – that really worked a lot more creatively.

These observations were, at first, simple behavioural cause–effect links, without any great reference to underlying cognitive processes, and echoing some of the ideas raised in the initial discussion. For example, the trainees, again, seemed to refer to creativity as a spontaneous process, but now as one which required the right level of constraint – not so constrained that it cannot flourish, but requiring enough guidance to provide reassurance. Such ideas have been expressed in studies of creativity in dance education, as a balance between control and freedom (Chappell 2007). It appeared that the trainees' ideas about creativity were becoming more sophisticated, as they suggested that their own creativity sometimes depended on the right level of constraint being provided by their tutor. One trainee reflected upon how she would have felt when performing a particular exercise with such guidance:

> I would have found it quite overwhelming, and I think I would have felt the need to impose guidelines upon myself, but if it's too constrained, then it stifles the creativity and you just don't have the kind of scope required for the kind of work and outcome you want to have.

The idea arose that individual differences existed among learners as to the level of constraint they needed, and this was not necessarily related to academic ability:

> We had a group of super-intelligent girls who sat there for 40 minutes really mulling it over and one of the boys just said to them, 'er ... why don't you do the title "the day I went mad with a spade"?', and they said '*that's it!*' and started writing.

The team suggested that perhaps these girls had been too analytical in their approach and become fixated. Fixation, when one idea or set of ideas becomes overly dominant, had been discussed in the seminar. This prompted the trainees to consider how thinking about creativity in cognitive terms might call into question some aspects of accepted practice, such as target setting and indicating learning outcomes at the beginning of a lesson:

> if you're telling them that at the end of the lesson they're going to be doing a performance, then straight away they're not in generative mode anymore.

As the trainees began to focus more upon underlying cognition, one voiced a realisation that such reflection could radically change their perceptions and their strategy:

> as soon as you build an understanding of how people work, and why they work like that, then you don't necessarily see someone's behaviour in the same way.

A practical workshop followed these discussions. This was aimed at providing trainees with experiences that could later, with support, be linked to some of the scientific concepts of mind and brain they had been introduced to. The workshop included an attempt at identifying what is creative by considering what is perceived as uncreative. Repetition, lack of originality and a tendency towards 'what is obvious' were characteristics that were deemed uncreative. Trainees engaged very actively in this discussion, in contrast to their participation in the next activity, 'Babble', which was a verbal improvisation exercise invented by the team. In 'Babble', students were invited to improvise dialogue by building incrementally from speech-like sounds, through unrelated words to snippets of sentences until they developed a conversation. The team had intended the trainees to engage with the exercise as a form of purposeful play, but the students took up suggestive cues and avoided deviating from them, apparently feeling more comfortable with the type of 'tight apprenticeship' model of learning described by Chappell (2006). However, the team's lack of success in engaging them with this exercise also provided a useful topic for later discussion. It was introduced with few 'rules' and without any physical or imaginative warm-up activity. The subsequent parts of the workshop were more successful. 'Ever-evolving statue' was a familiar physical improvisation exercise in which trainees were required to create physical postures in relation to one another's body positions and shapes. This built from working in pairs to fours to groups of eight. Postures relating to character or narrative development were discouraged in favour of kinaesthetically imaginative interaction. This exercise encouraged trainees to make links echoing the fMRI study, essentially making connections between disparate elements. A 'group morphing' activity provided a movement equivalent of this exercise, and an object improvisation exercise provided another such potential cross-reference between science and experience.

This workshop provided common foci for first reflections upon how ideas emerge. The research team noted the likely importance in developing the trainees' understanding of being able to identify transitions between G and A modes of thinking. So, after the workshop, trainees were asked to produce a line graph indicating where they had been along the G/A continuum at various points in the workshop. Outcomes were very varied but the process prompted trainees to begin reflecting upon their own creative cognitive processes:

> in the last task, you were able to be very, like ... um, generative in the process of creating. And then ... because we were in a group and we knew we had to perform ... we had to bring it back and be, like, analytical ... so my last line is going up and down. We did go back and look at what we were doing ... [laughter], but obviously not enough!

Trainees discussed the ease with which thinking can tend to the obvious, and how it feels when the obvious option is made less available. For example, trainees commented that the items they had selected themselves appeared to them already connected, and they had often begun making a story with them at once. When trainees were required to improvise by linking together unrelated objects selected by the research team, the task became more challenging and difficult, possibly reflecting the additional frontal medial activity observed in the fMRI study of semantic divergence:

> I felt really limited by the fact that you'd given us objects and the fact that we couldn't choose our own ... I felt really like I'd hit a wall and was going to have to really think about how I was going to move on.

The trainees identified that a lack of warm-up had contributed to the first ('Babble') exercise going astray, suggesting they needed a way of clearing away some of the unwanted foci of the day to make space for new ideas. There was a sense that everyone had been too willing to focus on the smallest suggestion of a context – a party – and become fixated on it. The trainees then became excited by the importance of relaxation and the generative state, and also discussed how planning one's actions can sometimes diminish generation of ideas. This gave rise to the idea that planning, in which one sets out the stages by which one will achieve a goal, can encourage a particular mind set that discourages generation of new directions and ideas. The trainees appeared comfortable classifying *tasks* as being creative or uncreative and seemed to avoid considering whether they supported the type of thinking required in a particular context. For example, one trainee had begun believing that planning always diminished creativity and the inclusion of randomness always increased it:

> I've got it into my head now that to be uncreative you plan and stuff – so now I think that the last improvisation we did was completely uncreative because I planned it! Because we discussed it as a group and I don't know, now, I'm all confused ... I think that the last task was more random ... you gave us lots of randomness.

The team gave examples of how different levels of planning can be good or bad for creativity depending on aspects of the situation such as the individuals involved and the types of cognition one might wish to encourage at a particular stage in a creative process. The generative part of creativity had been the main focus of discussion but the team felt it was important to remind them that analysis was also needed. The creative process, as described by Wallas (1926), was presented as a shift from analytical to generative and back to analytical.

Second cycle

There was a clear tendency emerging for trainees to make short cuts from strategies to outcomes without consideration of underlying cognitive processes and context. We needed to diminish the temptation to classify strategies as creative or uncreative, and to encourage the trainees to think more about the appropriateness of strategies in terms of the cognitive processes and whether, in terms of the context, these might be helpful in progress towards creative targets. It was clear that some of the students felt daunted by this task. The team identified the abstract nature of the cognitive concepts involved as a potential challenge for some. We wanted to make the cognitive model of creativity we had been referring to more concrete for the trainees. The trainees had been notably fascinated by a neuroscientific case study mentioned previously by the team, so it was decided to detail two such studies in the next seminar to illustrate extreme examples of the two modes of thinking. This was felt appropriate in the context of training teachers, but the use of such case studies with children would clearly raise some ethical issues. The team felt that classroom discussions about disorders of the mind might easily lead to misconceptions that could distress/confuse some pupils, if teachers leading the discussions were not versed in the necessary expertise.

In the next seminar, the trainees were introduced to a part of the brain called the cingulate cortex – an island of the cortex below the external surface of the brain. The front (anterior) part of this region shares a controlling function with the frontal lobes and is associated with executive attention – the cognitive mechanism by which we control the focus of our attention (Gehring and Knight 2000). Hyperactivity in this area has been associated with Obsessive Compulsive Disorder (OCD) and the associated preoccupation of sufferers with correcting perceived mistakes (Fitzgerald et al. 2005). The trainees were played an interview with a sufferer of OCD, who described her ritualistic repetitive routines. It was discussed how this type of rehearsal resembled the analytical and evaluative rehearsal processes used to hone a piece of creative work, but taken to an obsessive and very uncreative extreme. It was as if sufferers of OCD are caught in an analytical mode of thinking. In contrast, the team then presented a case of compulsive creativity (Lythgoe et al. 2005). The trainees were told that Tommy was a 51-year-old builder with no previous interest in the arts, who suffered a subarachnoid haemorrhage – a bleeding in the space around the front of the brain – resulting in frontal dysfunction. In the weeks following his injury, Tommy became a prolific artist. He first began filling notebooks with poetry, then began sketching and in the following months produced large-scale drawings on the walls of his house, sometimes filling whole rooms. His artistry continues to this day and has become more developed. Tommy cannot stop generating material, often only sleeping 2–3 hours a night between days filled with sculpting and painting. He shows verbal disinhibition, albeit creatively, by constantly talking in rhyming couplets and there are some signs of impaired executive function. Trainees discussed how Tommy appeared to be caught in a generative mode of thinking. Trainees listened to an interview with Tommy who explained what his world was like and they read a poem, 'Brain explorer – it's for you', that he had written for the author of his case study. The team hoped that listening to the voices of those suffering from very generative or analytical mental states would help characterise these modes of thinking more clearly for the trainees and support them in monitoring their own modes of thinking.

In the improvisational exercises that followed, trainees were occasionally interrupted and asked to hold up G or A cards to indicate their current mode of thinking. The first two exercise was 'talk for a minute', in which they had to speak without pause or hesitation on a topic chosen for them. That was followed by a 'delayed copying' exercise in which students had to continuously reproduce not the movement just made by the leader, but the movement previous to it. Trainees almost always held up the generative card when interrupted during the first exercise and the analytical card during the second. When talking-for-a-minute, trainees generated ideas with little time to reflect and reject unsatisfactory elements. When copying movements, trainees focused on a very specific routine, analysed what they saw and rehearsed this mentally before reproducing it. A more complex task followed called 'story in the round', in which trainees sat in a circle and, when asked, had to continue the story their neighbour had been telling. This produced a spread of A's and G's, which trainees explained in terms of individual differences in approach, but also according to where in their own creative process they were when asked to report. Trainees often held up a 'G' when generating links between their ideas and the story their neighbour was telling, or produced an 'A' when evaluating possible stories or those they were hearing. 'Tag improvisation', in which trainees had to step into an improvisation and take over from another performer, also provided an example of this complexity.

Trainees were then asked to produce a piece of movement using the textures and sounds they had encountered during an imaginary journey into a magic wardrobe. Researchers observed and interrupted when they identified points of transition, asking whether trainees were aware that a transition had occurred and whether they could explain why it had happened. Although some trainees had been initially unaware that transitions were even occurring, they quickly began recognising them. They often chose to explain them in terms of a need to move from one mode of thinking to the other. Transitions to rehearsal were often justified in terms of a need to evaluate and hone what had been generated, and thus any attempt to run through the work in progress was usually seen as a return to a more analytical thinking mode. This was something of a turning-point in the project, and the subsequent discussion developed a new richness and depth in terms of the trainees thinking about their experiences in the workshop itself and also their teaching.

Trainees began talking in reflective and often emotional terms about generating and analysing material. Generative processes were described in both positive and negative terms, as highly pleasurable but also slightly frightening. One trainee also described how analytical rehearsal, as in OCD, can become an unhelpful response to anxiety – i.e., the apprehension of having to generate ideas:

> when I'm creating work I feel like I have to keep going back, and like you said: 'what would happen if I didn't go back?' I don't know, but that's what I'm too afraid to find out, I couldn't just keep on creating.

The generative process was described as 'scary', 'like a void' but also as a 'delight', with the workshop reminding trainees how much they enjoyed being generative. Again, the spontaneous nature of creativity that had been mentioned in the earliest session arose, but this time spontaneity was assigned to a particular part of creativity: the ability to generate. The trainees had observed how young children can be highly generative in their thinking, although often less developed in their ability to critically rehearse their ideas. Adults, on the other hand, often find it difficult to maintain such effortless generation of ideas, needing instead to pause, analyse and refine meaning:

> when you told us to talk for a minute, I think the poem [by Tommy] is what we find so hard to do. Like in the poem where there's no links, you said to us don't worry about the links, but automatically everybody tried to make a story even when you'd told us that we didn't need to.

Metacognitive awareness, to the extent of regulating as well as monitoring cognitive processes, became evident:

> I started off by being analytical, thinking: 'What am I expected to get out of it? What am I supposed to be doing with this visualisation?' And then I just thought, 'No, right, cut that off, just leave it, let it go, and just made myself switch off that'.

Interjection by the research team during salient moments of transition not only raised awareness of cognition, but also appeared to encourage self-regulation:

> I knew I was trying to change it, and I knew you'd go, 'Why?'... but then I'd go, 'Oh, I'm being too analytical, let's just change it, let's just go with something different and not keep knocking our head against this brick wall'.

Third cycle

At the next research meeting, the team selected two pieces of footage from previous workshops that would be suitable for analysis with the trainees at the next seminar. At this final seminar, the team first showed footage of the failed ‘Babble’ exercise from the first workshop, and some excerpts from the discussion with trainees that had followed it. In reflecting upon the outcomes of the exercise, trainees watched themselves improvising on film and afterwards discussed the considerable repetition within and between individuals, the regular occurrences of blocking during the improvised dialogue and a tendency towards fixating upon cues from the team, and noted the feelings of discomfort and obligation that had been discussed afterwards. In understanding why the exercise had not succeeded in generating ideas, discussion centred on feelings of anxiety about not knowing what was required and the lack of a relaxation exercises. Additionally, the preceding tasks had been very analytical in their goal, including analysis of the term ‘uncreative’ and writing an ‘uncreative’ story which most students achieved by the self-imposition of constrained boundaries and use of frequent repetition. This may have impacted on generative tendencies in the subsequent exercise, a type of transfer that has been observed elsewhere (e.g., Howard-Jones, Taylor, and Sutton 2002). It was discussed whether seeing a member of the team carry out the task first would have helped. This gave rise to a discussion about mirror neurons which, it has been speculated, may provide a basis for the embodiment of cognition and even the unconscious communication of mental states (Rizzolatti et al. 2002).

Options were considered regarding what might have been done after the failure of this exercise. The trainees were asked: ‘Should we have stopped and evaluated what had gone wrong?’ ‘Should we have gone into some relaxation exercises?’ ‘Should we have just ploughed on to the next exercise?’ It was agreed that an evaluative exercise would probably have further entrenched everyone in an analytical mode of thinking. Recalling the effects of relaxation on free association (Forgays and Forgays 1992), there appeared a clear case for relaxation exercises. Continuing directly on to the next exercise (which is what actually happened) was the more uncertain course which, as it turned out, worked well. The trainees were then asked to consider why it might be that this subsequent exercise (object improvisation) did work better. Three issues emerged from the discussion. First, it was a familiar exercise and the trainees immediately felt more relaxed. Second, the task required links to be made between objects that the trainees had not selected themselves. Third, the trainees felt they had time within the exercise to produce ideas which, as discussed above, may be needed in order to select appropriate links between elements that are disparate. So, the trainees were asked: ‘If this was your class and you found one group was staying focused on the brief, asking a lot of questions about boundaries and unable to generate ideas beyond the obvious, what would you do?’ Alternatively: ‘If another group rushed straight into the improvisation and were generating a lot of incoherent ideas that were not being developed appropriately, what would you do?’ In this way, the trainees were encouraged to start thinking about their effect, as teachers, on the creative cognitive processes of their pupils.

After this session on analysis, the trainees were ‘hot-seated’ about reflections on their own practice. Volunteers took turns to sit in front of the group and recall specific instances in their own practice for discussion and analysis by the group, which now often included reference to their pupils’ modes of thinking. For example, it was discussed how questions about procedure and process often reflected an insecure adherence to analytical processes, and how the confidence to create was often accompanied by a diminishment in questioning the teacher. Lower-ability groups often suffer from this lack of confidence, and another trainee drew attention to how a teacher's response to questioning can also be used to orientate pupils' modes of thinking. This trainee described how she used 'teacher-in-role' and then prompted pupils' interpretations. Questions from the class about whether their idea was correct were deflected by the response 'it's whatever you think it is', leaving the arena open for other pupils while legitimising all suggestions as valid self-generated ideas. At first it was the louder children who were questioning her for the right answer, but then, when it was clear that none existed, the quieter children came forward with their ideas. The use of 'teacher-in-role' prompted many other accounts of how pupils can be directed towards a particular mind state through imitation, again producing references to the concept of mirror neurons. For example:

> they'd got to the point where, you know, they hadn't got much and what they had got was very limited and it was very clichéd ... they couldn't seem to generate ideas ... [but] they worked so much better when we showed that we were willing to generate ideas too.

There was a sense in which acting and generating in front of the children communicated both the types of mental processes required and their legitimacy:

> I can't do it wrong if I do what she's done ... so it's OK, I can take part in this now ... I can allow myself to be generative, even though people have told me I'm wrong before, this can't be wrong now.

Trainees spoke of there being transitions within a lesson, describing some lessons as 'like a sandwich' of thinking modes. They also discussed how transitions between dominant modes of thinking could sometimes be helpfully positioned at the boundary between lessons. Trainees also referred to instances when changing context and suspending evaluation had succeeded in dissipating fixated mind sets. Working with others was also seen as a valuable way of encouraging children to make links, including those links between interpretations of their own and others' ideas:

> but also working with other people and seeing what they do and taking your own interpretation of what they do – because they don't explain what they're doing and what they're saying – that, in turn, helps you generate ideas ... like with the Rorschach tests with the ink splots – what do you think you see? – you take your own interpretation and that helps you create your own mental links which puts you on further in the generative process.

Perhaps unsurprisingly, although the team had been at pains to point out that this was not the case, there remained a natural tendency for some trainees to assume a simple functional-anatomical mapping of cognitive processes, including those associated with generative and analytical modes of thinking:

> You're using almost two different parts of the brain there to do it, so like separating them into generative now and analytical at a different time ... so trying to switch.

Finally, the teacher trainees and their trainers were asked what they had got out of this experience of reflecting upon their practice in terms of psychological and neuropsychological concepts. First, there was a sense of having an improved theoretical understanding that supported existing practice, especially in terms of the role of 'warm ups'. Secondly, the trainees expressed a sense of being more empowered to intervene and support children's creative cognitive processes:

> so that when you go into the classroom, you can identify the different states, you know, that you can then manipulate or change it, and what's the point of that change. You as a teacher

> can then change their way of thinking and make a more productive learning environment for your pupils.

Trainees referred to a number of issues influencing creativity that they felt provided insights into their own practice, and overall there appeared a new sense of responsibility for fostering abilities they had initially considered as entirely spontaneous and not amenable to teacher intervention:

> not all children/pupils/adults find it that easy to be creative, then when we go into schools, you can't just expect them to just improvise, just 'cos we can do it. It's up to us as teachers, then, to differentiate.

Issues regarding the difficulty in combining the language and perspective of natural science with educational thinking remained salient even in this final discussion, as some trainees struggled to find the appropriate terms by which to express their thoughts:

> Trainee: I think its reawakened (1) my curiosity, and (2) some previous revelations about environment and the effects that it has on people, and what they're capable of doing and how – and this is the only way I can think of saying it, how you can psychologically manipulate [laughter] – there's probably a better way to say it!
> Other [suggesting]: '. . . effect change?'
> Trainee: That's the one . . . [laughter], but you can look at and influence the environment and [thereby] people's way of thinking, and how to change that, and get the best out of people by doing that.

Conclusion

Overall, during this short intervention, the trainee teachers showed progression in their attention to, and understanding of, creative cognition in the classroom. This progression passed through stages that included:

(1) an initial high degree of enthusiasm.
(2) a flourishing of initial behavioural and conveniently prescriptive neuromyths.
(3) a daunting realisation that things were more complex and required attention to cognition.
(4) increase in meta-cognition, with neuroscience helping to 'biologise', 'concretise' and deepen concepts.
(5) emergence of concepts, language and reflective capability that allows deeper reflection, sensitivity and insights around personal practice in specific contexts, in terms of mind and brain.

Trainees' efforts to understand their own personal experiences of learning/creativity in terms of underlying cognitive processes appeared an important step in developing related insights into their teaching practice. Trainees sought to apply their new understanding in a variety of areas, including environmental effects and issues around the planning of activities such as the sequence of events and providing for individual differences. fMRI and other research involving imaging can be very effective in engaging non-specialists with thinking about the mind and the brain although, with this power to engage, also arise attendant dangers of encouraging myths such as simplistic phrenology. It was also found that neuroscientific case studies had a role in helping trainee teachers understand the mind and the brain, although their appropriateness as a more general teaching tool in the area of education may need further ethical consideration.

Here we have reported on an exploratory study that focused on the process by which pedagogical concepts can be co-constructed across neuroscience and education. We have not reported in any detail on the concepts developed (see Howard-Jones 2008) and these have not been formally evaluated. If such ideas are, as we hope, an improvement on the many 'brain-based' learning ideas presently being marketed, several issues will still need to be considered in determining their value, two of which deserve mentioning here. First, scientific knowledge of the mind and brain will always be partial and pedagogical ideas that draw on such knowledge will always require continuous updating and improvement. For example, the trainees were encouraged to use research findings to gain reflective insight into the creative behaviour of their pupils. However, the fMRI studies of 'normal' cognitive function presented to the trainees had been carried out with adults, whereas children's cognitive and neural processes may differ significantly from those of adults. As research on mind and brain progresses, these differences will inevitably need to be considered in terms of their pedagogical implications. Related to such considerations, trainees judged the understanding they had gained to be useful and it appeared to improve their ability to reflect on their practice, but its value in terms of improving practice still requires further investigation. We tentatively suggest that the concepts developed from a project such as ours could provide a helpful and stimulating contribution to teachers' systematic enquiries into their own practice. Such enquiries, which help develop teachers as reflective learners, are considered in themselves to be an important ingredient of effective teaching and learning (Hofkins 2007).

In our project, insights about mind and brain successfully highlighted a general message about how creativity involves a generative mode of thinking that is essentially different to the analytical mode predominant in school education. On the other hand, as was emphasised to the trainees, it is clear that individual creativity will always be a journey whose destination is unknown. Every creative journey is a unique experience, just as every brain is unique in terms of both its structure and functioning. For these reasons alone, neuroscience cannot entirely explain or demystify creative cognition and experience. However, using a process of co-construction that attends to both educational and scientific perspectives may produce new ways to think and talk about creativity and, in this way, help us to reflect upon the daily decisions we make as educators when fostering creativity in our students.

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First insights on "neuropedagogy of reasoning"

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As stated by Jean-Pierre Changeux (2004) in his last book, *The Physiology of Truth*, objective knowledge does exist, and our brains are naturally equipped to recognise it. The results presented here provide the first insights on (1) the cerebral basis of reasoning errors, and (2) the neurocognitive dynamics that lead the human brain towards logical truth. We propose to call this new approach "neuropedagogy of reasoning".

> Our method correctly explains how we do not fall into error and how deductions are to be discovered so that we reach the knowledge of everything.
>
> René Descartes (1628)

Ever since Aristotle, it has been known that the essence of the human mind is the "logos". It encompasses both reason (i.e., logic) and language. However, as the seventeenth-century French philosopher René Descartes demonstrated, an important challenge for humans is the implementation of deductive rules for redirecting the mind from reasoning errors to logical thinking, which Descartes called the "Method".

Current research on the cognitive psychology of deduction has confirmed that most individuals do not spontaneously apply the principles of logic in problem solving; their reasoning is often biased by misleading strategies (Evans, 1989, 1998, 2003). It is also known that research on judgement and decision making that was initially presented in a series of fundamental works by Amos Tversky and Daniel Kahneman, the 2002 Nobel Prize Laureate in Economics, emphasises the role of short-cut heuristics in probability judgement and the cognitive biases that resulted from them (Kahneman, Slovic, & Tversky, 1982; Kahneman & Tversky, 2000). However, as stated by Jean-Pierre Changeux in his last book *The Physiology of Truth*, objective

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knowledge does exist, and our brains are naturally equipped to recognise it (Changeux, 2004). Thus, one of the crucial challenges for the cognitive and educational neuroscience of today is to discover the brain mechanisms that enable shifting from reasoning errors to logical thinking.

Neuroimaging data on this topic are scarce. In our research, conducted with the collaboration of Bernard and Nathalie Mazoyer at the brain-imaging centre, Cyceron, in Caen, France, we investigated three questions: (1) Do we reason with logic? (2) Why do we make reasoning errors (rather than reasoning according to the logical truth table)? (3) Can emotions help us reason? (Houdé & Tzourio-Mazoyer, 2003). This last question is in line with Antonio and Hanna Damasio's work on emotion and reasoning (Damasio, 1994, 1999, 2003).

DO WE REASON WITH LOGIC?

Contrary to Jean Piaget's theory (Inhelder & Piaget, 1964; Piaget, 1984), which described a logical stage of thinking as of the age of 14 or 15, new studies on cognitive psychology of reasoning have shown that adolescents and adults consistently make deduction errors in certain tasks, due to what are called "reasoning biases" (Evans, 1989, 1998, 2003; Houdé, 2000; Houdé & Moutier, 2004). For example, when the given task was to first read a rule such as "*if there is not a red square on the left, then there is a yellow circle on the right*", and then to select two geometrical shapes that would make the rule *false*, most subjects spontaneously placed a red square on the left of a yellow circle, believing they were completing the task correctly. This logic error is caused by what Jonathan Evans has called the "matching bias" (Evans, 1998). Subjects usually respond by using the shapes that are mentioned in the rule rather than reasoning according to the logical truth table, which, if used, would lead them to choose a case where the antecedent of the rule is true (i.e., not a red square) and the consequent is false (i.e., not a yellow circle) such as a blue square to the left of a green diamond. The logical response, therefore, requires the subjects to resist the elements perceived in the rule; that is, to inhibit the matching bias (Houdé, 2000). This is a good example of high-order abstraction, where logic needs to resist perception (even if Evans has referred to matching bias as "pragmatic" and not as "perceptual"; this is our own interpretation).

WHY DO WE MAKE REASONING ERRORS?

In an attempt to understand the type of error shown in the above example, we hypothesised that adolescents and adults have two competing reasoning strategies in their "neural/mental work space" (Changeux, 2004; Dehaene, Kerszberg, & Changeux, 1998), one logical, the other perceptual, and that they have trouble inhibiting the perceptual one. (Note that in other reasoning tasks, the biases to inhibit are semantic-based responses rather than perceptual.) Following this analysis, the difficulty lies not in mental logic per se, but in executive function, in this case, inhibition. This has also been shown in infants and children for elementary cognitive acquisitions (Diamond, 1991; Houdé, 2000).

To demonstrate this analysis, we conducted experimental psychology studies that tested the effectiveness of a "de-biasing (or error-correction) paradigm".[1] These studies were based on two experimental training conditions using the same type of deductive logic task but with different materials: (1) training in inhibition of the matching bias; (2) training in logic only. These were compared to a control condition of simple task repetition using the same design without training. We found that only inhibition training proved effective in reducing errors. We interpreted this to mean that an executive blocking mechanism was indeed what these adolescents and adults were lacking, not logic or practice (Houdé, 2000; Moutier, Angeard & Houdé, 2002; Moutier & Houdé, 2003) even though in some cases logical training is useful.[2]

Following this initial testing, we carried out a brain-imaging study to observe the cerebral changes that occurred before and after training under the matching bias inhibition condition (Houdé et al., 2000). We found a clear shift in cerebral activity from the posterior part of the brain (or the "perceptual brain") before training to the prefrontal part after training; that is, at the moment when the error-to-logic shift occurred (see Figure 1a and b). According to Joaquin Fuster's interpretation of our results in his last book *Cortex and Mind* (2003), "the exercise of logical reasoning seems to overcome [or to inhibit] the biasing influences from posterior cortex and to lend to prefrontal cortex the effective control of the reasoning task" (p. 231). This error-to-logic shift resulted namely in an enhanced activity in the left inferior frontal gyrus (IFG) or Broca's area (within the lateral part of the prefrontal cortex). Other authors have showed that this region is recruited by cognitive set shifting on the Wisconsin Card Sorting Test (Konishi et al., 1998), where subjects have to inhibit a previously active sort criterion. In our study, it is most likely reflects cognitive inhibition of the erroneous reasoning strategy used

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[1] Evans (1989, p. 113) used the term "debiasing" to refer to the problem of how to reduce or eliminate the impact of biases in reasoning, decision making, and problem solving.

[2] As stated by Evans (1989), "On the whole, there is very little evidence that deductive reasoning biases can be removed by verbal instruction relating to the underlying logical principles" (pp. 116–117).

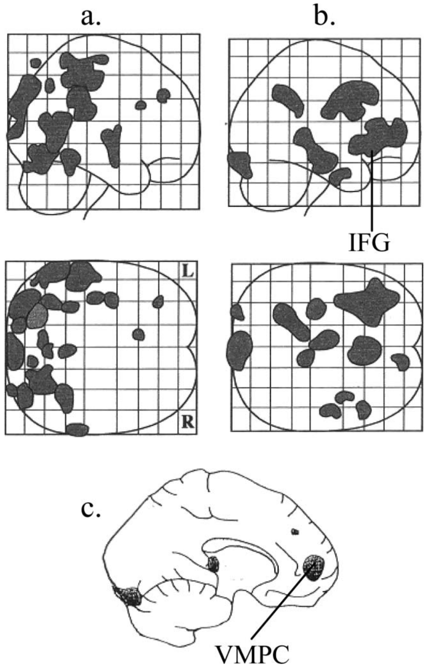

Figure 1. Neuropedagogy of reasoning: the case of error-inhibition training in a deductive logic task. The results from brain imaging show a clear reconfiguration of the neural activity, which shifted from (a) the posterior part of the brain (or the "perceptual brain") when subjects relied on matching bias to (b) the prefrontal part when, after error-inhibition training, they accessed deductive logic. (Top: lateral projections; bottom: superior projections; L = Left hemisphere; R = Right hemisphere; IFG = Inferior Frontal Gyrus). IFG sustains the inhibitory component of the brain's error-correction device. (c) Lateral projection showing that greater neural activity was observed in the right ventromedial prefrontal cortex (VMPC) at the moment when the error-to-logic shift occurred. VMPC sustains the emotional component of the brain's error-correction device (i.e., the emotional evaluation of error risks).

before training. Computational modelling investigations should be useful to better understand the brain processing components involved in this kind of error-to-logic shift. The related posterior-to-anterior shift is likely to reflect a top-down inhibitory control.

So it is now possible, thanks to neuroimaging, to know what happens in the human brain when a logic error is made (Figure 1a). We can thus assert that there is indeed a biological reality behind irrationality, as the philosopher Stephen Stich hypothesised in his book *The Fragmentation of Reason* (1990), or if we wish to avoid speaking of irrationality we can say, as Evans (2003) stated, that there are "two minds [or two rationalities] in one brain" (p. 458).

In the same vein, Goel and Dolan (2003a) conducted a brain-imaging study on bias inhibition and semantic beliefs. Although deductive reasoning is a closed system, our beliefs about the world can influence validity judgements in syllogistic tasks (Evans, 1989); for example, the invalid but believable conclusion "Some machines are not computers" follows from the premises "All calculators are machines" and "All computers are calculators". In this study, Goel and Dolan showed that the right lateral prefrontal cortex was specifically recruited in the condition where people had to inhibit belief-based responses, in contrast to neutral or facilitatory conditions.

Note that short-cut heuristics and the cognitive biases resulting from them (matching bias, belief bias, and so on) can often be adaptive in realistic constraint-based decision or judgement conditions. Inhibition and error correction are not required in such situations.

CAN EMOTIONS HELP US REASON?

Contrary to Descartes' well-known dichotomy between reason and emotion, Damasio offers eloquent support for the view that "the good use of reason" depends on emotion (Bechara, Damasio, Tranel, & Damasio, 1997; Damasio, 1994, 1999, 2003). In studying Phineas Gage's lesion (Damasio, Grabowski, Frank, Galaburda, & Damasio, 1994; Harlow, 1848) and other more recent cases, Hanna and Antonio Damasio have shown that ventromedial prefrontal damage causes defects in reasoning/decision making, emotion, and self-feeling. In line with their contributions, we hypothesised that there may be a close tie between emotion, self-feeling, and reasoning error inhibition in the human brain (Houdé et al., 2001, 2003; Houdé & Tzourio-Mazoyer, 2003).

Note that in our previous study (Houdé et al., 2000), training under the matching bias inhibition condition incorporated emotional warnings of the error risk (i.e., a "hot" kind of training), which were not present under the logic-only training condition (i.e., a "cold" kind of training). We then compared the impact of these two training conditions and found that under the matching bias inhibition condition (at the moment when the error-to-logic shift occurred), greater cerebral activity was observed in the right ventromedial prefrontal cortex (VMPC) (Houdé et al., 2001, 2003); that is, neural activity was present in the location of the lesion in Gage and in Damasio's patients (see Figure 1c). These data suggest that in healthy subjects this paralimbic area (Mesulam, 2000) participates in getting the mind intuitively on the "logical track".

The right ventromedial prefrontal cortex could therefore be the emotional component (internal warning/self-feeling) of the brain's error-correction device. More precisely, it could correspond, together with the anterior cingulated cortex, to the brain area that detects the conditions under which logical reasoning errors might occur (Botvinick, Cohen, & Carter, 2004; Bush, Luu, & Posner, 2000; Carter, Braver, Barch, Botvinick, Douglas, & Cohen, 1998; Houdé, 2003; Houdé & Tzourio-Mazoyer, 2003; MacDonald, Cohen, Stenger, & Carter, 2000).

In the same vein, Goel and Dolan (2003b) have stressed that logical choices are often influenced by emotional responses, sometimes to our detriment, sometimes to our advantage. To understand the neural basis of emotionally neutral ("cold") and emotionally salient ("hot") reasoning the authors conducted a brain-imaging study as adults made logical judgements about arguments that varied in emotional saliency. They showed that "cold" reasoning trials resulted in enhanced activity in lateral prefrontal cortex and suppression of activity in ventromedial prefrontal cortex. By contrast, "hot" reasoning trials resulted in enhanced activity in ventromedial prefrontal cortex and suppression of activity in lateral prefrontal cortex. These reciprocal patterns provide evidence for a dynamic neural system for reasoning, the configuration of which is strongly influenced by emotional saliency. Other brain-imaging studies have stressed the role of the medial part of the prefrontal cortex in the emotional evaluation of error risks in domains related to logical cognition, notably in the rapid processing of monetary gains and losses during economic reasoning (Gehring & Willoughby, 2002).

We also know that the medial part of the prefrontal cortex is involved in moral cognition (Casebeer, 2003), and that early damage in this region in infancy causes impairment of moral behaviour and moral knowledge during social development (Anderson, Bechara, Damasio, Tranel, & Damasio, 1999). On the possible tie between moral and logic, one should recall that the child psychologist Jean Piaget had remarkable insight when he stated that logic should be the moral of cognition as moral is the logic of action (see Vidal, 1994).

CONCLUSIONS

The results presented here provide the first insights on (1) the cerebral basis of reasoning errors, and (2) the neurocognitive dynamics that lead the human brain towards logical truth. We propose to call this new approach "neuropedagogy of reasoning". Along with other results on mathematical cognition (Dehaene, 1997; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Houdé & Tzourio-Mazoyer, 2003) these discoveries argue for the neurobiology of truth (Changeux, 2004) and of human values.

Despite these findings, there are many loose ends in the field. How can the brain-imaging findings presented here be extended more widely to encompass other reasoning forms and conditions? As stressed above, it can be useful to refer to a more detailed brain processing architecture: how may training precisely affect the brain circuits of posterior and prefrontal networks? Computational modelling can be a good tool to this end. Finally, it is important to stress that the first steps in this neuropedagogy-of-reasoning approach were taken through the study of training (or "micro-development") in adults. Although purely behavioural data from developmental psychology will certainly be brought to bear on this issue, brain-imaging studies of children should also provide invaluable information (Casey, Tottenham, Liston, & Durston, 2005). Influencing reasoning brain networks can have implications for education (Posner & Rothbart, 2005). Learning to inhibit misleading strategies through self-regulation after unsuccessful reasoning experiences, imitation, or formal instruction is no doubt important at school as well as in everyday life.

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Mathematics Education and Neurosciences: Relating Spatial Structures to the Development of Spatial Sense and Number Sense

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Abstract

The Mathematics Education and Neurosciences (MENS) project is aimed at exploring the development of the mathematical abilities of young (four- to six-year old) children. It is initiated to integrate research from mathematics education with research from educational neuroscience in order to come to a better understanding of how the early skills of young children can best be fostered for supporting the development of mathematical abilities in an educational setting. This paper is specifically focused on the design research that is being conducted from the perspective of mathematics education in which we are investigating the relationship between young children's insight into spatial structures and the development of spatial and number sense. This should result in a series of classroom activities that may stimulate children's development of spatial and number skills.

Keywords: young children, spatial thinking, design research

1. Introduction: The Project in Context

It may come as no surprise that several publications support the point that we, the educational researchers, have been failing to properly value the cognitive capacities of young (three- to six-year old) children. A report from the National Research Council (NRC, 2005) concluded that

> early childhood education, in both formal and informal settings, may not be helping all children maximize their cognitive capacities.

It is also clear that there is an increasingly critical attitude towards some of Piaget's work. The aforementioned report concludes that 'modern research describes unexpected competencies in young children and calls into action models of development based on Piaget, which suggested

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that children were unable to carry out sophisticated complex tasks, such as perspective taking' (NRC, 2005). Remarkably, scientists from a different discipline, the education neurosciences, have come to similar conclusions in a report on Numeracy and Literacy of young children (OECD, 2003).

The learning of young children is so intriguing, that it has engaged many different scientific disciplines. What is surprising, then, is that the brain scientists see no references in the educational research literature about the developments they see to be relevant and vice versa. Yet, the tide is changing. The OECD report 'Understanding the Brain. Towards a New Learning Science' (OECD, 2002) suggests trans-disciplinary research to be the way forward. This must bridge the brain sciences (called the 'hard sciences' by brain scientists) and ('more practical') educational research (Jolles et al., 2006).

Reflecting on these issues, a program called *TalentPower* (TalentenKracht) was initiated by van Benthem, Dijkgraaf and de Lange. Several universities and institutions in The Netherlands collaborate in this program to gain a better understanding of what talents, possibilities and qualities young children exhibit as they are engaged in scientific activities, how these talents and qualities may be enhanced, how they may be intertwined, and in what ways they may be connected to language development. Hence the goal of the project is to bring together scientists from various research perspectives, as well as parents and teachers in order to chart the talents of young children and to scientifically fundament how these talents may be used and developed in an optimal way (van Benthem, Dijkgraaf & de Lange, 2005).

As such, apart from the fundamental goal to investigate the possibilities of fostering young children's natural curiosity, an important goal in the methodology of *TalentPower* is the 'trans-disciplinary' approach. Given the abundance of research in the field of mathematics education, the project was designed to try to bridge the gap between the sciences of 'mathematics education' and 'educational neurosciences'. This is how the Mathematics Education and Neurosciences (MENS) project came into being.

The significance of the collaboration between the sciences lies in the grounding of research from the field of mathematics education in cognitive and neuroscientific theory while at the same time providing the research from the field of cognitive psychology and neurosciences with a strong practical basis from which testable predictions can be made. Many recent publications have emphasized how scientists from the disciplines of mathematics education, cognitive psychology and neuropsychology can and should contribute to each others research (Berninger & Corina, 1998; Byrnes & Fox, 1998; Davis, 2004; Griffin & Case, 1997; Jolles et al., 2006; Lester, 2007; Siegler, 2003; Spelke, 2002). As Cobb (2007) points out, comparing and contrasting research from various perspectives has the added benefit of deepening our understanding of the phenomena being studied and of broadening the practicality of the results.

Within the context of the development of mathematical abilities of young children, the authors of this paper are mainly concerned with the mathematics educational perspective. De Haan and Gebuis at Utrecht University are constructing and performing the educational neuroscientific experiments. In time, the results of research from these research perspectives will be compared, contrasted and combined in an effort to contribute to mathematics educational practices that can foster the early talents of young children. Ultimately our findings may help stimulate those children who may be prone to experiencing problems in the development of mathematical thinking.

In the present paper we spiral into the work that is being performed from the perspective of mathematics education. In the first part of the paper, we lay out the theoretical framework of our research. This starts with a rationale for our focus on young children, on the constructs of spatial sense and number sense and on the role of spatial structures in the development of mathematical abilities. Next, we introduce preliminary experimental support that has contributed to the refinement of the research questions, and finally we explain our research methodology. We begin with the primary interest of all mathematics research in *TalentPower*: the importance of attending to how young children develop in their mathematical thinking.

2. Young Children Doing Mathematics

The overwhelming scientific attention to the mathematics education of young children can be attributed to seven factors that Clements and Sarama (2007) articulate: that a growing number of children attend early care and education programs, that the importance of mathematics is increasingly being recognized, that differences in performance between nations as well as between socioeconomic groups exist, that researchers are shifting to a perspective that recognizes innate mathematical competencies, that mathematics achievement is strongly predicted by specific quantitative and numerical knowledge, and finally, that knowledge gaps often appear because of poor bridging between informal knowledge and school mathematics.

What repeatedly stands out from studies on development in early childhood is how young children may be characterized by their natural drive to go out and explore the world. This is particularly illustrated in research stemming from Piaget's work. As mentioned in the introduction above, however, Piaget's methodology has strongly been criticized by researchers such as Freudenthal for depending too much on expert-use and interpretation of underlying concepts and on the child's language skills (Freudenthal, 1984, 1991). Freudenthal was greatly concerned about the intertwinement of children's cognitive competencies with their language skills, where relatively underdeveloped language skills could potentially suppress how children may express their understanding. Research methodologies that relied on children's ability to communicate their thinking could, in his view, only assess this language component and nothing more. Yet, Freudenthal's experiences with young children convinced him that children typically do possess remarkable cognitive competencies that develop through early learning processes.

Children's early competencies have been compared to the behavior of scientists in the Theory Theory (Gopnik, 2004; Gopnik, Meltzoff, & Kuhl, 1999). She suggests that children are born with certain theories about the world that they continuously test and amend as they gain new insights from daily experiences. Certain parallels are also drawn between children, scientists and poets who resemble one another in their sense of wonder and in the intense way in which they experience the world (Gopnik et al., 1999). As Dijkgraaf (2007) observes: 'It is often said that young children are ideal scientists. They are curious about the world around them. They ask questions, make up theories, and carry out experiments.' This is what is said to give both scientists as well as children their drive to learn (Gopnik, 2004).

In summary, de Lange emphasizes the 'curious minds of young children' (de Lange, cited in Ros, 2006, p. 9) which 'have to be stimulated'. In this sense it is disconcerting to note that many early elementary mathematics curricula focus mainly on developing curricula that teach number sense (Casey, 2004; Clements & Battista, 1992). Indeed several researchers warn about the gap that has been observed at the start of formal schooling between children's informal, intuitive knowledge and interests, and the formal learning opportunities in school (cf. Griffin & Case, 1997; Hughes, 1986; Murphy, 2006). The key point that we are making, then, is that mathematics education for young children should intertwine with and originate from the natural experiences, the enthusiasm, and the interests of young children as they explore of the world.

Gopnik (2004) put the issue for science in general into the following words:

> If we could put children in touch with their inner scientists, we might be able to bridge the divide between everyday knowledge and the apparently intimidating and elite apparatus of formal science. We might be able to convince them that there is a deep link between the realism of everyday life and scientific realism (p 28).

Through acknowledging the early competencies of young children (concentrating on what the children can already do versus what they cannot yet do; see also Gelman & Gallistel, 1978), we should on the one hand be able to come to a greater understanding about what factors influence the development of mathematical thinking and learning, while, on the other hand, stimulating the child's innate curiosity and eagerness to learn mathematics. We focus our research on spatial sense and number sense, the core of mathematics in the early years (NCTM, 2000), and study whether and, if so, how the development of early spatial sense and emerging number sense may be related. For purposes of our argument, we now clarify what we understand to be number sense and spatial sense.

3. Emerging Number Sense

The concept of number sense can broadly be defined as the ease and flexibility with which children operate with numbers (Gersten & Chard, 1999). Berch (1999) compiled an extensive list of components that have been related to the construct of number sense from the literature of mathematical cognition, cognitive development, and mathematics education. As such, he states that

> possessing number sense ostensibly permits one to achieve everything from understanding the meaning of numbers to developing strategies for solving complex math problems; from making simple magnitude comparisons to inventing procedures for conducting numerical operations; and from recognizing gross numerical errors to using quantitative methods for communicating, processing, and interpreting information. (p. 334)

As children progress in their ability to count, they discover easier ways of operating with numbers and they come to understand that numbers can have different representations and can act as different points of reference (Berch, 1999; Griffin & Case, 1997; Van den Heuvel-

Panhuizen, 2001). Given the diversity of the definitions of number sense, we focus our research on the development of awareness of quantities, on learning to give meaning to quantities and on being able to relate the different meanings of numbers to each other. This knowledge can then be applied to determining a quantity, to comparing quantities and to preliminary adding and subtracting. Hence, a well-founded number sense is fundamental to the ease and level of understanding with which children progress to higher order mathematical skills and concepts.

Our focus on young children's ability to determine a quantity and to compare quantities is supported by the Central Conceptual Theory described by Griffin and Case (1997; Griffin, 2004b). This theory is grounded in cognitive research with findings on how children by the age of four can make global quantity comparisons and can count. As Gelman and Gallistel (1978) have shown, children by the age of four can count a set of objects and understand that the last named number word represents the quantity of the set. Much recent cognitive research has supported this finding and has extended it to mathematics operations. Berger, Tzur and Posner (2006), for instance, found that six-month old infants can recognize simple addition errors and that the corresponding brain activity can be compared to that of adults detecting an arithmetic error.

Apart from children's ability to count, research by Starkey (1992), for example, has shown that four-year olds possess numerical knowledge that is not yet numerical, but that allows them to make quantity comparisons. Indeed, more recent cognitive psychological research on children's numerical abilities has provided evidence on how infants as young as six months can differentiate between amounts of objects that differ by a 2.0 ratio (i.e. eight versus sixteen objects; Lipton & Spelke, 2003; Xu & Spelke, 2000). This ability has been seen to improve within months as nine-month old infants can already differentiate sets that differ in number at a 1.5 ratio (i.e. nine versus six objects).

Griffin and Case (1997) describe the ability to compare quantities and the ability to count initially as two separate schemas. At the age of four, children have difficulty integrating these competencies, as if 'the two sets of knowledge were stored in different "files" on a computer, which cannot yet be "merged"' (p. 8). A revolutionary developmental step is said to occur by the age of five or six, in which these two schemas merge into 'a single, super-ordinate conceptual structure for number' (Griffin, 2004a, p. 40) in a manner that is described in the Central Conceptual Structure Theory (Griffin, 2004b; Griffin & Case, 1997). Such a conceptual structure covers 'the intuitive knowledge that appears to underlie successful learning of arithmetic in the early years of formal schooling' (1997, p. 8). It connects an understanding of quantity with number and enables children to use numbers without having to rely on objects that are physically present. Hence, this new conceptual structure provides children with the conceptual foundation for number sense which is believed to fundament all higher-level mathematics (Griffin, 2004a).

The learning of number and operations in early childhood may be the best-developed area in mathematics education research (Baroody, 2004; Clements, 2004; Fuson, 2004; Steffe, 2004). Yet, other research has shown that spatial thinking skills and mathematics achievement of relatively older children are related (Bishop, 1980; Clements, 2004; Guay & McDaniel, 1977; Smith, 1964; Tartre, 1990a, 1990b). For this reason, the NCTM standards (1989, 2000) strongly recommend increasing the emphasis on the development of spatial thinking skills through the teaching of geometry (the mathematics of space; Bishop, 1983) and spatial sense. In the next section we discuss three components of spatial sense that we consider to play an essential role in the development of young children's mathematical abilities.

4. Early Spatial Sense

Spatial sense can be defined as the ability to 'grasp the external world' (Freudenthal, in National Council of Teachers of Mathematics [NCTM], 1989, p. 48). In our view, this spatial sense consists of three main components that are most essential for enabling young children to 'grasp the world' and to develop mathematical thinking: spatial visualization, geometry ('shapes' in short), and spatial orientation ('space' in short). These components can be recognized in the foundations of comprehensive mathematics curricula for the middle grades such as Mathematics in Context (1998).

Spatial visualization involves the ability to imagine the movements of objects and spatial forms. In spatial visualization tasks, all or part of a representation may be mentally moved or altered (Bishop, 1980; Clements, 2004; Tartre, 1990a). This has been conceptualized as the ability to make object-based transformations where only the positions of the objects are moved with respect to the environmental frame of reference whereas the frame of reference of the observer stays constant (Zacks, Mires, Tversky & Hazeltine, 2000).

An example of a daily activity in which, already, young children have to apply spatial visualization skills, is when they imagine where in the kitchen it is that they can find their snack before they walk into the kitchen to get it. Recent cognitive research on children's spatial skills has shown how 16-24 month old infants can use the concept of distance to localize objects in a sandbox (Huttenlocher, Newcombe, & Sandberg, 1994). This has suggested an early competence to judge distances that is manifested regardless of the presence of any references in the direct surroundings of the child. Such an ability requires spatial visualization skills for creating a mental picture of the location of the object.

Geometry lessons in school should teach young children about shapes and figures and help them learn to refer to familiar structures such as their own body, to geometrical structures such as mosaics, and to geometrical patterns such as dot configurations on dominoes (cf. Clements & Sarama, 2007). This type of communication may help increase their vocabulary and enrich their imagination (Casey, 2004; Newcombe & Huttenlocher, 2000). Hence, geometric activities can stimulate the children's ability to sharpen and talk about their perceptions, which in turn helps develop children's spatial sense and reasoning skills (Van den Heuvel-Panhuizen & Buys, 2005). Indeed NCTM (1989, p. 48) has described spatial understandings as necessary for interpreting, understanding, and appreciating our inherently geometric world.

The third component that we name in the context of how children may 'grasp the world' is spatial orientation. This is the term that Clements (2004, p. 284) uses to describe how we 'make our way' in space. As children discover their surroundings, they gain experiences that help them to understand the relative positioning and sizes of shapes and figures (Van den Heuvel-

Panhuizen & Buys, 2005). As such, children learn to orientate themselves, to take different perspectives, to describe routes and to understand shapes, figures, proportions and relationships between objects.

Many of the activities in spatial orientation are examples of competencies that are typically manifested even before these children begin their formal schooling. A cognitive study with four and five-year olds, for example, provided evidence that at this age children can already compare proportions and figures (Sophian, 2000). The children in this study were able to match the correctly shrunken picture to the original picture without being distracted by pictures that not only were smaller, but also disproportional to the original picture. Studies such as this one exemplify the remarkably developed spatial sense that many children possess prior to the start of formal schooling.

Now that we have illustrated what we mean by emerging number sense and early spatial sense, we turn to why and how in our research we suspect a relationship to exist between these two constructs.

5. Relating Early Spatial Sense to Emerging Number Sense: Spatial Structures

To analyze the development of number and spatial sense of young children, we must first take a step back and find inspiration in how young children learn and think in general. In the process of learning and understanding, young children continuously try to organize new concepts and information about the world (de Lange, 1987; Gopnik, 2004; van den Heuvel-Panhuizen, 2001). Structuring is one fundamental method for children to organize the world (Freudenthal, 1987). In effect, this method of organization contributes to gaining insight into important mathematical concepts such as patterning, algebra, and the recognition of basic shapes and figures (Mulligan, Mitchelmore, & Prescott, 2006; Waters, 2004). Freudenthal even believed that there is no other science in which organization plays such a crucial role as in mathematics (1991). He described mathematics as

> an activity of solving problems, of looking for problems, but it is also an activity of organizing subject matter. This can be matter from reality which has to be organized according to mathematical patterns if problems from reality have to be solved. (1971, p. 413-414)

As children develop through experience, they improve their ability to organize incoming information and they learn to amend their organization schemes accordingly. Piaget regarded knowledge as structures that become increasingly complex through the processes of accommodation, assimilation, and equilibration. When a child with a certain method of thinking experiences something that no longer fits with this method of thinking (cannot assimilate), then it is put off balance until the method of thinking is adjusted (accommodated) and the system is balanced again (equilibrated). In this way, children are believed to reach more sophisticated means of thinking.

Van den Heuvel-Panhuizen (2001) gives an example of a practical mathematical situation in which the learning process illustrated above can be recognized. In this example, four-year old Anita is trying to connect meaning and purpose to the numbers that she is hearing:

> Anita is in a pancake restaurant with her father. They have just chosen a pancake from the menu. “I want pancake twelve,” says her father to the waitress. “And pancake seven for this young lady.” Anita cries: “But I can’t eat *that* many pancakes...!” (p. 29)

Experiences such as these can set young children’s thinking off balance and force them to adjust their definitions and frames of reference. Children learn from this, adjust the structure of their mode of thinking and, in doing so, reach a higher level of understanding.

The type of structure discussed thus far is mostly conceptual in nature in the way that it contributes to learning and understanding. Much research has concentrated on such a type of structure in thinking (cf. Dienes, 1960; Sriraman, 2004; Van Hiele, 1997). The particular type of structure that our study is concerned with is analogous to this conceptual structure, and yet it is more concrete. It is structure that fits with children’s experiences and current levels of spatial reasoning and it is structure which they may impose on manipulatives to support their mathematical learning and understanding.

To illustrate what we define as structure, we make use of the definition that Battista (1999) gave to describe the act of spatial structuring. In his view, spatial structuring is

> the mental operation of constructing an organization or form for an object or set of objects. It determines the object’s nature, shape, or composition by identifying its spatial components, relating and combining these components, and establishing interrelationships between components and the new object. (p. 418)

A spatial structure, then, is a product of this act of organizing space. Such a structure is an important element of a pattern. In line with Papic and Mulligan (2005), we may define a spatial structure in terms of a pattern. A pattern is a numerical or spatial regularity and the relationship between the elements of a pattern, then, is its structure. In particular, we refer to a spatial structure as a configuration of objects in space. This relates to the component ‘spatial regularity’ in the given definition of a pattern. The component ‘numerical regularity’ refers to numerical sequences that are not relevant to the mathematical abilities of four- to six-year old children. Examples of spatial structures that children of this age are typically familiar with are dot configurations on dice, finger counting images, rows of five and ten, bead patterns, and block constructions (illustrated in Figure 1).

In reference to the three components of early spatial sense that we elaborated on earlier, we suggest that spatial structures may play a supportive role in the development of number sense. Specifically, the intertwinement of the three components may contribute to children’s understanding of quantities and relationships between numbers. We propose that once children can imagine (i.e. spatially visualize) a spatial structure of a certain number of objects (i.e. configuration of objects that makes up a shape) that are to be manipulated (in a space), then learning to understand quantities as well as the process of counting (i.e. emerging number sense) should greatly be simplified. This hypothesized relationship between early spatial sense and emerging number sense is depicted in the figure below.

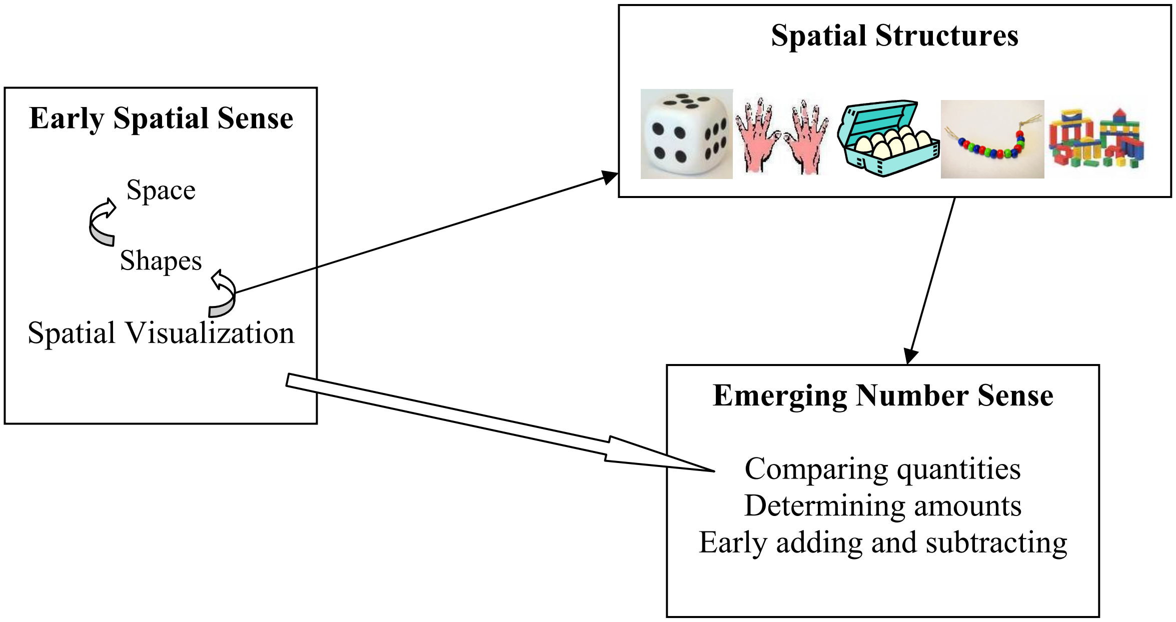

Figure 1. Spatial structures as a key factor in how early spatial sense may support the development of emerging number sense

After setting out why we suspect spatial structures to relate early spatial sense to emerging number sense, we continue our argument with illustrations of how spatial structures may play a supporting role in the development of mathematical abilities.

6. Spatial Structures in Early Numeracy Problems

To illustrate and support our concern with the role of spatial structures in the development of emerging number sense, we refer to Arcavi (2003) as one researcher who set out to define visualization and to analyze the various different roles that it may play in the learning and teaching of mathematics. Visualization, in his context, requires spatial visualization since it involves the interpretation and reflection upon pictures and images. Arcavi considers visualization to be at the service of problem solving because it may inspire the solution to a problem. In determining how many matches were needed to build an exemplar nxn square, for instance, most students used visual means to solve the problem. These visual means took different forms, one of which was the decomposition into what the students perceived to be easily countable units. This was a first step into changing the ‘gestalt’ (roughly the whole or the form) of the configuration.

It is the use of the term ‘gestalt’ in this context that supports our argument and indicates how students can simplify the mathematical problem by spatially visualizing objects into particular shapes in a space. For Arcavi’s students, the ‘gestalt’ could involve ‘breaking and rearranging the original whole’ or ‘imposing an “auxiliary construction” whose role consisted of providing visual “crutches”, which in themselves were not counted, but which supported and facilitated the visualization of a pattern that suggested a counting strategy’ (Arcavi, 2003, p. 229).

Several studies have related the Gestalt laws to early development. Spelke and colleagues (1993), for example, found that while the perceptions of adults were strongly influenced by the Gestalt relations of color, texture similarity, good continuation, and good form, the perceptions of 5- and 9-month olds were only weakly affected, and the perceptions of 3-month olds were not at all affected. This suggests a developmental course of these particular Gestalt relations (cf. Quinn et al., 1993; 2002). Taken together, these studies highlight how even infants as young as three months are capable of distinguishing particular elements of and establishing crude perceptual coherence.

An anecdote of Richardson (2004) about the children in her preschool classroom illustrates how the extraction of spatial structures may occur in practice. Richardson had her children work with dot cards (showing configurations such as those on dice) so that they could learn to recognize amounts in such arrangements. When, one day, she asked the children to count out a certain number of counters, she was astonished to find that instead of correctly counting out the counters, the children made an ‘X’ shape to match what the children recognized to be the shape of five dots on a card, and they made a square shape to match what they recognized to be the arrangement of nine dots. Apparently, then, these children extracted a shape from the individual dots on cards and taught themselves that this shape should resemble a particular number.

Richardson (2004) concludes from this experience that teachers must always interact with the children to check whether what they are doing makes sense to them, because performing without understanding interferes with the development of their mathematical abilities. More than that, it is a practical example of how children extract a general shape from individual elements and it adds on to the finding that infants can deploy Gestalt principles to make sense of the real-world and to establish perceptual coherence. The ability to process the gestalt, the whole, is an important requirement for mathematical skill as it is one ability that should help simplify and shorten the children’s process of learning to determine quantities (Van Eerde, 1996; Van Parreren, 1988). Such supporting evidence for children’s tendencies to organize the world through the use of spatial structures, should encourage mathematics educators to take care to weave spatial abilities into early mathematics curricula.

Children typically begin to formalize their understanding of quantities by connecting a certain quantity with spatial structures such as a number of fingers that are being held up on a hand or dot configurations on a pair of dice. As Smith (1964, as cited in Tartre, 1990a) put it,

> the process of perceiving and assimilating a gestalt...[is] a process of abstraction (abstracting form or structure)... It is possible that any process of abstraction may involve in some degree the perception, retention in memory, recognition and perhaps reproduction of a pattern or structure” (p. 213-214).

These spatial structures require a child to use its spatial visualization skills for organizing and making sense out of visual information. The mental extraction of structures from spatial configurations is also what Arcavi (2003) found to aid the counting process of his students.

Although the students in Arcavi's study were older than the age group in our project, one can imagine how young children can also use 'gestalts' to rearrange objects that are to be counted, for example. The spatial structure that subsequently arises can help the child to oversee the quantity (Van Eerde, 1996; Van Parreren, 1988).

As illustrated in Figure 1, we propose that the spatial visualization abilities help the child to perceive the 'gestalt' or spatial structure, in order to either mentally or physically be able to rearrange the objects in a space. The spatial structure that subsequently arises can simplify early numerical procedures. When young children are asked to determine the quantity of a randomly arranged set of objects, they initially tend to count each object. As the set of objects grows, this procedure eventually confronts them with the difficulties of keeping track of which objects have already been counted and with the time-consuming process that accompanies the counting of larger sets.

The benefit of applying spatial structure to mathematical problems is evident, for instance, when reading off a quantity (i.e. seeing the quantity of six as being three and three), when comparing a number of objects (i.e. one dot in each of four corners is less than the same configuration with a dot in the center), when continuing a pattern (i.e. generalizing the structure) and when building a construction of blocks (i.e. relating the characteristics and orientations of the constituent shapes and figures). Here too, then, children's ability to grasp spatial structure appears essential for developing mathematical abilities such as ordering, comparing, generalizing and classifying (NCTM, 2000; Papic & Mulligan, 2005; Waters, 2004).

More formal mathematical skills require even further insight into and use of spatial structure. This is particularly the case for addition, multiplication and division (i.e. $8 + 6 = 14$ because $5 + 5 = 10$ and $3 + 1 = 4$ so $10 + 4 = 14$; Van Eerde, 1996), for using variables in algebra, for proving, predicting and generalizing, and for determining the structure of a shape in order to subsequently mentally rotate or manipulate it (Kieran, 2004). Various studies have shown that children with serious mathematical problems tend not to use any form of structure and continue to count objects one by one (Mulligan, Mitchelmore, & Prescott, 2005; Van Eerde, 1996). This accentuates the need for children to be familiar with various spatial structures in order to simplify the progression to more formal mathematical concepts and procedures.

7. Preliminary Experimental Support

Thus far, we have set out much of the theoretical support for why and how we propose that early spatial sense and emerging number sense may be related. Alongside this are some preliminary outcomes of a previously conducted explorative study (van Nes & de Lange, in press; van Nes & Doorman, 2006) in which we set out to investigate the strategies that four- to six-year old children use to solve various number sense and spatial thinking problems.

One outcome from the explorative study was that four- to six-year old children with relatively stronger mathematical skills seemed to make more use of spatial structures than other children did. These children recognized the spatial structures that were presented and knew to implement these spatial structures for simplifying and speeding up counting procedures. Interestingly, however, there were several low achieving five- and six-year old children who seemed to recognize the spatial structures, and yet who did not proceed to applying the structures to solve the problems. These particular cases triggered our interest into what role insight into spatial structures may play in the development of emerging number sense and, ultimately, in the child's level of mathematical achievement.

The findings from our explorative study complement research of Mulligan, Prescott and Mitchelmore (2004) in which they conducted an analysis of structure present in 103 first graders' representations for various tasks across a range of mathematical domains. They coded the individual profiles as one of four stages of structural development and found that mathematical structure in children's representations generalizes across various mathematical domains. Recently, Mulligan, Mitchelmore and Prescott (2005; 2006) developed a Pattern and Structure Assessment (PASA) interview and a Pattern and Structure Mathematics Awareness Program (PASMAP) to study whether the mathematics of low achieving students can be improved through explicit instruction about structures and patterns in mathematical domains. The preliminary results showed improved mathematical achievement, suggesting that explicit instruction of mathematical pattern and structure can stimulate student's learning and understanding of mathematical concepts and procedures.

Taking the theoretical background and the preliminary findings together, we summarize the research questions of the present study from the perspective of mathematics education as:

1. How are early spatial sense and emerging number sense related and what role may spatial structures play in this development?
2. How can spatial visualization be implemented in educational practices to support the development of number sense?

In order to answer these two research questions we concentrate on designing a teaching experiment in which we may study how the development of spatial sense and number sense may be stimulated in an educational setting. This last issue will be investigated in terms of a design research methodology.

8. An Instruction Experiment

In gaining an understanding of how children recognize and apply spatial structures to numerical problems, it is important to decide on a methodology that is appropriate for highlighting the processes that occur in the mind of the child from the perspective of the child. The methodology that appears to be most in line with the principles of TalentPower, is inspired by the main theoretical insights of researchers in mathematics education such as Freudenthal (1984, 1991), Dienes (1960) and Van Parreren (1988). This generally concerns a methodology that is focused on a child's learning processes, that applauds dialogue and interaction, that emphasizes the stimulation of the own actions of the child, and that rejects mechanistic mathematics education (Van Eerde, 1996).

The activities for the instruction experiment stem from the tasks that we developed, tried out and improved in the previous exploratory studies (van Nes & de Lange, in press; van Nes & Doorman, 2006). Next to being based on the abovementioned theoretical insights, these tasks were originally inspired by experimental outcomes and practical experiences as described in related literature (van den Heuvel-Panhuizen, 2001, for example) and developed with input from experts. We also assessed the appropriateness of the tasks in terms of their coherence with the outcomes of the Utrecht Numeracy Test (UNT, van Luit et al., 1994). This is a normed test for assessing the number sense of 4.5- to 7-year old children. We compared the children's scores on this test with their accuracy scores as well as with the level and types of strategies that they used on the tasks. As we were easily able to come to a consensus about the scoring of the tasks, the strategy classifications and their agreement with the UNT scores, we decided that the tasks would be suitable to work out into a series of activities for use in the instruction experiment.

As the methodology is based on the guidelines of 'design research' (Freudenthal, 1978; Gravemeijer, 1994, 2004; Gravemeijer, Bowers, & Stephan, 2003; Streefland, 1988), our theory will cohere with direct experiences from an educational setting. This should keep the findings both theoretical and practical. It will involve an iterative procedure of theory-driven adjustments to the intervention and amendments to the hypotheses that lead to an improved and evidence-based theory (Freudenthal, 1978; Gravemeijer, 1994; Streefland, 1988). Freudenthal (1991) referred to such a research design as an instruction experiment because the activities are meant to broaden the children's insight into spatial visualization, into the perception and application of spatial structures, and, ultimately, into the characteristics of quantities and numbers while, at the same time, providing the researchers with a greater understanding of the children's learning processes. The aim, then, is not necessarily to conclude *that* the series of activities teach the children about spatial structures, but more to come to an analysis about *why* the series of activities may have stimulated the children's thinking (Gravemeijer et al., 2003).

In order to study the children's thinking processes, the series of activities should guide the children along a so-termed conjectured local instruction theory (Gravemeijer, 1994; Simon, 1995). The conjectured local instruction theory is a learning trajectory based on mathematical, psychological, and didactical insights about how we expect that the children will progress from their original way of thinking to our aspired way of thinking. To ensure the practicality of our findings, we must take into account both the cognitive development of the individual students, as well as the social context (i.e. people, setting and type of instruction) in which the instruction experiment is to take place (Cobb & Yackel, 1996).

The cyclical process that characterizes design research is illustrated in the diagram below. In practice this means that we will implement the series of activities in an instruction experiment, perform retrospective analyses on the transcripts from these lessons, adjust our hypotheses accordingly in a thought experiment and improve the activities in line with the amended conjectured local instruction theory. Then we repeat the procedure by implementing the new set of activities in a subsequent cycle, and learning from the class-experiences for, once again, fuelling the next thought experiment. This process will contribute to establishing and refining our conjecture local instruction theory.

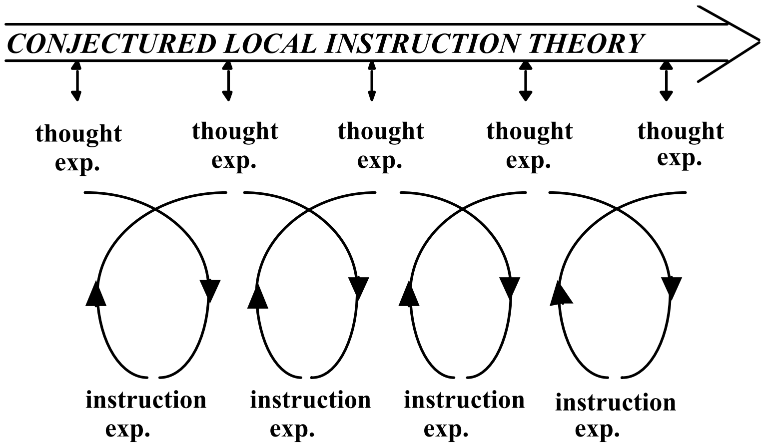

Figure 2. The cyclical procedure of design research (Gravemeijer, 2004)

9. Summary and Conclusion

After providing a broad overview of the theoretical framework that is propelling the MENS research, it is clear that young children possess spatial and numerical skills that should be cultivated in educational practice. As such, the aim of this research is to bring the spatial sense of young children to the fore and illustrate how spatial skills could function to stimulate the development of more formal mathematical skills that require number sense.

Supported by various fields of research, we consider spatial visualization, insight into shapes and an understanding of space to be three main components that make up young children's early spatial sense. As such, we suggest that children's spatial visualization skills contribute to their ability to organize representations of objects into spatial structures (such as dice configurations and finger images). These spatial structures relate to the children's conceptions of shapes with which they become familiar through exploring their surrounding space. Children's concepts of quantities and number, then, may greatly be stimulated when children are made aware of the simplifying effects of structuring manipulatives.

As soon as we have cycled through enough instruction and thought experiments to fundament our conjectured local instruction theory, we will turn to our colleagues for comparing and contrasting the results of the research perspectives of mathematics education and educational neurosciences. The neuroscientific perspectives may supplement our research with results from studies on brain behavior and neural correlates with respect to early spatial and numerical thinking. Ultimately, in line with the principles of *TalentPower*, the collaboration of these research perspectives should provide a more all-round and in-depth understanding of how education can foster the talents of young children and possibly stimulate those children who may be prone to experiencing problems in the development of mathematical skills.

As Tartre (1990a) stated in a discussion on spatial orientation,

> attempting to understand and discuss something like spatial orientation skill, which is by definition intuitive and nonverbal, is like trying to grab smoke: the very act of reaching out to take hold of it disperses it (p. 228).

She notes that any attempt to verbalize spatial thinking no longer is spatial thinking since spatial thinking is only a mental activity. We recognize that research into spatial sense is always an indirect attempt at trying to understand what is happening in the mind. Nevertheless, by taking into account the three components that we associate with spatial sense, and by relating them to each other in the way that we are, we aim to gain an understanding of how young children's early spatial skills may help them progress in their mathematical development. This is how we intend to better appreciate and more effectively cultivate young children's cognitive capacities that too often are underestimated or even neglected.

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Mathematics Education and Neurosciences: Relating Spatial Structures to the Development of Spatial Sense and Number Sense

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Abstract

The Mathematics Education and Neurosciences (MENS) project is aimed at exploring the development of the mathematical abilities of young (four- to six-year old) children. It is initiated to integrate research from mathematics education with research from educational neuroscience in order to come to a better understanding of how the early skills of young children can best be fostered for supporting the development of mathematical abilities in an educational setting. This paper is specifically focused on the design research that is being conducted from the perspective of mathematics education in which we are investigating the relationship between young children's insight into spatial structures and the development of spatial and number sense. This should result in a series of classroom activities that may stimulate children's development of spatial and number skills.

Keywords: young children, spatial thinking, design research

1. Introduction: The Project in Context

It may come as no surprise that several publications support the point that we, the educational researchers, have been failing to properly value the cognitive capacities of young (three- to six-year old) children. A report from the National Research Council (NRC, 2005) concluded that

> early childhood education, in both formal and informal settings, may not be helping all children maximize their cognitive capacities.

It is also clear that there is an increasingly critical attitude towards some of Piaget's work. The aforementioned report concludes that 'modern research describes unexpected competencies in young children and calls into action models of development based on Piaget, which suggested

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that children were unable to carry out sophisticated complex tasks, such as perspective taking' (NRC, 2005). Remarkably, scientists from a different discipline, the education neurosciences, have come to similar conclusions in a report on Numeracy and Literacy of young children (OECD, 2003).

The learning of young children is so intriguing, that it has engaged many different scientific disciplines. What is surprising, then, is that the brain scientists see no references in the educational research literature about the developments they see to be relevant and vice versa. Yet, the tide is changing. The OECD report 'Understanding the Brain. Towards a New Learning Science' (OECD, 2002) suggests trans-disciplinary research to be the way forward. This must bridge the brain sciences (called the 'hard sciences' by brain scientists) and ('more practical') educational research (Jolles et al., 2006).

Reflecting on these issues, a program called *TalentPower* (TalentenKracht) was initiated by van Benthem, Dijkgraaf and de Lange. Several universities and institutions in The Netherlands collaborate in this program to gain a better understanding of what talents, possibilities and qualities young children exhibit as they are engaged in scientific activities, how these talents and qualities may be enhanced, how they may be intertwined, and in what ways they may be connected to language development. Hence the goal of the project is to bring together scientists from various research perspectives, as well as parents and teachers in order to chart the talents of young children and to scientifically fundament how these talents may be used and developed in an optimal way (van Benthem, Dijkgraaf & de Lange, 2005).

As such, apart from the fundamental goal to investigate the possibilities of fostering young children's natural curiosity, an important goal in the methodology of *TalentPower* is the 'trans-disciplinary' approach. Given the abundance of research in the field of mathematics education, the project was designed to try to bridge the gap between the sciences of 'mathematics education' and 'educational neurosciences'. This is how the Mathematics Education and Neurosciences (MENS) project came into being.

The significance of the collaboration between the sciences lies in the grounding of research from the field of mathematics education in cognitive and neuroscientific theory while at the same time providing the research from the field of cognitive psychology and neurosciences with a strong practical basis from which testable predictions can be made. Many recent publications have emphasized how scientists from the disciplines of mathematics education, cognitive psychology and neuropsychology can and should contribute to each others research (Berninger & Corina, 1998; Byrnes & Fox, 1998; Davis, 2004; Griffin & Case, 1997; Jolles et al., 2006; Lester, 2007; Siegler, 2003; Spelke, 2002). As Cobb (2007) points out, comparing and contrasting research from various perspectives has the added benefit of deepening our understanding of the phenomena being studied and of broadening the practicality of the results.

Within the context of the development of mathematical abilities of young children, the authors of this paper are mainly concerned with the mathematics educational perspective. De Haan and Gebuis at Utrecht University are constructing and performing the educational neuroscientific experiments. In time, the results of research from these research perspectives will be compared, contrasted and combined in an effort to contribute to mathematics educational practices that can foster the early talents of young children. Ultimately our findings may help stimulate those children who may be prone to experiencing problems in the development of mathematical thinking.

In the present paper we spiral into the work that is being performed from the perspective of mathematics education. In the first part of the paper, we lay out the theoretical framework of our research. This starts with a rationale for our focus on young children, on the constructs of spatial sense and number sense and on the role of spatial structures in the development of mathematical abilities. Next, we introduce preliminary experimental support that has contributed to the refinement of the research questions, and finally we explain our research methodology. We begin with the primary interest of all mathematics research in *TalentPower*: the importance of attending to how young children develop in their mathematical thinking.

2. Young Children Doing Mathematics

The overwhelming scientific attention to the mathematics education of young children can be attributed to seven factors that Clements and Sarama (2007) articulate: that a growing number of children attend early care and education programs, that the importance of mathematics is increasingly being recognized, that differences in performance between nations as well as between socioeconomic groups exist, that researchers are shifting to a perspective that recognizes innate mathematical competencies, that mathematics achievement is strongly predicted by specific quantitative and numerical knowledge, and finally, that knowledge gaps often appear because of poor bridging between informal knowledge and school mathematics.

What repeatedly stands out from studies on development in early childhood is how young children may be characterized by their natural drive to go out and explore the world. This is particularly illustrated in research stemming from Piaget’s work. As mentioned in the introduction above, however, Piaget’s methodology has strongly been criticized by researchers such as Freudenthal for depending too much on expert-use and interpretation of underlying concepts and on the child’s language skills (Freudenthal, 1984, 1991). Freudenthal was greatly concerned about the intertwinement of children’s cognitive competencies with their language skills, where relatively underdeveloped language skills could potentially suppress how children may express their understanding. Research methodologies that relied on children’s ability to communicate their thinking could, in his view, only assess this language component and nothing more. Yet, Freudenthal’s experiences with young children convinced him that children typically do possess remarkable cognitive competencies that develop through early learning processes.

Children’s early competencies have been compared to the behavior of scientists in the Theory Theory (Gopnik, 2004; Gopnik, Meltzoff, & Kuhl, 1999). She suggests that children are born with certain theories about the world that they continuously test and amend as they gain new insights from daily experiences. Certain parallels are also drawn between children, scientists and poets who resemble one another in their sense of wonder and in the intense way in which they experience the world (Gopnik et al., 1999). As Dijkgraaf (2007) observes: ‘It is often said that young children are ideal scientists. They are curious about the world around them. They ask questions, make up theories, and carry out experiments.’ This is what is said to give both scientists as well as children their drive to learn (Gopnik, 2004).

In summary, de Lange emphasizes the ‘curious minds of young children’ (de Lange, cited in Ros, 2006, p. 9) which ‘have to be stimulated’. In this sense it is disconcerting to note that many early elementary mathematics curricula focus mainly on developing curricula that teach number sense (Casey, 2004; Clements & Battista, 1992). Indeed several researchers warn about the gap that has been observed at the start of formal schooling between children’s informal, intuitive knowledge and interests, and the formal learning opportunities in school (cf. Griffin & Case, 1997; Hughes, 1986; Murphy, 2006). The key point that we are making, then, is that mathematics education for young children should intertwine with and originate from the natural experiences, the enthusiasm, and the interests of young children as they explore of the world.

Gopnik (2004) put the issue for science in general into the following words:

> If we could put children in touch with their inner scientists, we might be able to bridge the divide between everyday knowledge and the apparently intimidating and elite apparatus of formal science. We might be able to convince them that there is a deep link between the realism of everyday life and scientific realism (p 28).

Through acknowledging the early competencies of young children (concentrating on what the children can already do versus what they cannot yet do; see also Gelman & Gallistel, 1978), we should on the one hand be able to come to a greater understanding about what factors influence the development of mathematical thinking and learning, while, on the other hand, stimulating the child’s innate curiosity and eagerness to learn mathematics. We focus our research on spatial sense and number sense, the core of mathematics in the early years (NCTM, 2000), and study whether and, if so, how the development of early spatial sense and emerging number sense may be related. For purposes of our argument, we now clarify what we understand to be number sense and spatial sense.

3. Emerging Number Sense

The concept of number sense can broadly be defined as the ease and flexibility with which children operate with numbers (Gersten & Chard, 1999). Berch (1999) compiled an extensive list of components that have been related to the construct of number sense from the literature of mathematical cognition, cognitive development, and mathematics education. As such, he states that

> possessing number sense ostensibly permits one to achieve everything from understanding the meaning of numbers to developing strategies for solving complex math problems; from making simple magnitude comparisons to inventing procedures for conducting numerical operations; and from recognizing gross numerical errors to using quantitative methods for communicating, processing, and interpreting information. (p. 334)

As children progress in their ability to count, they discover easier ways of operating with numbers and they come to understand that numbers can have different representations and can act as different points of reference (Berch, 1999; Griffin & Case, 1997; Van den Heuvel-

Panhuizen, 2001). Given the diversity of the definitions of number sense, we focus our research on the development of awareness of quantities, on learning to give meaning to quantities and on being able to relate the different meanings of numbers to each other. This knowledge can then be applied to determining a quantity, to comparing quantities and to preliminary adding and subtracting. Hence, a well-founded number sense is fundamental to the ease and level of understanding with which children progress to higher order mathematical skills and concepts.

Our focus on young children's ability to determine a quantity and to compare quantities is supported by the Central Conceptual Theory described by Griffin and Case (1997; Griffin, 2004b). This theory is grounded in cognitive research with findings on how children by the age of four can make global quantity comparisons and can count. As Gelman and Gallistel (1978) have shown, children by the age of four can count a set of objects and understand that the last named number word represents the quantity of the set. Much recent cognitive research has supported this finding and has extended it to mathematics operations. Berger, Tzur and Posner (2006), for instance, found that six-month old infants can recognize simple addition errors and that the corresponding brain activity can be compared to that of adults detecting an arithmetic error.

Apart from children's ability to count, research by Starkey (1992), for example, has shown that four-year olds possess numerical knowledge that is not yet numerical, but that allows them to make quantity comparisons. Indeed, more recent cognitive psychological research on children's numerical abilities has provided evidence on how infants as young as six months can differentiate between amounts of objects that differ by a 2.0 ratio (i.e. eight versus sixteen objects; Lipton & Spelke, 2003; Xu & Spelke, 2000). This ability has been seen to improve within months as nine-month old infants can already differentiate sets that differ in number at a 1.5 ratio (i.e. nine versus six objects).

Griffin and Case (1997) describe the ability to compare quantities and the ability to count initially as two separate schemas. At the age of four, children have difficulty integrating these competencies, as if 'the two sets of knowledge were stored in different "files" on a computer, which cannot yet be "merged"' (p. 8). A revolutionary developmental step is said to occur by the age of five or six, in which these two schemas merge into 'a single, super-ordinate conceptual structure for number' (Griffin, 2004a, p. 40) in a manner that is described in the Central Conceptual Structure Theory (Griffin, 2004b; Griffin & Case, 1997). Such a conceptual structure covers 'the intuitive knowledge that appears to underlie successful learning of arithmetic in the early years of formal schooling' (1997, p. 8). It connects an understanding of quantity with number and enables children to use numbers without having to rely on objects that are physically present. Hence, this new conceptual structure provides children with the conceptual foundation for number sense which is believed to fundament all higher-level mathematics (Griffin, 2004a).

The learning of number and operations in early childhood may be the best-developed area in mathematics education research (Baroody, 2004; Clements, 2004; Fuson, 2004; Steffe, 2004). Yet, other research has shown that spatial thinking skills and mathematics achievement of relatively older children are related (Bishop, 1980; Clements, 2004; Guay & McDaniel, 1977; Smith, 1964; Tartre, 1990a, 1990b). For this reason, the NCTM standards (1989, 2000) strongly recommend increasing the emphasis on the development of spatial thinking skills through the teaching of geometry (the mathematics of space; Bishop, 1983) and spatial sense. In the next section we discuss three components of spatial sense that we consider to play an essential role in the development of young children's mathematical abilities.

4. Early Spatial Sense

Spatial sense can be defined as the ability to 'grasp the external world' (Freudenthal, in National Council of Teachers of Mathematics [NCTM], 1989, p. 48). In our view, this spatial sense consists of three main components that are most essential for enabling young children to 'grasp the world' and to develop mathematical thinking: spatial visualization, geometry ('shapes' in short), and spatial orientation ('space' in short). These components can be recognized in the foundations of comprehensive mathematics curricula for the middle grades such as Mathematics in Context (1998).

Spatial visualization involves the ability to imagine the movements of objects and spatial forms. In spatial visualization tasks, all or part of a representation may be mentally moved or altered (Bishop, 1980; Clements, 2004; Tartre, 1990a). This has been conceptualized as the ability to make object-based transformations where only the positions of the objects are moved with respect to the environmental frame of reference whereas the frame of reference of the observer stays constant (Zacks, Mires, Tversky & Hazeltine, 2000).

An example of a daily activity in which, already, young children have to apply spatial visualization skills, is when they imagine where in the kitchen it is that they can find their snack before they walk into the kitchen to get it. Recent cognitive research on children's spatial skills has shown how 16-24 month old infants can use the concept of distance to localize objects in a sandbox (Huttenlocher, Newcombe, & Sandberg, 1994). This has suggested an early competence to judge distances that is manifested regardless of the presence of any references in the direct surroundings of the child. Such an ability requires spatial visualization skills for creating a mental picture of the location of the object.

Geometry lessons in school should teach young children about shapes and figures and help them learn to refer to familiar structures such as their own body, to geometrical structures such as mosaics, and to geometrical patterns such as dot configurations on dominoes (cf. Clements & Sarama, 2007). This type of communication may help increase their vocabulary and enrich their imagination (Casey, 2004; Newcombe & Huttenlocher, 2000). Hence, geometric activities can stimulate the children's ability to sharpen and talk about their perceptions, which in turn helps develop children's spatial sense and reasoning skills (Van den Heuvel-Panhuizen & Buys, 2005). Indeed NCTM (1989, p. 48) has described spatial understandings as necessary for interpreting, understanding, and appreciating our inherently geometric world.

The third component that we name in the context of how children may 'grasp the world' is spatial orientation. This is the term that Clements (2004, p. 284) uses to describe how we 'make our way' in space. As children discover their surroundings, they gain experiences that help them to understand the relative positioning and sizes of shapes and figures (Van den Heuvel-

Panhuizen & Buys, 2005). As such, children learn to orientate themselves, to take different perspectives, to describe routes and to understand shapes, figures, proportions and relationships between objects.

Many of the activities in spatial orientation are examples of competencies that are typically manifested even before these children begin their formal schooling. A cognitive study with four and five-year olds, for example, provided evidence that at this age children can already compare proportions and figures (Sophian, 2000). The children in this study were able to match the correctly shrunken picture to the original picture without being distracted by pictures that not only were smaller, but also disproportional to the original picture. Studies such as this one exemplify the remarkably developed spatial sense that many children possess prior to the start of formal schooling.

Now that we have illustrated what we mean by emerging number sense and early spatial sense, we turn to why and how in our research we suspect a relationship to exist between these two constructs.

5. Relating Early Spatial Sense to Emerging Number Sense: Spatial Structures

To analyze the development of number and spatial sense of young children, we must first take a step back and find inspiration in how young children learn and think in general. In the process of learning and understanding, young children continuously try to organize new concepts and information about the world (de Lange, 1987; Gopnik, 2004; van den Heuvel-Panhuizen, 2001). Structuring is one fundamental method for children to organize the world (Freudenthal, 1987). In effect, this method of organization contributes to gaining insight into important mathematical concepts such as patterning, algebra, and the recognition of basic shapes and figures (Mulligan, Mitchelmore, & Prescott, 2006; Waters, 2004). Freudenthal even believed that there is no other science in which organization plays such a crucial role as in mathematics (1991). He described mathematics as

> an activity of solving problems, of looking for problems, but it is also an activity of organizing subject matter. This can be matter from reality which has to be organized according to mathematical patterns if problems from reality have to be solved. (1971, p. 413-414)

As children develop through experience, they improve their ability to organize incoming information and they learn to amend their organization schemes accordingly. Piaget regarded knowledge as structures that become increasingly complex through the processes of accommodation, assimilation, and equilibration. When a child with a certain method of thinking experiences something that no longer fits with this method of thinking (cannot assimilate), then it is put off balance until the method of thinking is adjusted (accommodated) and the system is balanced again (equilibrated). In this way, children are believed to reach more sophisticated means of thinking.

Van den Heuvel-Panhuizen (2001) gives an example of a practical mathematical situation in which the learning process illustrated above can be recognized. In this example, four-year old Anita is trying to connect meaning and purpose to the numbers that she is hearing:

> Anita is in a pancake restaurant with her father. They have just chosen a pancake from the menu. "I want pancake twelve," says her father to the waitress. "And pancake seven for this young lady." Anita cries: "But I can't eat *that* many pancakes...!" (p. 29)

Experiences such as these can set young children's thinking off balance and force them to adjust their definitions and frames of reference. Children learn from this, adjust the structure of their mode of thinking and, in doing so, reach a higher level of understanding.

The type of structure discussed thus far is mostly conceptual in nature in the way that it contributes to learning and understanding. Much research has concentrated on such a type of structure in thinking (cf. Dienes, 1960; Sriraman, 2004; Van Hiele, 1997). The particular type of structure that our study is concerned with is analogous to this conceptual structure, and yet it is more concrete. It is structure that fits with children's experiences and current levels of spatial reasoning and it is structure which they may impose on manipulatives to support their mathematical learning and understanding.

To illustrate what we define as structure, we make use of the definition that Battista (1999) gave to describe the act of spatial structuring. In his view, spatial structuring is

> the mental operation of constructing an organization or form for an object or set of objects. It determines the object's nature, shape, or composition by identifying its spatial components, relating and combining these components, and establishing interrelationships between components and the new object. (p. 418)

A spatial structure, then, is a product of this act of organizing space. Such a structure is an important element of a pattern. In line with Papic and Mulligan (2005), we may define a spatial structure in terms of a pattern. A pattern is a numerical or spatial regularity and the relationship between the elements of a pattern, then, is its structure. In particular, we refer to a spatial structure as a configuration of objects in space. This relates to the component 'spatial regularity' in the given definition of a pattern. The component 'numerical regularity' refers to numerical sequences that are not relevant to the mathematical abilities of four- to six-year old children. Examples of spatial structures that children of this age are typically familiar with are dot configurations on dice, finger counting images, rows of five and ten, bead patterns, and block constructions (illustrated in Figure 1).

In reference to the three components of early spatial sense that we elaborated on earlier, we suggest that spatial structures may play a supportive role in the development of number sense. Specifically, the intertwinement of the three components may contribute to children's understanding of quantities and relationships between numbers. We propose that once children can imagine (i.e. spatially visualize) a spatial structure of a certain number of objects (i.e. configuration of objects that makes up a shape) that are to be manipulated (in a space), then learning to understand quantities as well as the process of counting (i.e. emerging number sense) should greatly be simplified. This hypothesized relationship between early spatial sense and emerging number sense is depicted in the figure below.

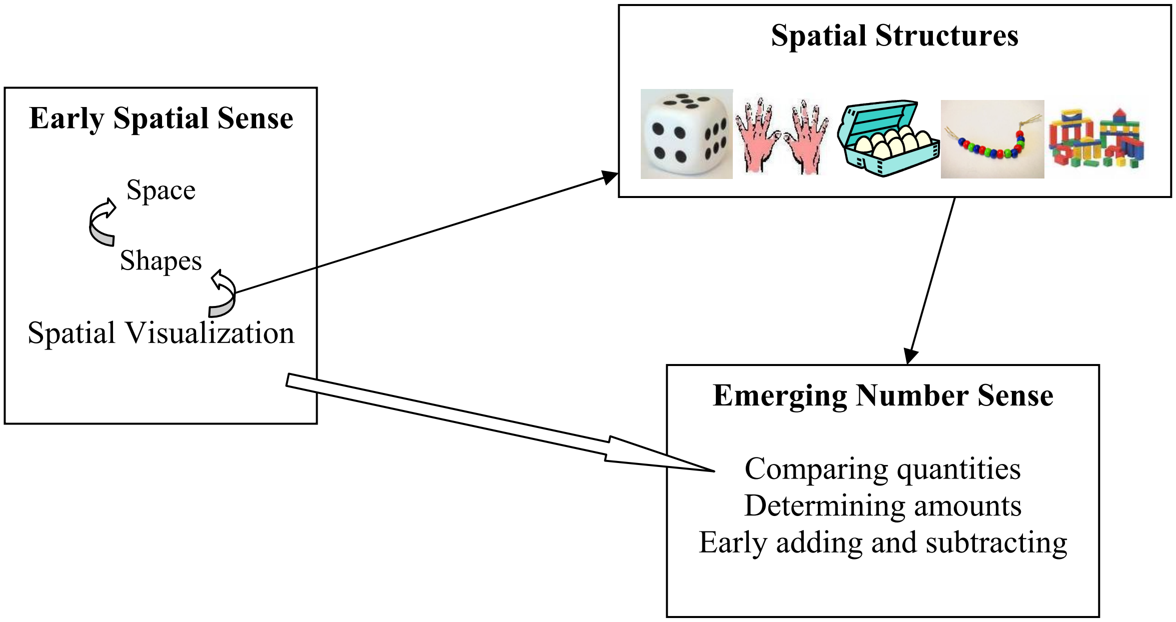

Figure 1. Spatial structures as a key factor in how early spatial sense may support the development of emerging number sense

After setting out why we suspect spatial structures to relate early spatial sense to emerging number sense, we continue our argument with illustrations of how spatial structures may play a supporting role in the development of mathematical abilities.

6. Spatial Structures in Early Numeracy Problems

To illustrate and support our concern with the role of spatial structures in the development of emerging number sense, we refer to Arcavi (2003) as one researcher who set out to define visualization and to analyze the various different roles that it may play in the learning and teaching of mathematics. Visualization, in his context, requires spatial visualization since it involves the interpretation and reflection upon pictures and images. Arcavi considers visualization to be at the service of problem solving because it may inspire the solution to a problem. In determining how many matches were needed to build an exemplar nxn square, for instance, most students used visual means to solve the problem. These visual means took different forms, one of which was the decomposition into what the students perceived to be easily countable units. This was a first step into changing the ‘gestalt’ (roughly the whole or the form) of the configuration.

It is the use of the term ‘gestalt’ in this context that supports our argument and indicates how students can simplify the mathematical problem by spatially visualizing objects into particular shapes in a space. For Arcavi’s students, the ‘gestalt’ could involve ‘breaking and rearranging the original whole’ or ‘imposing an “auxiliary construction” whose role consisted of providing visual “crutches”, which in themselves were not counted, but which supported and facilitated the visualization of a pattern that suggested a counting strategy’ (Arcavi, 2003, p. 229).

Several studies have related the Gestalt laws to early development. Spelke and colleagues (1993), for example, found that while the perceptions of adults were strongly influenced by the Gestalt relations of color, texture similarity, good continuation, and good form, the perceptions of 5- and 9-month olds were only weakly affected, and the perceptions of 3-month olds were not at all affected. This suggests a developmental course of these particular Gestalt relations (cf. Quinn et al., 1993; 2002). Taken together, these studies highlight how even infants as young as three months are capable of distinguishing particular elements of and establishing crude perceptual coherence.

An anecdote of Richardson (2004) about the children in her preschool classroom illustrates how the extraction of spatial structures may occur in practice. Richardson had her children work with dot cards (showing configurations such as those on dice) so that they could learn to recognize amounts in such arrangements. When, one day, she asked the children to count out a certain number of counters, she was astonished to find that instead of correctly counting out the counters, the children made an ‘X’ shape to match what the children recognized to be the shape of five dots on a card, and they made a square shape to match what they recognized to be the arrangement of nine dots. Apparently, then, these children extracted a shape from the individual dots on cards and taught themselves that this shape should resemble a particular number.

Richardson (2004) concludes from this experience that teachers must always interact with the children to check whether what they are doing makes sense to them, because performing without understanding interferes with the development of their mathematical abilities. More than that, it is a practical example of how children extract a general shape from individual elements and it adds on to the finding that infants can deploy Gestalt principles to make sense of the real-world and to establish perceptual coherence. The ability to process the gestalt, the whole, is an important requirement for mathematical skill as it is one ability that should help simplify and shorten the children’s process of learning to determine quantities (Van Eerde, 1996; Van Parreren, 1988). Such supporting evidence for children’s tendencies to organize the world through the use of spatial structures, should encourage mathematics educators to take care to weave spatial abilities into early mathematics curricula.

Children typically begin to formalize their understanding of quantities by connecting a certain quantity with spatial structures such as a number of fingers that are being held up on a hand or dot configurations on a pair of dice. As Smith (1964, as cited in Tartre, 1990a) put it,

> the process of perceiving and assimilating a gestalt...[is] a process of abstraction (abstracting form or structure)... It is possible that any process of abstraction may involve in some degree the perception, retention in memory, recognition and perhaps reproduction of a pattern or structure” (p. 213-214).

These spatial structures require a child to use its spatial visualization skills for organizing and making sense out of visual information. The mental extraction of structures from spatial configurations is also what Arcavi (2003) found to aid the counting process of his students.

Although the students in Arcavi's study were older than the age group in our project, one can imagine how young children can also use 'gestalts' to rearrange objects that are to be counted, for example. The spatial structure that subsequently arises can help the child to oversee the quantity (Van Eerde, 1996; Van Parreren, 1988).

As illustrated in Figure 1, we propose that the spatial visualization abilities help the child to perceive the 'gestalt' or spatial structure, in order to either mentally or physically be able to rearrange the objects in a space. The spatial structure that subsequently arises can simplify early numerical procedures. When young children are asked to determine the quantity of a randomly arranged set of objects, they initially tend to count each object. As the set of objects grows, this procedure eventually confronts them with the difficulties of keeping track of which objects have already been counted and with the time-consuming process that accompanies the counting of larger sets.

The benefit of applying spatial structure to mathematical problems is evident, for instance, when reading off a quantity (i.e. seeing the quantity of six as being three and three), when comparing a number of objects (i.e. one dot in each of four corners is less than the same configuration with a dot in the center), when continuing a pattern (i.e. generalizing the structure) and when building a construction of blocks (i.e. relating the characteristics and orientations of the constituent shapes and figures). Here too, then, children's ability to grasp spatial structure appears essential for developing mathematical abilities such as ordering, comparing, generalizing and classifying (NCTM, 2000; Papic & Mulligan, 2005; Waters, 2004).

More formal mathematical skills require even further insight into and use of spatial structure. This is particularly the case for addition, multiplication and division (i.e. $8 + 6 = 14$ because $5 + 5 = 10$ and $3 + 1 = 4$ so $10 + 4 = 14$; Van Eerde, 1996), for using variables in algebra, for proving, predicting and generalizing, and for determining the structure of a shape in order to subsequently mentally rotate or manipulate it (Kieran, 2004). Various studies have shown that children with serious mathematical problems tend not to use any form of structure and continue to count objects one by one (Mulligan, Mitchelmore, & Prescott, 2005; Van Eerde, 1996). This accentuates the need for children to be familiar with various spatial structures in order to simplify the progression to more formal mathematical concepts and procedures.

7. Preliminary Experimental Support

Thus far, we have set out much of the theoretical support for why and how we propose that early spatial sense and emerging number sense may be related. Alongside this are some preliminary outcomes of a previously conducted explorative study (van Nes & de Lange, in press; van Nes & Doorman, 2006) in which we set out to investigate the strategies that four- to six-year old children use to solve various number sense and spatial thinking problems.

One outcome from the explorative study was that four- to six-year old children with relatively stronger mathematical skills seemed to make more use of spatial structures than other children did. These children recognized the spatial structures that were presented and knew to implement these spatial structures for simplifying and speeding up counting procedures. Interestingly, however, there were several low achieving five- and six-year old children who seemed to recognize the spatial structures, and yet who did not proceed to applying the structures to solve the problems. These particular cases triggered our interest into what role insight into spatial structures may play in the development of emerging number sense and, ultimately, in the child's level of mathematical achievement.

The findings from our explorative study complement research of Mulligan, Prescott and Mitchelmore (2004) in which they conducted an analysis of structure present in 103 first graders' representations for various tasks across a range of mathematical domains. They coded the individual profiles as one of four stages of structural development and found that mathematical structure in children's representations generalizes across various mathematical domains. Recently, Mulligan, Mitchelmore and Prescott (2005; 2006) developed a Pattern and Structure Assessment (PASA) interview and a Pattern and Structure Mathematics Awareness Program (PASMAP) to study whether the mathematics of low achieving students can be improved through explicit instruction about structures and patterns in mathematical domains. The preliminary results showed improved mathematical achievement, suggesting that explicit instruction of mathematical pattern and structure can stimulate student's learning and understanding of mathematical concepts and procedures.

Taking the theoretical background and the preliminary findings together, we summarize the research questions of the present study from the perspective of mathematics education as:

1. How are early spatial sense and emerging number sense related and what role may spatial structures play in this development?
2. How can spatial visualization be implemented in educational practices to support the development of number sense?

In order to answer these two research questions we concentrate on designing a teaching experiment in which we may study how the development of spatial sense and number sense may be stimulated in an educational setting. This last issue will be investigated in terms of a design research methodology.

8. An Instruction Experiment

In gaining an understanding of how children recognize and apply spatial structures to numerical problems, it is important to decide on a methodology that is appropriate for highlighting the processes that occur in the mind of the child from the perspective of the child. The methodology that appears to be most in line with the principles of TalentPower, is inspired by the main theoretical insights of researchers in mathematics education such as Freudenthal (1984, 1991), Dienes (1960) and Van Parreren (1988). This generally concerns a methodology that is focused on a child's learning processes, that applauds dialogue and interaction, that emphasizes the stimulation of the own actions of the child, and that rejects mechanistic mathematics education (Van Eerde, 1996).

The activities for the instruction experiment stem from the tasks that we developed, tried out and improved in the previous exploratory studies (van Nes & de Lange, in press; van Nes & Doorman, 2006). Next to being based on the abovementioned theoretical insights, these tasks were originally inspired by experimental outcomes and practical experiences as described in related literature (van den Heuvel-Panhuizen, 2001, for example) and developed with input from experts. We also assessed the appropriateness of the tasks in terms of their coherence with the outcomes of the Utrecht Numeracy Test (UNT, van Luit et al., 1994). This is a normed test for assessing the number sense of 4.5- to 7-year old children. We compared the children's scores on this test with their accuracy scores as well as with the level and types of strategies that they used on the tasks. As we were easily able to come to a consensus about the scoring of the tasks, the strategy classifications and their agreement with the UNT scores, we decided that the tasks would be suitable to work out into a series of activities for use in the instruction experiment.

As the methodology is based on the guidelines of 'design research' (Freudenthal, 1978; Gravemeijer, 1994, 2004; Gravemeijer, Bowers, & Stephan, 2003; Streefland, 1988), our theory will cohere with direct experiences from an educational setting. This should keep the findings both theoretical and practical. It will involve an iterative procedure of theory-driven adjustments to the intervention and amendments to the hypotheses that lead to an improved and evidence-based theory (Freudenthal, 1978; Gravemeijer, 1994; Streefland, 1988). Freudenthal (1991) referred to such a research design as an instruction experiment because the activities are meant to broaden the children's insight into spatial visualization, into the perception and application of spatial structures, and, ultimately, into the characteristics of quantities and numbers while, at the same time, providing the researchers with a greater understanding of the children's learning processes. The aim, then, is not necessarily to conclude *that* the series of activities teach the children about spatial structures, but more to come to an analysis about *why* the series of activities may have stimulated the children's thinking (Gravemeijer et al., 2003).

In order to study the children's thinking processes, the series of activities should guide the children along a so-termed conjectured local instruction theory (Gravemeijer, 1994; Simon, 1995). The conjectured local instruction theory is a learning trajectory based on mathematical, psychological, and didactical insights about how we expect that the children will progress from their original way of thinking to our aspired way of thinking. To ensure the practicality of our findings, we must take into account both the cognitive development of the individual students, as well as the social context (i.e. people, setting and type of instruction) in which the instruction experiment is to take place (Cobb & Yackel, 1996).

The cyclical process that characterizes design research is illustrated in the diagram below. In practice this means that we will implement the series of activities in an instruction experiment, perform retrospective analyses on the transcripts from these lessons, adjust our hypotheses accordingly in a thought experiment and improve the activities in line with the amended conjectured local instruction theory. Then we repeat the procedure by implementing the new set of activities in a subsequent cycle, and learning from the class-experiences for, once again, fuelling the next thought experiment. This process will contribute to establishing and refining our conjecture local instruction theory.

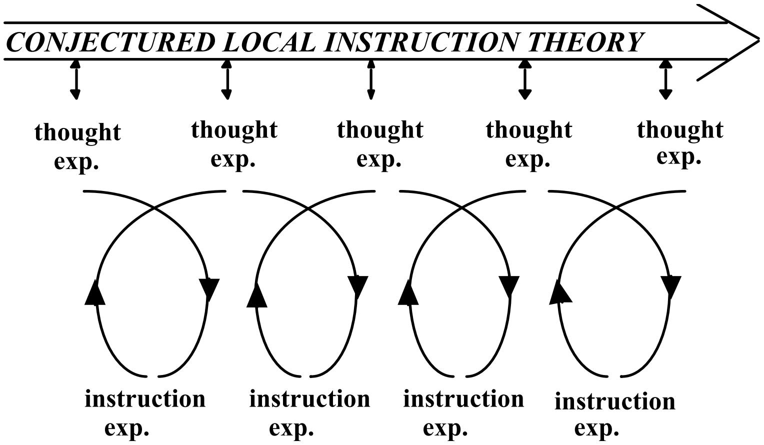

Figure 2. The cyclical procedure of design research (Gravemeijer, 2004)

9. Summary and Conclusion

After providing a broad overview of the theoretical framework that is propelling the MENS research, it is clear that young children possess spatial and numerical skills that should be cultivated in educational practice. As such, the aim of this research is to bring the spatial sense of young children to the fore and illustrate how spatial skills could function to stimulate the development of more formal mathematical skills that require number sense.

Supported by various fields of research, we consider spatial visualization, insight into shapes and an understanding of space to be three main components that make up young children's early spatial sense. As such, we suggest that children's spatial visualization skills contribute to their ability to organize representations of objects into spatial structures (such as dice configurations and finger images). These spatial structures relate to the children's conceptions of shapes with which they become familiar through exploring their surrounding space. Children's concepts of quantities and number, then, may greatly be stimulated when children are made aware of the simplifying effects of structuring manipulatives.

As soon as we have cycled through enough instruction and thought experiments to fundament our conjectured local instruction theory, we will turn to our colleagues for comparing and contrasting the results of the research perspectives of mathematics education and educational neurosciences. The neuroscientific perspectives may supplement our research with results from studies on brain behavior and neural correlates with respect to early spatial and numerical thinking. Ultimately, in line with the principles of *TalentPower*, the collaboration of these research perspectives should provide a more all-round and in-depth understanding of how education can foster the talents of young children and possibly stimulate those children who may be prone to experiencing problems in the development of mathematical skills.

As Tartre (1990a) stated in a discussion on spatial orientation,

> attempting to understand and discuss something like spatial orientation skill, which is by definition intuitive and nonverbal, is like trying to grab smoke: the very act of reaching out to take hold of it disperses it (p. 228).

She notes that any attempt to verbalize spatial thinking no longer is spatial thinking since spatial thinking is only a mental activity. We recognize that research into spatial sense is always an indirect attempt at trying to understand what is happening in the mind. Nevertheless, by taking into account the three components that we associate with spatial sense, and by relating them to each other in the way that we are, we aim to gain an understanding of how young children's early spatial skills may help them progress in their mathematical development. This is how we intend to better appreciate and more effectively cultivate young children's cognitive capacities that too often are underestimated or even neglected.

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How should educational neuroscience conceptualise the relation between cognition and brain function? Mathematical reasoning as a network process

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How should educational neuroscience conceptualise the relation between cognition and brain function? Mathematical reasoning as a network process

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Background: There is increasing interest in applying neuroscience findings to topics in education.
Purpose: This application requires a proper conceptualisation of the relation between cognition and brain function. This paper considers two such conceptualisations. The *area focus* understands each cognitive competency as the product of one (and only one) brain area. The *network focus* explains each cognitive competency as the product of collaborative processing among multiple brain areas.
Sources of evidence: We first review neuroscience studies of mathematical reasoning – specifically arithmetic problem-solving and magnitude comparison – that exemplify the area focus and network focus. We then review neuroscience findings that illustrate the potential of the network focus for informing three topics in mathematics education: the development of mathematical reasoning, the effects of practice and instruction, and the derailment of mathematical reasoning in dyscalculia.
Main argument: Although the area focus has historically dominated discussions in educational neuroscience, we argue that the network focus offers a complementary perspective on brain function that should not be ignored.
Conclusions: We conclude by describing the current limitations of network-focus theorising and emerging neuroscience methods that promise to make such theorising more tractable in the future.

Keywords: educational neuroscience; mathematics education; arithmetic; dyscalculia; magnitude comparison; large-scale cortical networks

Introduction

The relationship between education and neuroscience has been the subject of productive debate (Ansari and Coch 2006; Blakemore and Frith 2005; Bruer 1997; Byrnes and Fox 1998; Geake 2004; Goswami 2006; Varma, McCandliss and Schwartz in press). We supplement this discussion by describing two approaches to explaining how the brain gives rise to cognitive competence, and how they might contribute to educational thinking.

One appeal of cognitive neuroscience is that it is a ‘place-based’. The topology of the brain yields the prospect of a spatial map that ties functions to areas. The place-based grounding of neuroscience theories makes them different from psychological theories, which are cast in terms of more abstract constructs like schemas, IQ and identity. It is literally possible to search databases by brain area to see which tasks cause them to

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activate – without ever entering a psychological keyword (e.g., Laird, Lancaster, and Fox 2005).

Figure 1 depicts two dominant approaches for understanding the place-based nature of cognition. The *area focus* typifies earlier theorising in cognitive neuroscience, and continues to characterise discussions in educational neuroscience. It decomposes cognition into a set of tasks and maps them to brain areas in a one-to-one fashion. Said differently, it seeks to identify *the* brain area that activates most selectively for each task competency. In contrast, the *network focus* explains task competency as the product of coordination among multiple brain areas. Network-focus research typically builds upon pioneering area-focus research that has identified initial landmarks. It expands the unit of analysis from the functioning of individual brain areas to the co-functioning of networks of brain areas.

Our concern is that the area focus currently dominates discussions in educational neuroscience, and it risks inappropriate inferences for improving educational practice. The one-to-one mapping of competencies to brain areas easily leads to the conclusion that students just need to exercise one part of their brain to develop or remediate a skill. It also naturally leads to the complaint that 'knowing where it sits in the brain does not tell us anything useful'. The problem with area-focus reasoning is that most tasks that educators care about are complex and multifaceted (especially compared with those studied by cognitive neuroscientists). These tasks are likely to map to brain areas in a many-to-many fashion. Said another way, most tasks activate multiple brain areas, and conversely most brain areas activate for multiple tasks. Moreover, the same task can be accomplished by different networks depending on experience (Tang et al. 2006). This paper argues that exclusively adopting an area focus risks the uptake of educational neuroscience in a seductive but premature form, and that a complementary network focus should also be emphasised. It grounds the argument primarily in the content area of mathematics.

This paper has the following structure. It first describes the area focus and illustrates its application to topics in mathematics education. Much of the discussion centres on two brain areas: intraparietal sulcus (IPS) and angular gyrus (AG). These areas are shown in Figure 2, along with a number of other areas that are mentioned below. Next, the area focus is incrementally broadened into the network focus through a broader consideration

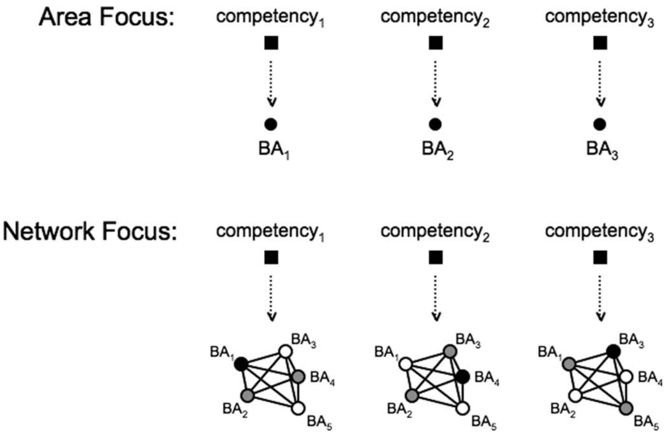

Figure 1. The area focus and network focus. The darker a circle, the more a brain area (BA) contributes to a competency.

of neuroscience findings on mathematical reasoning. Finally, the value of the network focus is illustrated by applying it to three topics in mathematics education: the development of mathematical reasoning, the effects of practice and instruction and the derailment of mathematical reasoning in dyscalculia.

The area focus for mathematical reasoning

The area focus has thus far dominated discussions in educational neuroscience. One reason for this dominance is that the methods of neuroscience have historically been well suited for isolating the brain areas necessary for a given ability. For example, in the nineteenth century, Broca encountered a patient with intact receptive language but impaired expressive language. Although the patient could comprehend language, he could only produce the utterance 'tan'. An autopsy revealed a lesion to a single brain area (left inferior frontal gyrus). Broca localised the expressive language competency to this area. A few years later, Wernicke applied the same logic to localise the receptive language competency to a different area (left posterior superior temporal gyrus). Another example of an area focus on brain function is the work conducted by the neurosurgeon Penfield in the early twentieth century. He electrically stimulated the brains of awake patients and observed their responses and impairments. A famous result of this research was the homunculi – topographical maps of somatosensory and motor cortex where adjacent brain areas coded sensation and action for adjacent regions of the body.

The area focus has been the dominant way to understand the results of neuroimaging experiments. Perhaps the most popular technique is functional magnetic resonance imaging (fMRI). When neurons fire, they make metabolic demands, consuming local stores of glucose and oxygen. This brings a haemodynamic response to replenish these

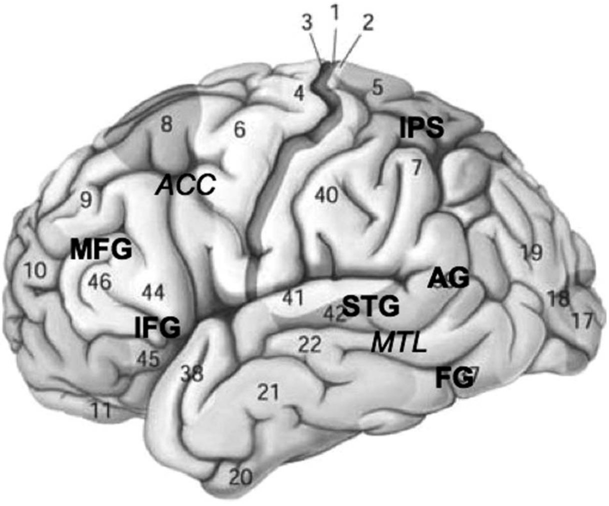

Figure 2. Important brain areas for mathematical reasoning: intraparietal sulcus (IPS), angular gyrus (AG), Broca's area/inferior frontal gyrus (IFG), Wernicke's area/prosterior superior temporal gyrus (STG), fusiform gyrus (FG), medial temporal lobe/hippocampus (MTL), middle frontal gyrus (MFG) and anterior cingulate cortex (ACC). Lateral areas (i.e., near the outside of the brain) are labelled in bold, medial areas (i.e., near the centre of the brain) in italics. The numbers are according to Brodmann's scheme.

stores: the vascular system carries oxygenated blood to the region via arteries and carries deoxygenated blood away from the region via veins. Oxygenated blood and deoxygenated blood have different magnetic susceptibilities. As a result, differences in their relative concentration in a region produce differences in the magnetic resonance signal emanating from that region, and these differences can be used to generate images. As this brief description makes clear, fMRI is a rather indirect measure of neuronal activity: it registers the vascular response to metabolic activity in support of neuronal activity (for a more comprehensive description of fMRI see Huettel, Song, and McCarthy 2004). fMRI is popular because it can non-invasively measure activity in behaving brains, and because it provides good spatial resolution (i.e., each picture element has a volume in the order of 10 cubic millimeters) and acceptable temporal resolution (i.e., an image can be acquired every second or so).

The design and analysis of fMRI experiments have historically depended on the use of *tight subtractions*.[1] Participants complete two nearly identical tasks (e.g., naming digits versus naming letters). The fMRI scan produces a map of activation across the brain for each task. The map will include activation in areas of little theoretical interest, for example, due to moving the eyes or pressing a response button. To remove this 'noise', researchers subtract the activation map of the control task (e.g., letter naming) from the activation of the target task (e.g., digit naming). This leaves only the activation due to the competency of interest (e.g., accessing number). Over the past 15 years, thousands of fMRI experiments have used tight subtractions to map competencies to brain areas in a one-to-one manner.

In addition to the availability of suitable methods, another allure of the area focus is that it can be straightforwardly applied to understand the neural bases of complex forms of cognition. For example, consider the mathematical competency of being able to reason about numbers as magnitudes (Case et al. 1997) – what is also called 'number sense' (Dehaene 1997) and understanding 'numerosity' (Butterworth 2005; Landerl, Bevan, and Butterworth 2004). The area focus asks which brain area implements this competency. Neuroscientists have pursued this question by capitalising on the symbolic distance effect (SDE) – the finding that the time taken to compare two digits decreases as the distance between them increases; for example, people are faster to judge which of 1 versus 9 is larger than to judge which of 1 versus 3 is larger (Moyer and Landauer 1967). The SDE is commonly interpreted as evidence that people reason about numerical magnitudes using a 'mental number line' that is psychophysically scaled, so that, much like perceptual discriminations (e.g., loudness and softness), values that are closer together on the number line are harder to discriminate than values that are far apart. Neuroscientists have used the SDE to identify the 'numerical magnitude area' of the brain. A representative study is by Pinel et al. (2004). Participants compared pairs of digits, judging which was greater. A handful of brain areas showed an increase in activation that paralleled the increasing response times for closer comparisons. Most prominent among them was IPS.[2] From an area focus, this is evidence that this brain area is the primary correlate of the numerical magnitude competency – that it is the seat of the mental number line.

The area focus can also provide insights about individual differences, which present a natural bridge from neuroscience to education (Kosslyn and Koenig 1992). The area focus describes a deficit as a dysfunction of the brain area that implements the relevant ability. This is a variant of the reasoning that Broca and Wernicke applied to understand language impairments, augmented with the assumption that a structurally intact area can be rehabilitated by exercising it through repeated practice of the relevant task. The application of this reasoning produced the biggest success story in educational neuroscience to date, the remediation of one subtype of dyslexia. In a representative study, Eden et al. (2004) used fMRI to first identify the networks of brain areas recruited by typical readers and those with dyslexia. Dyslexic readers showed reduced activation in AG, which has been implicated in mapping orthography to phonology. Next, the dyslexic readers participated in a program developed by educational researchers for remediating phonological difficulties. Post-test fMRI scans revealed that successful remediation was associated with increased activation in AG. From an area-focus approach, this 'weak' brain area had been 'strengthened'.

An area focus is currently being applied to understand dyscalculia, the mathematical analog of dyslexia. Dyscalculia is defined as scoring in the lowest 5% (or so) on tests of mathematical achievement relative to age, education level and intelligence (Butterworth 2005). This is a coarse clinical definition, and dyscalculia is likely a blanket term that includes multiple subtypes. Molko et al. (2003) applied the logic of the area approach to understand the mathematical impairment of a relatively homogeneous group of dyscalculics – those with Turner syndrome. They focused on the mathematical competency of arithmetic problem-solving – the ability to compute or retrieve the answers to addition and subtraction problems (and, in other experiments, multiplication and division problems) where the operands are small positive integers. They capitalised on the *problem size effect*: the finding that the time to solve problems with large operands (e.g., $8 + 9$) is slower than the time to solve problems with small operands (e.g., $4 + 3$) (Ashcraft 1992). Stanescu-Cosson et al. (2000) had previously identified a neural analog of the problem size effect in normal adults, finding that operand size correlates positively with activation in IPS. Molko et al. (2003) found that patients with dyscalculia failed to show a problem size effect in IPS (or any other brain area).[3] An area-focus interpretation of this finding is that under-activation of IPS in this group of dyscalculics is correlated with their impaired arithmetic problem-solving. The next logical step would be a training study to exercise this 'mental muscle', with the expected result that performance would improve and IPS activation would come to resemble that of people without dyscalculia.

The network focus for mathematical reasoning

Although an area focus is important for initially mapping the functional terrain of the brain, it ultimately presents an oversimplified view of the neural bases of mathematical reasoning. That one area is necessary for a particular ability does not imply that it is sufficient. A broader consideration of neuroimaging studies reveals that many mathematical competencies are better viewed as emergent products of networks of brain areas. As a corollary, some impairments of mathematical reasoning may be better viewed as breakdowns in network function; consequently, remediation may require exercises that *coordinate* areas rather than strengthen them in isolation.

The network focus has been a minor theme in neuroscience theorising for decades. An early example comes from Lashley, who incrementally removed portions of rats' brains to identify 'the memory area'. His conclusion was that no such area existed, and that the rat brain instead worked by *mass action*: the more that was removed, the more performance declined. Though it ultimately proved to be an untenable account of memory, the proposed distribution of function served as a useful counterweight to the area focus. Another early example of a focus on network function is Luria (1966), who observed that focal brain lesions often impair not a single competency, but rather a range of competencies, some more than others. More recently, Mesulam (1990) has argued that attention and language are better understood as the products of partially overlapping, large-scale cortical networks. In this view, most competencies are implemented by multiple areas, and most areas contribute to multiple competencies.

fMRI studies are increasingly focusing on the network of brain areas that activates for a given task, rather than the single area that activates most selectively. For example, consider the neural bases of face recognition. Early studies found evidence that fusiform gyrus (an area in inferior temporal cortex) selectively activates for processing faces when activation associated with the processing of other visual categories, such as houses, is subtracted away (Kanwisher, McDermott, and Chun 1997). This led to the label 'fusiform face area' and the concomitant assumption that the ability to discriminate faces had enough survival value that the human brain evolved a dedicated area. However, subsequent studies revealed that fusiform gyrus activates not just for faces, but also for other visual categories such as houses and furniture, though to a lesser extant (Ishai et al. 1999). Conversely, other inferior temporal areas that activate selectively for other visual categories also activate for faces, though to a lesser extant. In this way, an initial area-based understanding of face recognition has been articulated into a more nuanced network-based understanding. The remainder of this section describes a similar (and ongoing) shift, where an initial area-based understanding of arithmetic problem-solving is being refined into a network-based understanding.

Early neuroimaging studies of adults found selective activation of IPS when subtracting single-digit operands. Within the area focus, this was interpreted as evidence that IPS implements the subtraction competency. Because other researchers had found activation in this area during visuospatial processing, Dehaene et al. (2003) proposed that subtraction problems are solved by imagining and moving along a mental number line. In contrast, early studies of multiplication found selective activation of AG. This was interpreted as evidence that this area implements the multiplication competency. Because other researchers had found AG activation during retrieval of phonological information, Dehaene et al. (2003) proposed that multiplication is performed by look-up in a verbally coded, mental multiplication table. In this way, the area focus made sense of early neuroimaging studies – subtraction involves visuospatial processing and multiplication verbal processing.

Though simple and elegant, the area focus can miss potential complexities revealed by a network focus. For example, Lee (2000) had participants solve subtraction and multiplication problems in the scanner and found network effects. Multiple brain areas activated more for subtraction than multiplication; IPS was one, but it was not the only one. Conversely, multiple brain areas activated more for multiplication than subtraction; AG was one, but it was not the only one. These results suggested that mathematical competencies might be better understood as the products of networks of brain areas, not single brain areas.

In the preceding examples, researchers used tight subtractions: activation during multiplication was subtracted from activation during subtraction, and vice versa. By definition, each activation peak was associated with one, and only one, arithmetic operation. This led naturally to the inference of *independent* brain areas in the case of Dehaene et al. (2003) and *independent* (i.e., non-overlapping) networks of brain areas in the case of Lee (2000). Other studies have used 'loose subtractions' to isolate activation patterns. In a loose subtraction, activation from a relatively low-level control condition, such as viewing a fixation cross, is subtracted from activations during the experimental conditions of interest. The result is a more complete picture of the network recruited by each experimental condition. Studies employing loose subtractions reveal that subtraction and multiplication activate a *common* network of brain areas, although they activate different areas to different degrees. For example, Chochon et al. (1999) subtracted activation when viewing a fixation cross from activation during subtraction and multiplication respectively. They found that subtraction activated a network of brain areas, one that included IPS. Critically, they found that multiplication activated almost the same network. This network included IPS, although it was activated less intensely.

Duffau et al. (2002) conducted a neurosurgical study of a patient with a tumour in AG. Before removing the tumour, electro-stimulation was used to map competencies within AG. Among other tasks, the patient solved different kinds of arithmetic problems. Electrical stimulation was directly applied to different sites within AG, so it was possible to see which competencies were disrupted. Consistent with an area focus, the researchers found a multiplication site within AG. Critically, they also found a subtraction site in the same brain area, as well as a site common to both operations. These results suggest that it is a mistake to narrowly construe AG as *the* multiplication area. Rather, it is a component of a larger arithmetic network, and it plays a role not just in multiplication, but also in subtraction (and likely other aspects of mathematical reasoning as well).

These network findings indicate that the mapping of behaviour to the brain is more complex than that suggested by an area focus and frequently communicated to educators and educational researchers. The different pictures of arithmetic painted by the area and network approaches are important for education because they may have different implications for how best to teach. The area focus suggests that subtraction should be taught using spatial referents such as number lines to capitalise on the functional specialisation of IPS; and that multiplication should be taught verbally, for example, by rehearsing times tables, to recruit AG. In contrast, the network approach is consistent with instruction that targets the development of number sense (Baroody 1985). Children should be given opportunities to integrate different meanings and operations of number by engaging in activities that yield coordinated networks (Case et al. 1997). Note that this prescription does not preclude development of a mental number line, nor large doses of mathematical fact memorisation. However, it does suggest that a number line representation is not sufficient for achieving flexible subtraction competence, and memorisation is not sufficient for achieving flexible multiplication competence. As we describe below, there is a place for both meaning and memorisation in arithmetic.

Using the network approach to understand topics in mathematics education

The area focus currently dominates how neuroscience findings are packaged for educational researchers. As a result, the potential of the network focus remains largely untapped. This section illustrates this potential. It applies the network focus to three topics of interest to mathematics education: the development of mathematical reasoning, the effects of practice and instruction and the derailment of mathematical reasoning in dyscalculia. The examples show how a network focus can refine the broad-stroke neuroscience models one might use to explain educationally relevant phenomena.

Qualitative shifts underlying continuous behavioural changes

Developmental neuroscientists were among the first to adopt a network focus (e.g., Johnson et al. 2002). Consider the development of the understanding that digits name quantities or magnitudes. The SDE (i.e., the difference in response times for comparing near digits versus far digits) is indicative of whether people have developed an interpretation of number that includes its magnitude interpretation. In a cross-sectional study, Sekuler and Mierkiewicz (1977) documented that the SDE (i.e., the difference in response times for comparing near digits versus far digits) is present as early as kindergarten and decreases continuously into adulthood (but never completely). The area focus predicts that this continuous change in the degree of the SDE should be accompanied by a continuous change in the activation of IPS.[4] Ansari et al. (2005) tested this prediction by having adults and 10-year-old children make numerical comparisons. The adults showed an SDE in a network of brain areas that included IPS, replicating prior studies. Critically, for the children, an activation pattern differentiating near versus far comparisons was not observed in IPS, though it was observed in other brain areas. In the case of numerical magnitude, a continuous developmental change at the behavioural level belies a qualitative shift at the neural level.

Another example, from the domain of arithmetic problem solving, comes from a cross-sectional study by Rivera et al. (2005). Children between the ages of 8 and 19 solved simple addition and subtraction problems. Although accuracy was constant across development, there was a continuous improvement in solution speed with age. Recall that the area focus predicts that a continuous change in behavioural performance with development should be accompanied by a continuous change in the activation level of the corresponding neural correlate. However, the Rivera et al. (2005) results were more consistent with the network focus. Some areas of the arithmetic network were more active early in development. These areas have been implicated in domain-general forms of cognition (i.e., prefrontal areas associated with controlled processing and executive function and medial temporal areas associated with declarative long-term memory). Other areas became more active with development, including those known to be associated with visuospatial processing (IPS) and verbal processing (AG). These are more domain-specific forms of cognition. Once again, a continuous developmental change at the behavioural level – faster addition and subtraction – is better understood as a qualitative shift in the underlying network, in this case, reflecting a transition from domain-general to domain-specific processing.[5] This qualitative shift raises the question of whether educational activities should change over time to help students move from early domain-general processing to later domain-specific processing. Whether a constant dose of thought-provoking problems is the best way to encourage the shift, or whether practising the same types of problems repeatedly better encourages the shift, are interesting empirical questions raised by a network focus.

Effects of memorisation and strategy training

The network approach helps clarify the effects of practice on mathematical reasoning. Delazer et al. (2003) trained participants on complex multiplication problems, where a two-digit operand is multiplied by a one-digit operand. They were then scanned as they solved the same problems they had studied, plus a set of new problems of similar difficulty. This design makes it possible to identify the learning effects of memorising specific mathematical facts through practice versus computing them. Activation in AG (and some other areas) increased for the trained problems, suggesting that answers were being accessed from a verbal store. In addition, activation in IPS (and some other areas) decreased for trained problems, suggesting that less computation was performed for familiar problems. One interpretation of these results is that practice produced a shift in the arithmetic network that reflected a transition from a more computational visuospatial strategy to a more retrieval-based verbal strategy for the trained problems.

The Delazer et al. (2003) study is important because it addresses the effects of practice, an issue of interest to mathematics education. Delazer et al. (2005) took the next step in a study that examined the effects of pure memorisation versus learning an algorithm for computing solutions. They taught participants a novel arithmetic operation using two kinds of instruction. The memorisation group memorised the answers to problems with specific operands. They never learned how to compute the operation. By contrast, the strategy group was taught an algorithm for computing the answer given the same operands. Both groups then solved familiar and novel problems in the scanner.

The results showed that participants in the memorisation condition organised one network of brain areas to perform the operation and participants in the strategy condition another. For example, the memorisation network included AG, which has been implicated in the retrieval of verbally coded knowledge, whereas the strategy network included the anterior cingulate cortex, which has been implicated in controlled cognitive processing. This difference is important for two reasons. First, it is a difference at the brain level that matters at the behavioural level, and is thus relevant for education. The network organised by participants in the strategy condition supported transfer to novel problems (78% accuracy), whereas the network organised by participants in the memorisation condition did not (15% accuracy). Memorisation and calculation strengthen different networks rather than strengthening the same one, and thus the network analysis helps explain the differential effects of memorising versus learning to calculate. A second important contribution of this study for the prospects of educational neuroscience is that it demonstrates that fMRI can be used to study the consequences of instruction delivered outside the scanner over a relatively long period of time.

Dyscalculia as network under-activation

Recall that Molko et al. (2003) contrasted a group of normal controls with a group of dyscalculics as they solved addition problems. The critical finding was that normal controls displayed a problem size effect in the activation of IPS, whereas dyscalculics did not. Although the results of this study are comprehensible from an area focus, those of a more recent study of dyscalculia are better understood from a network focus. Kucian et al. (2006) imaged a group of dyscalculics and a group of normal controls as they performed a range of mathematical tasks. In one task, approximate addition, they found under-activation of the entire arithmetic network in the dyscalculic group relative to the normal control group. The implicated areas included bilateral IPS, inferior frontal gyrus, middle frontal gyrus and anterior cingulate cortex. These results suggest that understanding dyscalculia will require focusing on both the dysfunction of individual brain areas and the dysfunction of networks of brain areas.[6] It is an open question of what kinds of instruction may be able to organise a dysfunctioning network (as opposed to a dysfunctioning brain area, which we saw above in the dyslexia example: Eden et al. 2004)? We return to this question below.

Conclusion

This paper has considered two approaches to understanding the relationship between cognition and brain function. The area focus maps cognitive competencies to brain areas in a one-to-one fashion. The network focus understands each cognitive competency as the emergent product of information processing in a network of brain areas. Although the area focus has historically dominated discussions, we argued the network focus offers a complementary perspective on brain function that educational neuroscience should not ignore.

Two of the examples presented above bring the area focus and network focus into particularly sharp contrast. The first concerns the arithmetic problem-solving of typical adults. Initial studies adopted an area focus. Their findings suggested that subtraction selectively activates IPS, and thus involves visuospatial processing, whereas multiplication selectively activates AG, and thus involves verbal processing (Dehaene et al. 2003). Subsequent studies adopted a network focus. In contrast, they found evidence for a common arithmetic network whose component brain areas are taxed differently by different operations (Chochon et al. 1999; Duffau et al. 2002; Lee 2000). The second example where both the area focus and network focus have been adopted is dyscalculia. Although the study of this impairment is still in its infancy, an early study by Molko et al. (2003) adopted an area approach. It found that a neural correlate of dyscalculia was dysfunction of IPS. By contrast, the more recent study by Kucian et al. (2006) adopted a network focus. It found under-activation not of a single brain area, but rather the entire arithmetic network. The network-focus conclusions are consistent with the views of many in mathematics education (Baroody 1985; Case et al. 1997), namely that arithmetic problem-solving is the product of an interrelated set of mathematical competencies, and that the failure to properly coordinate these competencies results in poor mathematical achievement. For this reason, we expect the network focus to become increasingly important as educational neuroscience matures.

We conclude by describing the current limitations of network focus theorising and emerging neuroscience methods that promise to make such theorising more tractable in the future. An important limitation of the network focus for education is that it posits a complex, many-to-many mapping of mathematical competencies to brain areas. This makes it difficult to make predictions about the effects of network function and dysfunction, and therefore to draw implications for questions of interest to educational researchers. By contrast, the area focus maps mathematical competencies to brain areas in a one-to-one fashion, with a deficit in a particular competency understood as a dysfunction of the corresponding brain area. This has a natural educational implication: to design instruction that 'strengthens' that 'weak' area, presumably improving performance. Although this approach has had a few limited successes (e.g., Eden et al. 2004), its prospects are ultimately limited by the fact that the brain is *not* carved at the same functional joints that make sense at the behavioural level. Rather, brain areas appear to be specialised for lower-level functions, and it is only through their organisation in large-scale networks that these functions coalesce into mathematical competencies that matter at the behavioural level, and are thus of interest to educational researchers.

However, there are methods that make network-style theorising more tractable. They should enable studies that ask how brain areas become connected and coordinated in networks, as when children learn to coordinate cardinal and ordinal conceptions of quantity (Case et al. 1997). One example is *functional connectivity analysis*, which looks for correlated activity in different brain areas during task performance (e.g., Friston 1994). The inference is that correlated brain areas are communicating as part of a large-scale network. For example, Büchel, Coull, and Friston (1999) found that learning gains were associated not with changes in the activation of a single brain area, but rather with increases in correlated activity among brain areas. Functional connectivity analysis may be useful for understanding the network-wide under-activations in dyscalculia documented by Kucian et al. (2006). This deficit may be better understood as a dysfunction of how well brain areas communicate with, and therefore co-activate, one another. Another promising neuroscience method is *diffusion tensor imaging* (DTI), which directly images the anatomical connections – the white matter tracts – over which brain areas communicate (e.g., Le Bihan et al. 2001). The potential of DTI to inform topics in education is illustrated by a recent study by Niogi and McCandliss (2006), who found that the integrity of left temporo-parietal white-matter tracts is correlated with reading ability in elementary school children. Future functional connectivity and DTI studies of mathematical reasoning, literacy and other forms of cognition of interest to educational neuroscientists promise to benefit from a network focus.

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Notes

1. The use of subtraction has declined over the years as other experimental designs and methods of analysis have been developed. We describe two of these advancements in the 'Conclusion' section.
2. Pinel et al. (2004) also had participants compare stimuli along physical dimensions, such as size and luminance. These comparisons also produced SDEs in IPS. Comparisons of numerical magnitude and physical size activated roughly the same peak coordinates in IPS, whereas the comparisons of physical luminance activated different peak coordinates, though in the same area.
3. The dyscalculic patients did show a behavioural problem size effect, but it was exaggerated relative to normal controls, suggesting use of a different strategy (e.g., verbal counting versus magnitude-based processing).
4. Whether the change is an increase or decrease in activation depends on one's conception of what develops (Poldrack 2000). If one believes that representations get richer, then the prediction is increasing activation. If one believes that representations are shaped or tuned (i.e., made more efficient), then the prediction is decreasing activation.
5. There are other ways to interpret this shift. Rivera et al. (2005) favour an attentional interpretation, from more controlled to more automatic processing. Importantly, this interpretation is also a network explanation.
6. The Kucian et al. (2006) results do not strictly compel a network interpretation. It is possible to interpret them from an area focus if one assumes that the dyscalculia is not a homogeneous deficit, but rather is composed of multiple subtypes; and that each subtype is associated with dysfunction of a single competency, and thus a single brain area.

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Co-construcción de una comprensión de la creatividad en la educación del drama que se basa en los conceptos neuropsicológicos.

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Antecedentes: En la neurociencias es poco probable que se produzca encuentros para la inmediata aplicación en el salón de clases. El valor educativo y las implicaciones practicas del conocimiento acerca de la mente y el cerebro, inevitablemente, requiere de un cierto nivel de interpretación, aunque los múltiples ejemplos de la no científica “basado en el cerebro” conceptos educativos sugieren que este proceso de interpretación es potencialmente problemático. Es necesaria la investigación en las formas más adecuadas de desarrollo de dichos conceptos.

Propósito: Este papel reporta en un intento para desarrollar un proceso de co-construcción de conceptos pedagógicos, enriquecidos por los conocimientos acerca del cerebro y la mente, con un grupo de profesores en formación dirigida por un equipo con experiencia tanto en lo educativo y científico.

Ejemplo, el diseño y métodos: Un equipo de investigación compuesto por dos formadores y un psicólogo seguido una espiral de investigación-acción que incluyó a 16 profesores en formación que exploraron su propia creatividad, y la psicología y la neurociencia cognitiva de la creatividad en seminarios, debates y talleres prácticos, con la objetivo pedagógico de desarrollar su capacidad de reflexión propia.

Resultados: Los resultados se ilustran tanto los peligros y las oportunidades asociadas con el desarrollo de conceptos uniendo la neurociencia y la educación. La comprensión en los entrenados se desarrolla en las etapas que en términos generales podría describirse como encantamiento inicial, mitológico, el desencanto, un mayor énfasis en la metacognición y, por último, una probada capacidad para reflexionar sobre su propia práctica docente con una mayor sensibilidad a las cuestiones de los procesos cognitivos subyacentes.

Conclusiones: El tipo de proceso de "co-construcción" aquí presentados pueden ayudar a reducir algunos de los mitos más populares y problemáticas que surgen en el desarrollo de conceptos pedagógicos que involucran el cerebro y la mente. Se necesita más investigación para evaluar el impacto de tales conceptos sobre la práctica.

Palabras claves: creatividad; drama; cognición; neurociencia

Introducción

Una importante área de desafío para la nueva área interdisciplinaria de la neurociencia y la educación es el cultivo de ideas pedagógicas que apropiadamente combinan conocimientos educativos con conceptos acerca del cerebro y la mente. La historia ya ha demostrado como puede suceder esto en una variedad de insatisfactorias y pocas maneras no científicas. (véase Geake, en ese edición). Además de la utilidad práctica de un concepto pedagógico, la validez de cualquier base científica pretendida para su validez es también una cuestión importante, sobre todo porque muchos maestros le gustaría saber no sólo lo que funciona, pero ¿por qué y cómo? (Pickering y Howard Jones 2007). Esta comprensión de los procesos subyacentes puede también contribuir a una aplicación más eficaz y la evaluación. Sin embargo, la producción de conceptos creíbles que abarcan la neurociencia y la educación puede basarse en el desarrollo de la mejora de la comunicación y el lenguaje, y el surgimiento de un diálogo de dos vías en lugar de una transferencia de un solo sentido (Geake 2004). En el proyecto que se describe aquí, un proceso de co-construcción es perseguido por dos educadores (profesores formadores) y un psicólogo con un poco de experiencia educativa y neurocientífica. Se presenta en los esfuerzos de colaboración dentro de un contexto particular de la formación del profesorado, pero se espera que los puntos de vista sobre el proceso de co-construcción puedan ser útiles en el desarrollo de proyectos similares en otras áreas de la educación.

El contexto elegido para este estudio fue el fomento de la creatividad en la educación dramática. La complejidad potencial y la diversidad de los procesos creativos hicieron de éste un contexto un tanto desalentador para trabajarlo. Sin embargo, hay un creciente interés en la creatividad en el currículo y una sorprendente falta de orientación para los profesores en prácticas en el fomento de la creatividad, especialmente en el campo de la educación dramática. Fue esta la escasez de investigaciones en curso y la comprensión que siempre la motivación principal para el proyecto que aquí que, en términos pedagógicos, con el objetivo de desarrollar la capacidad reflexiva de los docentes en formación de teatro en lo que respecta al fomento de la creatividad, a través de una mayor conciencia de la subyacente los procesos cognitivos y neurocognitivos implicados. Este objetivo atiende a la las llamadas de aquellos que, como Chappell (2007), que también ha puesto de relieve la necesidad dentro de la formación del profesorado de un mayor énfasis en la práctica reflexiva en la enseñanza de la creatividad. Cabe señalar, sin embargo, que el equipo no tenía la intención de producir un enfoque pedagógico basado únicamente en los hallazgos científicos.

Preguntas sobre el proceso por el cual maestros y profesores en formación podrían integrar con éxito sus conocimientos y experiencias pedagógicas surgió durante el esfuerzo por lograr un ciclo más amplio de múltiples perspectivas de la actividad de la investigación implicando enfoques biológicos, sociales y experimentales para investigar la creatividad. Este papel se centra sólo en este tema del desarrollo de conceptos pedagógicos prácticos y creíbles, pero el ciclo más amplio se reproduce en la figura 1, con el fin de ilustrar los contextos más amplios de investigación en la que se llevó a cabo el estudio. Como parte del esfuerzo más amplio de investigación, los alumnos del Curso Licenciatura en Educación drama mismo como nuestros participantes presentes ya había participado con una imagen de resonancia magnética funcional (fMRI) de una estrategia destinada a fomentar la creatividad (Howard-Jones et al. 2005). (Sin embargo, ninguno de los alumnos que participan aquí había participado en el estudio de resonancia magnética funcional, o ha recibido ningún conocimiento especializado de la psicología o la neurociencia cognitiva como parte de su experiencia universitaria.) Este estudio de fMRI había centrado en "las estrategias al azar" - es decir, estratégias que requieren la incorporación de elementos en un resultado creativo que no están relacionados entre sí y / o de cualquier contexto de la breve. Según lo confirmado por el estudio, este tipo de estrategias en general, mejorar la creatividad percibida de los resultados, pero los resultados fMRI mostraron también incrementos en la actividad asociados con el esfuerzo creativo. Esto apoyo la noción que estrategias alientan el incremento en el procesamiento de un tipo asociado con la creatividad del pensamiento, en lugar de proporcionar un atajo cognitivo sin esfuerzo a la mejora de las puntuaciones. Por sugerir que ellos alientan ensayos de los procesos cognitivos que podríamos llamar creativo, los resultados apoyan la probabilidad de que sean a más largo plazo los beneficios para el alumno. Por lo tanto, este estudio de fMRI produjo un hallazgo que podría ser relevante a la práctica, pero los problemas rápidamente surgieron cuando se considera como tal conclusión debe ser enviada a los educadores. En primer lugar, cualquier conclusión acerca de la creatividad científica individuo reside en el contexto de un conjunto más amplio de los conocimientos de la psicología y la neurociencia cognitiva y debe ser entendida dentro de ese contexto. Por ejemplo, sin la referencia para relacionar los modelos cognitivos, aisladas imágenes biológicas del flujo sanguíneo en el cerebro puede ser una distracción, pero tienen poco que ofrecer a la educación (Bruer, 1997). Estaba claro que la "traducción" de la comprensión de las neurociencias al salón de clases estaría cargado de peligros de la interpretación científica y / o salida de un entendimiento a tierra educativo. Construir un puente conceptual útil que se extiende por la neurociencia y la educación que requieren la comunicación de cuestiones más amplias y conceptos, y co-construcción del conocimiento por aquellos con experiencia en ambos lados. Por lo tanto, además del objetivo pedagógico identificado anteriormente, el objetivo de investigación del proyecto era proporcionar una mejor comprensión de este proceso de co-construcción, ya que esto puede ser útil para cualquier empresa en el futuro la integración de la neurociencia y la educación.

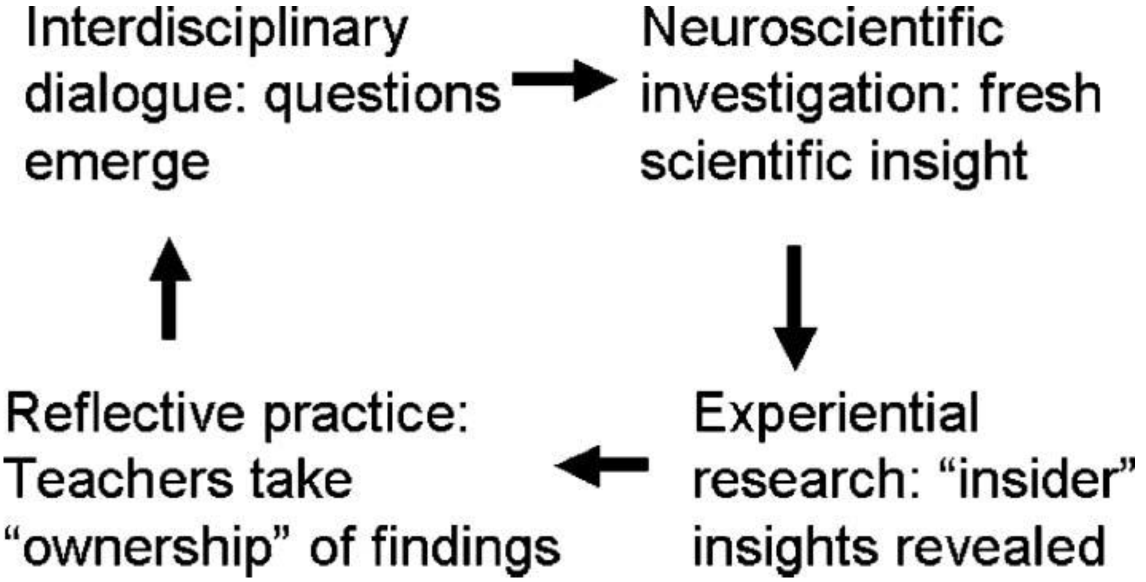

Figura 1. El trabajo reportado aquí es parte de un más amplio ciclo de actividades de investigación dirigido a incrementar el entendimiento sobre la creatividad, involucrando la experimentación y enfoques más interpretativos. El ciclo comenzó por consultar con los maestros y docentes capacitadores (superior izquierda) para ayudar a formular hipótesis que pueden ser probados usando técnicas neurocientificas así como funcional resonancia magnética (fMRI) (superior derecha). Investigaciones experimentales (inferior derecha) entonces temas examinados desde el punto de vista del (de adentro), usando talleres teatrales para explorar aspectos que investigadores científicos encuentran típicamente problemático, así como esos asociados con libre voluntad y autonomía. Finalmente (inferior izquierda), los encuentros desde ambos el “forastero”

estudios científicos y “el de adentro” investigaciones experimentales fueron llevados a delante al estudio del presente, permitiendo practicantes, con experto soporte, tomar la posesión sobre los hallazgos en terminos de su significancia educacional, usando estas y otros hallazgos para co-construir conceptos que pueden apoyar mejoradas prácticas reflexivo. Tales diálogos interdisciplinarios pueden dar crecimiento a más potenciales preguntas de investigación.

Método

El equipo de investigación consistió de dos maestros entrenadores y el investigador de neuroeducación quien dirigio el estudio original de fMRI. Los métodos usados para comunicar los conceptos y los detalles de los contendidos cubierto en las sesiones fue negociado entre miembros del equipo de investigación e informado por las respuestas de los entrenados durante el progreso del proyecto. En términos de contenido, se tomo nota sobre lo que los aprendices encontraron útil en términos de comprender sus propias experiencias y la de sus alumnos y el aprendizaje. En términos de métodos de desarrollo de comunicación, el equipo de investigación tomo nota en particular del apropiado, relevancia y valor de las ideas expresas por los aprendices durante las sesiones.

Dieciséis maestros aprendices, en el segundo año de su entrenamiento, voluntariamente tomaron parte en lo que fue anunciado como un programa corto de seminarios y talleres basados en actividades explorando conceptos sobre la creatividad. Una acción de investigación espiral (Elliot 1991) fue seguido por los investigadores (Figura 2) consistiendo en una reunión inicial del equipo de investigadores y discusión inicial con los maestros aprendices, seguido por tres ciclos de reuniones de investigación, seminarios, talleres y debate en estudiante, terminando en una reunión final del equipo para reflexionar sobre el proyecto como un todo. Talleres, seminarios, y debate de aprendices fueron grabados en video, con consentimiento informado por escrito de los participantes. Después de cada de estos eventos, un análisis de los datos de video fue usando como una base para discutir durante las subsecuentes reuniones de los equipos de investigación que delibero sobre el progreso y revisado plantes del futuro (véase figura 2). Una grabación de audio fue hecha de estas reuniones del equipo de investigación y esto fue transcrito para ayudar a rastrear las cuestiones planteadas y las decisiones que se hicieron.

Resultados y análisis

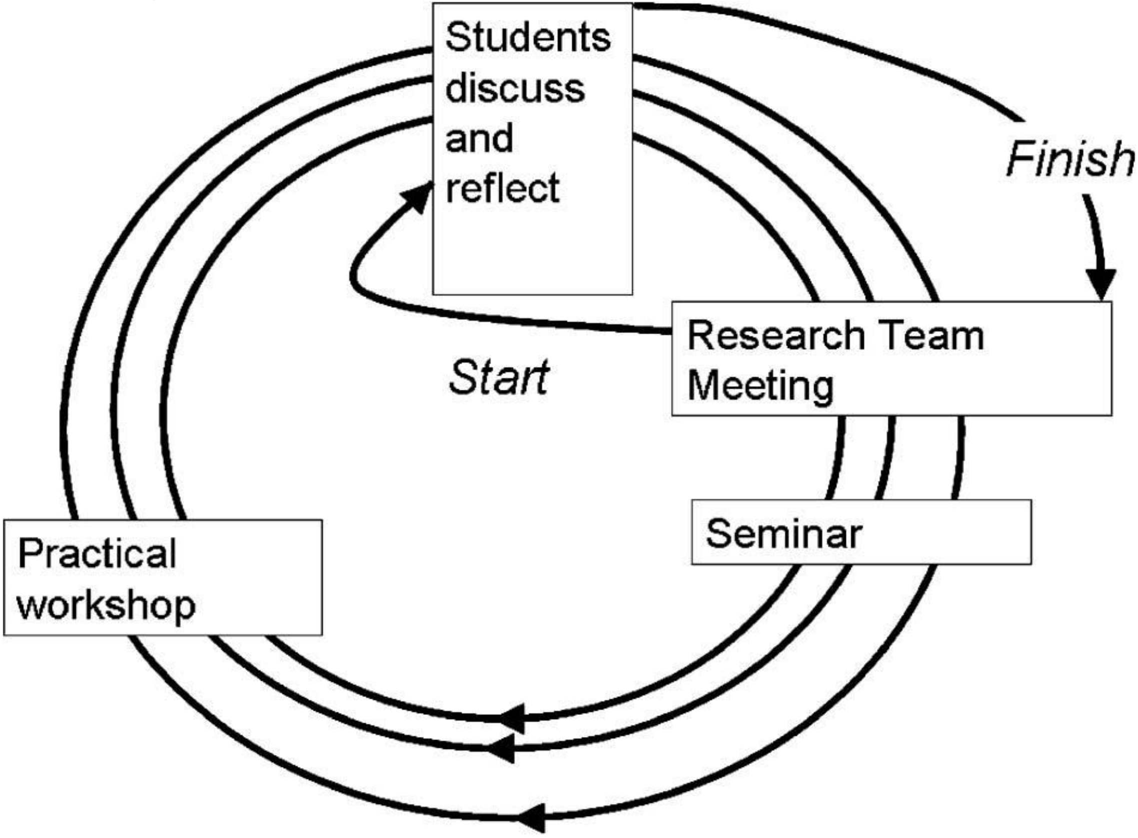

Figura 2. La acción de la investigación espiral seguido por los investigadores. Después de una reunión inicial del equipo de investigación y discusión con los participantes estudiantiles (maestros aprendices), habían tres ciclos de la reunión de investigación, seminario, talleres y debate con participantes, acabando en una reunión final del equipo de investigación para reflejar sobre el proyecto como un todo.

Resultados y análisis

El progreso para los cuales conceptos pedagógicos fueron construidos ahora son reportados sobre un orden cronológico en el cual sucedieron, comenzando con datos que surgieron desde el debate preliminar de los alumnos, seguido por cada uno de los tres ciclos de actividad, a su vez.

Discusión inicial con aprendices sobre como fomentar a la creatividad de sus alumnos
Antes de introducir los nuevo conceptos, tuvimos una discusión inicial con los aprendices proporciono algún sentido de la línea base con respecto a ideas existentes sobre creatividad. Como observado por Hayes (2004), aunque el término creatividad es frecuentemente usado, su definición directa se mantiene problemática, con intentos recientes enfatizando el rol de factores más alla del nivel del individuo, y asuntos de ética y moralidad (ejemplo, Craft 2000, 2006). En las discusiones iniciales, el equipo se baso en una simple definición de creatividad como el tipo de pensamiento imaginativo que produce un resultado que posee algún nivel de originalidad, así como algún sentido de valor (NACCCE 1999). Aprendices se sintieron cómodos con esta definición y expresaron fuertes convicciones personales sobre la importancia de la creatividad, una capacidad que enriqueció muchas partes de sus vidas y fue especialmente apreciado en la drama de la educación. Muchos han escogido ser maestros de drama porque, como

alumnos ellos mismos, ellos han descubierto que drama es su área de sujeto que abrazaba la creatividad. Aunque, la creatividad era visto generalmente como un proceso espontaneo sobre todo fuera de la influencia y simplemente se debe permitir que florezca:

Niños, simplemente, ellos sacan muchas cosas de tantos lugares, y pueden aportar todos los elementos y ellos pueden – y ahí esta tu creatividad- no lo puedes enseñar.

Aprendices generalmente hacen hincapié en una idea de "manos-libres" de la creatividad como un tipo de pensamiento que apareció en la ausencia de una enseñanza deficiente y no como resultado de la buena enseñanza. Esto era evidente en el uso frecuente de frases como "les estas permitiendo ser creativos".

Primer ciclo

El equipo se puso de acuerdo que la primera prioridad seria que se presente un simple modelo cognitivo de creatividad. El modelo usado fue originalmente desarrollado para soportar la enseñanza del diseño (Howard-Jones 2002) y describe la cognición creativa como involucra dos modos de pensar: generativo (G) y analítico (A). El modelo enfatiza la diferencia entre el proceso de pensamiento que usamos para evaluar críticamente un resultado y esos que usamos para generarlo en primer lugar, el más tarde que requiere el acceso a los conceptos que están más remotamente asociados con el asunto en cuestión. Cuando se activa en el pensamiento analítico, un individuo se espera que esté centrado y para limitar su atención sobre el análisis. Sin embargo, cuando se acceden asociados remotos, hay un beneficio de ser menos enfocada y que permite la atención a la deriva hacía conceptos que no han sido previamente asociados directamente con el problema. El pensamiento analítico también puede ser útil en otras partes en el proceso creativo, como por ejemplo cuando investigando un tema o contexto antes de generar ideas. La creatividad, entonces, puede ser caracterizada por una habilidad para mover de un modo de pensamiento al otro sin ninguna dificultad. La existencia de dos modos distintos de pensar no es una nueva, pero construye en las ideas de Ernst Kris (1952), Wudt (1896) y Werner (1948).

Después de ser introducido a este modelo de la cognición creativa, aprendices fueron presentados con la investigación ilustrando como las condiciones para apoyar el pensamiento analítico y generativo pueden ser muy diferentes. Fueron recordados como nuestras habilidades analíticas pueden a menudo ser apoyados por ser alentados a permanecer concentrados, siendo ofrecidas una recompensa monetaria por nuestro desempeño o por el leve estrés de saber que podemos ser evaluados y valorados. Habilidad generativa, por el otro lado, pueden beneficiar de otros cambios en contexto (Howard-Jones y Murray 2003), tareas que requieren asociación con divergencia semántica (Howard-Jones et al, 2005), innovaciones intrínsecas como por ejemplo la fascinación y la curiosidad (Cooper y Jayatilaka 2006) y relajación (Forgays y Forgays 1992). Producción de una singular idea creativa puede requerir alternación entre un estado analítico enfocado cuando explorando lo que es conocido sobre un tema, un estado generativo cuando encontrando asociaciones más allá del contexto del tema en sí y un regreso al estado analítico para acceder al valor de lo que ha sido generado. Sin embargo, hasta en la producción de una historia corta, más complejos trayectos entre estos dos modos de pensar pueden ser asumidos.

Para entender como la creatividad de los alumnos puede ser directamente influenciado por un maestro, aprendices fueron introducidos a “estrategias aleatorias” que requieren la realización de enlaces entre elementos elegidos con un cierto tipo de aleatoriedad. En el estudio fMRI discutido en la introducción de este papel, las correlaciones neurales de la creatividad en la tarea de narración de cuentos fueron identificados por medio de la comparación de actividad cerebral cuando aprendices trataban de ser creativos y para ser poco creativo mientras producían su historia (Howard-Jones et al. 2005). Participantes tenían que incluir diferentes conjuntos de tres palabras para cada historia. La actividad en algunas áreas asociadas con este esfuerzo creativo incremento aún más cuando las palabras fueron escogidas con cierto grado de aleatoriedad y por lo tanto no eran relacionadas una con la otra. (La creatividad de tales historias, mientras evaluados por un diferente panel de jueces, también incremento como esperado.) El jefe del área en la cual se correlaciona de esfuerzo creativo incrementado cuando se use esta estrategia era la circunvolución medial derecha- una área asociada con alto nivel de control de la conciencia, presumiblemente debido a una mayor cantidad de filtración fuera de las inapropiadas combinaciones de ideas. Así, aunque la estrategia fomento mayor generación de ideas, también puede haber requerido mayores cantidades de análisis y esfuerzo concienzudo.

En la discusión que le siguió al seminario, considerable entusiasmo fue expresado por usar lo que conocíamos sobre el cerebro y la mente para enriquecer la pedagogía. Mucho del dialogo enfocado en el estudio fMRI. El poder de imágenes cerebrales para captar el interés es bien conocido e investigación a mostrado que estimula los sentidos de evidencia objetiva “fiscalización” de conceptos de la mente (Cohn 2004). Hay peligros concomitantes en este interés tales como fomentaba nociones del estado estático del cerebro caracterizado por actividad que es restringida a pocas áreas limitadas. Sin embargo, como observado aquí, puede ayudar “concretar” conceptos psicológicos que pueden de otra manera mantenerse muy abstractos para ser tomados por personal no especializado. Aprendices fueron afiliados para encontrar analogías del mundo real con las tareas experimentales del fMRI y resonancias con sus propias experiencias. Un aprendiz reporto como ella había recientemente preguntado cada alumno de su clase que construyan una historia alrededor de cualquier dos o cuatro elementos: un mapa, un juego de llaves del carro, un zapato de ballet y una botella. Dos de estos elementos- ejemplo, el mapa y las llaves del carro- parecen ser más obvias relacionadas y ella notó el efecto en la creatividad del alumno:

La mayoría de las personas en la clase escogieron el mapa y las llaves y había justo las diferentes variaciones de choques automovilísticos y esto es más o menos lo que se les ocurrió, y la botella y el zapato de ballet- esto realmente trabajo mucho la creatividad.

Estas observaciones fueron, al principio, conductual simple porque- efecto enlaza, sin ninguna gran referencia a subyacente proceso cognitivo, un eco de algunas ideas alzaron el debate inicial. Por ejemplo, los aprendiz, de nuevo, parecían referirse a la creatividad como un proceso espontaneo, pero ahora como una requería un adecuado nivel de restricción- no tan restringido que no pueda florecer, pero requiriendo suficiente guía para proporcionar seguridad. Tales ideas han sido expresadas en estudios de creatividad en la educación de la danza, como un balance entre control y libertad (Chapell 2007). Apareció que las ideas de los aprendices sobre la creatividad se estaban haciendo más sofisticadas, como ellos sugirieron que su propia creatividad a veces dependía sobre el

correcto nivel de restricción siendo proporcionado por su tutor. Un aprendiz reflexiona sobre como ella se hubiera sentido cuando se realiza un ejercicio en particular con tal guía:
Yo lo hubiera sentido un poco abrumador, y yo creo que yo hubiera sentido la necesidad de imponer directrices sobre mi misma, pero si esta muy restringida, entonces ahoga la creatividad y tu nada más no tienes el tipo de alcance requerido para el tipo de trabajo y resultado que quieres tener.

La idea surgió que existían diferencias individuales entre los aprendices en cuanto al nivel de restricción que necesitaban, y esto no era necesariamente relacionado con la habilidad académica:

Teníamos un grupo de niñas súper inteligentes que se sentaban ahí por 40 minutos realmente reflexionando sobre esto, y uno de los niños nada más les dijo a ellas, ´er…..¿por qué no escribes el titulo "el día que me volví loca con una pala"?´, y ellas dijeron ´¡eso es!´ y empezaron escribir.

El equipo sugirió que a la mejor estas niñas había sido muy analíticas en su enfoque y se convierten en una fijación. Fijación, cuando una idea o conjunto de ideas se convierten demasiado dominantes, habían sido discutido en el seminario. Esto llevo a los aprendices a considerar como pensar en la creatividad en términos cognitivos puede poner en duda algunos aspectos de la práctica aceptada, como la fijación de objetivos e indicando los resultados en el comienzo de la lección:
Si les estas diciendo que al final de la lección ellos van estar haciendo una presentación, entonces de inmediato ellos no van a estar más en modo generativo.

A medida que los aprendices comienzan a centrarse más en la cognición de base, una expreso una realización que tal reflexión podría cambiar sus percepciones y sus estrategias.

Tan pronto como construyas una comprensión una comprensión de que como la gente trabaja, y porque trabajan así, entonces no necesariamente vez el comportamiento de alguien de la misma manera.

Un taller práctico siguió estos debates. Esto tenía por objeto proporcionar aprendices con experiencias que más adelante, con apoyo, estar vinculadas a algunos conceptos científicos de la mente y el cerebro que habían sido introducidos a. El taller incluyo un intento de identificar lo que es creativo, teniendo en cuenta lo que es percibido como poco creativo. Repetición, falta de originalidad y una tendencia hacia "lo que es obvio" fueron características que se consideraron poco creativos. Aprendices participan muy activamente en este debate, en contraste a su participación en la siguiente actividad, "Balbuceo", el cual era un ejercicio de improvisación verbal inventado por el equipo. En el "Balbuceo", los estudiantes fueron invitados a improvisar dialogo mediante la construcción gradual de sonidos tipo discurso, a través de palabras no relacionadas con fragmentos de oraciones hasta que desarrollaron una conversación. El equipo había tenido la intención que los aprendices se comprometieran con el ejercicio como una forma de juego a propósito, pero los estudiantes tomaron las señales sugeridas y evitaron debatir de ellos, aparentemente sintiéndose más cómodos con el tipo de modelo de "aprendizaje ajustado" del aprendizaje descrito por Chappell (2006). Sin embargo, la falta del éxito del equipo en la participación de este ejercicio también proporciono un tema útil para el debate posterior. Se introdujo con pocas reglas y sin ninguna actividad de calentamiento físico o imaginativo. Las partes subsecuentes del taller fueron más exitosas. “ La estatua en constante evolución” fue un ejercicio familiar de improvisación físico en los cuales aprendices fueron requeridos a crear posturas físicas en relación a las posiciones y formas de un cuerpo de otro. Esta construido de trabajo en parejas en pares de cuatro a ocho grupos. Las posturas relacionadas con desarrollo de carácter o narrativo fueron desalentados a favor de la interacción cinestésicamente imaginativa. Este ejercicio animo a aprendices establecer vínculos haciendo eco en estudio fMRI, esencialmente haciendo conexiones entre elementos dispares. Una actividad del “grupo de mutación” proporciona un movimiento equivalente a este ejercicio, y un objeto de improvisación otro tal potencial de referencia cruzada entre ciencia y experiencia.

Este taller proporciona focos común para primera reflexión sobre como las ideas surgen. El equipo de investigación noto la probable importancia in desarrollar la comprensión de los aprendices de poder identificar transiciones entre G y A modos de pensar. Por lo tanto, después del taller, los aprendices se les pidieron producir una línea grafica indicando donde había estado a lo largo del G/A de continuidad en varios puntos en el taller. Los resultados fueron muy variados pero el proceso les solicito a aprendices a comenzar a reflexionar sobre sus propios procesos cognitivos creativos:

En la última tarea, tu eras capaz de ser muy, como…un, generativo en el proceso de creación. Y luego…porque estábamos en un grupo y sabíamos que teníamos que desempeñar…teníamos que traerlo de regreso y ser, como, analítico…así que mi última línea esta subiendo y bajando. Nosotros sí regresamos y vimos lo que estamos haciendo…[risa], pero obviamente no lo suficiente!

Aprendices discutieron la facilidad con la que el pensar puede tender a lo obvio y como se siente cuando la opción obvia se hace menos disponible. Por ejemplo, aprendices comentan que los artículos que había seleccionado ellos mismos les apareció ya estar conectado, y habían comenzado a menudo hacer una historia a la vez. Cuando aprendices fueron requeridos a improvisar uniendo objetos seleccionados no relacionados por el equipo de investigación, la tarea se hizo más desafiante y difícil, posiblemente reflejando la actividad adicional frontal media observada en el estudio fMRI de divergencia semántica:

Me sentí muy limitada por el hecho de tus nos dabas objetos y el hecho de que no podíamos escoger el nuestro… Me sentí como si me hubiera topado con una pared y tenía que pensar muy bien como iba a continuar.

Los aprendices identificaron la falta de calentamiento habían contribuido al primer (balbuceo) ejercicio que iba por el mal camino, sugiriendo que ellos necesitaban una manera de despejar algunos focos no deseados del día para hacer espacio a nuevas ideas. Había una sensación de que todo el mundo había sido demasiado dispuesto a centrarse a la menor sugerencia de un contexto-una parte-y están determinadas en el mismo. Los aprendices que entonces se emocionaron por la importancia de la relajación y el estado generativo, y también discutieron como planeando las acciones de uno puede a veces disminuir ideas la generación de ideas. Esto dio lugar a la idea de que la planificación, en la que presentan las etapas por las cuales uno podrá conseguir su objetivo, puede alentar una mentalidad en particular que desalienta la generación de nuevas orientaciones e ideas. Los aprendices parecían cómodos clasificando tareas como ser creativo o no creativo y parecía no considerar a si apoyaban el tipo de pensamiento que se requería en un contexto en particular. Por ejemplo, un aprendiz había comenzado a creer que planear siempre disminuía la creatividad y la inclusión de aleatoriedad siempre lo incrementaba.

Ahora lo tengo en mi cabeza que para ser poco creativo planeas y esas cosas- por lo que ahora creo que la última improvisación que hicimos fue completamente sin creatividad porque lo planeé! Porque lo discutimos como grupo y no sé, ahora, estoy muy confundido….creo que la última tarea fue más aleatoria…nos diste un montón aleatoriedad.

El equipo dio ejemplos de cómo diferentes niveles de planeación pueden ser buenos o malos para la creatividad dependiendo de los aspectos de la situación tales como los individuos involucrados y los tipos de cognición que uno puede desear ser alentados a una etapa en particular en un proceso creativo. La parte generativa de la creatividad había sido enfocada a la discusión pero el equipo había sentido que era importante recordarles que el análisis también era necesario. El proceso creativo, como descrito por Wallas (1926), fue presentado como un cambio de analítico a generativo y de regreso a analítico.

Segundo Ciclo

Había una clara tendencia emergiendo para los aprendices para hacer atajos de estrategias a resultados sin consideración subyacente de procesos cognitivos y el contexto. Necesitábamos disminuir la tentación de clasificar estrategias como creativas y poco creativas, y alentar a los aprendices a pensar más sobre la adecuación de las estrategias en términos del proceso cognitivo y si, en términos de contexto, esto puede ser de ayuda en el proceso hacia objetivos creativos. Era claro que algunos estudiantes sentían intimidados por esta tarea. El equipo identifico la naturaleza abstracta de los conceptos cognitivos involucrados como un potencial desafío para algunos. Queríamos hacer el modelo cognitivo de la creatividad que habíamos estado refiriendo a algo más concreto para los aprendices. Los aprendices habían sido notablemente fascinados por un caso de estudio neurocientifico mencionado previamente por el equipo, por lo que se decidió detallar dos tales estudios en el siguiente seminario para ilustrar ejemplos extremos de los dos modos de pensar. Esto se considero apropiado en el contexto de maestros enseñantes, pero el uso de tales casos de estudios con niños claramente aumentaría algunos temas de ética. El equipo sentía que las discusiones en clase sobre desordenes de la mente pueden fácilmente llevar a conceptos erróneos que pueden des estresar/ confundir algunos alumnos, si los profesores que conducen la discusión no estaban versados en la necesaria experiencia.

En el siguiente seminario, los aprendices fueron introducidos a una parte del cerebro llamado la corteza cingulado- una isla de la corteza debajo de la superficie externa del cerebro. La parte frontal (anterior) de esta región comparte un función controladora con los lóbulos frontales y esta asociado con la atención ejecutiva-el mecanismo cognitivo por el cual controlamos el enfoque de nuestra atención (Gehring y Knight 2000). La hiperactividad en esta área ha sido asociado con el trastorno obsesivo compulsivo (TOC) y la asociada preocupación de sufridores con corrección de errores de percepción (Fitzgerald et al. 2005). Los aprendices fueron jugados una entrevista con persona que sufre del TOC, que describieron sus rutinas respectivas rituales. Fue discutido como este tipo de ensayo tenia parecía al proceso de ensayo analítico y evaluativo usado para afilar un pedazo de trabajo creativo, pero llevado a un extremo obsesivo y muy poco creativo. Era como si las personas que sufren de TOC están atrapadas en un modo analítico de pensamiento. En contraste, el equipo entonces presente el caso de creatividad compulsiva (Lythgoe et al. 2005). A los aprendices se les dijo que Tommy era un constructor de 51 años de edad con ningún interés previo en las artes, quién sufría una hemorragia subaracnoidea- un sangrado de el espacio alrededor de enfrente del cerebro- resultando en una disfunción frontal. En las semanas seguidas de su lesión, Tommy se volvió un artista prolífico. Primero comenzó a llenar cuadernos con poesía, luego empezó a esbozar y en los siguientes meses produjo dibujos en gran escala en las paredes de su casa, a veces llenando recamaras enteras. Su arte continua hasta este día y se ha convertido más desarrollada. Tommy no puede parar de generar más material, la mayoría de las veces durmiendo nada más 2-3 horas por noche entre días llenados de escultura y la pintura. El muestra desinhibición verbal, aunque la creatividad, mediante el constante hablar en pareados de rima y hay algunas señales de función impar ejecutiva. Los aprendices discutieron como Tommy parece ser atrapado en el modo generativo de pensamiento. Los aprendices escucharon una entrevista con Tommy quien explico como era su mundo y ellos leyeron un poema, “Explorador del Cerebro-es para ti”, que él había escrito para el autor de su caso de estudio. El equipo esperaba que escuchando las voces de esos que sufrían de estados mentales muy generativos o analíticos les ayudaría a caracterizar estos modos de pensar con mayor claridad para los aprendices y los apoyaba en monitorear sus propios modos de pensar.

En los ejercicios improvisados que siguieron, aprendices fueron ocasionalmente interrumpidos y se les pedía que alzaran sus cartas G o A para indicar sus modos actuales de pensar. Los primeros dos ejercicios eran “hablar por un minuto”, en la cual tenían que hablar sin pausa ni vacilación en un tema escogidos para ellos. Esto fue seguido por un “atraso de copeado” ejercicio en el cual los estudiantes tenían que continuamente producir no el movimiento que apenas se había hecho el líder, sino el movimiento anterior a este. Los aprendices casi siempre alzaron la carta generativa cuando interrumpido durante el primer ejercicio y la carta analítica durante la segunda. Cuando hablaban por un minuto, los aprendices generaron ideas con poco tiempo para reflexionar y rechazar elementos insatisfactorios. Cuando copeaban movimientos, los aprendices se enfocaban en muy específicas rutinas, analizaban lo que veían y ensayaban mentalmente antes de reproducirlo. Una tarea más compleja siguió, llamada “historia en lo redondo”, en el cual aprendices se sientan en un círculo y cuando se les pida, tienen que continuar la historia que su vecino había estado contando. Esto produjo una difusión de As y Gs, lo cual los aprendices explicaron en términos de diferencias individuales en el enfoque, pero también de acuerdo a donde su propio proceso creativo estaban cuando se les pedía reportar. Los aprendices a menudo alzaban un “G” cuando generaban ligas entre sus ideas y la historia que su vecino estaba contando, o producían una “A” cuando evaluaban historias posibles o aquellos que estaban escuchando. “Improvisación de etiqueta” en la cual aprendices tienen que intervenir en improvisación y hacerse cargo de otro intérprete, también proporcionar un ejemplo de esta complejidad.

A los aprendices luego se les pidió producir un pedazo de movimiento usando las texturas y sonidos que se habían encontrado durante un viaje imaginario hacia un mágico armario. Investigadores observaron e interrumpieron cuando identificaron puntos de transición, preguntando si los aprendices estaban consientes que una transición había ocurrido y si podían explicar porque había ocurrido. Aunque algunos aprendices no estaban inicialmente inconscientes que incluso estaban ocurriendo las transiciones, empezaron rápidamente reconociéndolos. Muchas veces escogían explicarlos en términos de una necesidad de mover desde un modo de pensar de lo otro. Transiciones a ensayos fueron muchas veces justificados in términos de una necesidad para evaluar y afilar lo había sido generado y así cualquier intento por correr a través del trabajo en proceso era usualmente visto como un regreso a un modo de pensamiento más analítico. Esto fue un especie de punto de inflexión en el proyecto, y la discusión subsecuente desarrollo una nueva riqueza y profundidad en cuanto del pensar de los aprendices sobre sus experiencias en el taller propiamente dicho y también su enseñanza.

Aprendices comenzaron hablar en términos de reflexivos y a menudo emocionales sobre la generación y análisis de material. Procesos Generativos fueron descrito por tanto términos positivos como negativos, que altamente placentera pero también ligeramente aterrador. Un aprendiz también describió como el ensayo analítico, como en el TOC, puede llegar a ser una respuesta de ansiedad inútil- es decir, el temor de tener que generar ideas:

Cuando estoy creando trabajo siento que tengo que seguir regresando, y como tu dijiste: "¿qué pasaría si no regresaba?" no lo sé, pero eso es lo que tengo miedo de encontrar, yo no podría seguir nada más creando.

El proceso generativo fue descrito como "asustadizo", "como un vacío" pero también como una delicia, con el taller recordándoles a los aprendices cuanto ellos disfrutan siendo generativos. De nuevo, la naturaleza espontanea de la creatividad que ha sido mencionado en las anteriores sesiones surgió, pero esta vez espontaneidad fue asignado a una particularidad parte de la creatividad: la habilidad de generar. Los aprendices habían observado como niños jóvenes pueden ser altamente generativos en su pensar, aunque a menudo menos desarrollan en su habilidad para críticamente ensayar sus ideas. Adultos, por otro lado, a menudo lo encuentran difícil de mantener tales fortalezas de generación de ideas, necesitando entonces hacer una pausa, analizar y refinar el significado:

Cuando nos dijiste que habláramos por un minuto, yo pienso que el poema [por Tommy] es lo que nosotros encontramos tan duro de hacer. Como en el poema donde no hay ligas, tu nos dijiste no te preocupes sobre las ligas, pero automáticamente todo el mundo trato de hacer una historia incluso cuando nos dijiste que no teníamos que hacerlo.

Conciencia metacognitiva, en la medida de regular así como también monitorear el proceso cognitivo, se hizo evidente.

Comencé siendo analítico, pesando: "¿Qué esperan que saque de esto? ¿Qué es lo que supuestamente debo de hacer con esta visualización?" Y luego nada más pensé, "No, deja de hacer eso, déjalo, déjalo ir, y solo me hice apagar eso".

Interjección por el equipo de investigación durante momentos salientes de transición no solamente levanto conciencia, pero también apareció alentar regulación propia:

Yo sabía que estaba tratando de cambiarlo, y sabía que tu te ibas a ir, "¿Por qué?...pero luego me iría, "Oh, estoy siendo demasiado analítico, vamos a nada más cambiarlo, vamos a algo más diferente y no seguir golpeando nuestras cabezas contra esta pared de ladrillo".

Tercer Ciclo

En la siguiente junta de investigación, el equipo selecciono dos pedazos de secuencias de talleres previos que serian adecuados para analizar con los aprendices en el siguiente seminario. En este seminario final, el equipo primero enseño secuencias del fallido ejercicio de "balbuceo" del primer taller, y algunos extractos de la discusión con los aprendices que lo había seguido. En reflexión sobre los resultados del ejercicio, aprendices se vieron a ellos mismos improvisando en la película y después discutieron la considerable repetición dentro y entre los individuos y las ocurrencias regulares de bloqueo durante el dialogo improvisado y una tendencia hacia fijación en las señales del equipo, y notaron los sentimientos de incomodidad y obligación que habían sido discutido después. En el entendimiento de porque el ejercicio no había sido exitoso en la generación de ideas, la discusión se centro en los sentimientos de ansiedad sobre no saber que es requerido y la falta de ejercicios de relajación. Adicional, las siguientes tareas habían sido muy analíticas en su meta, incluyendo análisis en el termino poco creativo y escribiendo una historia "poco creativa" de los cuales la mayoría de los estudiantes lo logran por el auto imposición de limites restringidos y el uso de repetición frecuente. Esto pudo haber impactado en tendencias generativas en el ejercicio subsecuente, el tipo de transferencia que ha sido observado en otra parte (por ejemplo, Howard-Jones, Taylor, y Sutton 2002). Fue discutido si ver a un miembro de equipo sacar adelante la primera tarea hubiera ayudado. Esto dio lugar a una discusión sobre neuronas espejo, lo cual fue especulado, puede proporcionar una base a la encarnación de cognición y hasta la inconsciente comunicación de estados mentales (Rizzolatti et al. 2002).

Opciones fueron consideradas con respecto a que pudo haberse hecho después de la falla en este ejercicio. A los aprendices se les pidió: "¿Deberíamos haber parado y evaluado lo que había salido mal?" ¿Deberíamos haber entrado a unos ejercicios de relajación?" "¿Deberíamos haber entrado nada más al siguiente ejercicio?" Se acordó que un ejercicio evaluativo probablemente hubiera atrincherado más a todos en un modo analítico de pensar. Retomando los efectos de relajación en asociación libre (Forgays y Forgays 1992), ahí apareció un claro caso para ejercicios de relajación. Continuando directamente al siguiente ejercicio (que es lo que actualmente paso) era el más incierto curso, el cual como resulto, funciono bien. A los aprendices entonces se les pidió considerar porque puede ser que este ejercicio subsecuente (objeto de improvisación) si funciono mejor. Tres temas emergieron desde la discusión. El primero, fue un ejercicio familiar y los aprendices inmediatamente se sintieron más relajados. El segundo, la tarea requirió hacer ligas entre los objetos que los aprendices no habían seleccionado por ellos mismos. El tercero, los aprendices sintieron que tenían tiempo dentro del ejercicio para producir ideas en el cual, como discutido arriba, puede ser necesario para seleccionar las ligas apropiadas entre elementos que son dispar. Por tanto, a los aprendices se les pregunto: "si esta fuera tu clase y encontraras que un grupo se quedaba enfocado en el breve, haciendo muchas preguntas, sobre límites y sin poder generar ideas más allá de lo obvio, ¿qué harías?" Alternativamente: "si otro grupo se apresuraba directo a la improvisación y estuvieran generando muchas ideas incoherentes que no se estaban desarrollando apropiadamente, ¿qué harías? De esta manera, a los aprendices se les alentó a comenzar a pensar sobre sus efectos, como maestros, en el proceso de creatividad cognitivo de sus alumnos.

Después de esta sesión de análisis, los aprendices estaban en “silla-caliente” sobre las reflexiones en sus propias practicas. Voluntarios tomaron turno en sentarse enfrente del grupo y recordaban instancias especificas en su propia practica para discusión y análisis por el grupo, el cual es ahora a menudo incluye referencias para el modo de pensamiento de sus alumnos. Por ejemplo, fue discutido que cuestiones sobre procedimientos y procesos a menudo reflejaban una adhesión insegura para los procesos de análisis, y como la confianza para crear era a menudo acompañado por una disminución en el cuestionamiento del maestro. Grupos de habilidad baja a menudo sufrían de esta falta de confianza, y otro aprendiz llamo la atención sobre la respuesta de un profesor a un cuestionamiento también se puede utilizar para orientar los modos de pensar de los alumnos. Este aprendiz describió como ella uso “profesor en papel” y luego llevaron a interpretaciones de los alumnos. Preguntas de la clase sobre si su idea era correcta fueron desviados por la respuesta “es lo que quieras que pienses que sea”, dejando el campo abierto para otros alumnos mientras legitimando todas las sugerencias como válidas ideas autogeneradoras. Al principio fue niños ruidosos quienes le estaban cuestionando por la respuesta correcta, pero luego cuando fue claro que ninguna existía, los niños más callados dieron a conocer sus ideas. El uso del “profesor en papel” llevo a muchos otro relatos de cómo los alumnos pueden ser dirigidos hacia un estado en particular de la mente a través de la imitación, de nuevo produciendo referencias al concepto de las neuronas espejo. Por ejemplo:

Llegaron al punto en la cual, tu sabes, que no habían conseguido mucho y lo que habían conseguido era muy limitado y era muy cliché…no eran capaz de generar ideas… [pero] trabajaron mucho mejor cuando le mostramos que estábamos dispuestos a generar ideas también.

Había un sentido en el cual actuar y generar enfrente de los niños comunico ambos tipos de procesos mentales y su legitimidad:

No lo puedo hacer mal si hago lo que ella ha hecho…entonces esta bien, puedo tomar parte en esto ahora…puedo permitirme a mi misma ser generativa, aunque la gente me ha dicho que he estado mal anteriormente, esto no puede estar equivocado ahora.

Aprendices hablaron de que había transiciones dentro de la lesión, describiendo algunas lesiones así como “como un sándwich” de los modos de pensamiento. También discutieron como las transiciones entre modos de pensar dominantes pueden algunas veces ser servicialmente posicionados en el límite entre las lesiones. Aprendices también se refirieron a algunas instancias cuando cambiaban de contexto y suspendiendo evaluación habían sido un éxito en disipar conjuntos de mentes fijas. Trabajando con otros también era visto como una manera valiosa para alentar a los niños para hacer enlaces, incluyendo esos enlaces entre sus propias interpretaciones y otras ideas:

Pero también trabajando con otras personas y viendo lo que hacen y tomando tu propia interpretación de lo que ellos hacen- porque ellos no explican lo que están haciendo y lo que están diciendo- que, en regreso, te ayuda a generar ideas… como con los exámenes de Rorschach con las tintas splots- ¿qué crees que ves?- toma tu propia *interpretación y eso te ayuda a crear tus propios enlaces mentales, los cuales te ponen aún más en un proceso generativo.*

A la mejor como era de esperar, aunque el equipo había estado en dolor para apuntar que esta no era el caso, ahí se mantuvo una tendencia natural para algunos aprendices para asumir un simple mapeo anatómico-funcional del proceso cognitivo, incluyendo a esos asociados con modos de pensar generativos y analíticos:

Tu estas usando casi dos diferentes partes del cerebro ahí para hacerlo, así que separándolos interrogativamente ahora y analíticamente a un diferente tiempo…por lo que tratar de cambiar.

Finalmente, los maestros aprendices, y sus entrenadores se les pregunto ¿Qué habían obtenido de esta experiencia de reflexionar sobre su práctica en términos de conceptos psicológicos y neuropsicológicos? Primero había un sentido de tener un mejor entendimiento teórico que apoyaba la práctica existente, especialmente en el papel de "calentamientos". En segundo, los aprendices expresaron un sentido de ser más poderosa para intervenir y apoyar la creatividad de proceso cognitivo de los niños:

Para cuando tu vas a un salón de clases, tu puedas identificar los diferentes estados, tu sabes, que ahora tu puedes manipular o cambiarlo, y cual es el punto de ese cambio. Tú como maestro puedes cambiar la manera de pensar y hacer una más productiva ambiente de aprendizaje para tus alumnos.

Aprendices se refirieron a un número de temas influenciando la creatividad y se sintieron proporcionados con ideas en sus propias prácticas, y sobre todo parecía un nuevo sentido de responsabilidad para fomentar habilidades que ellos inicialmente habían considerado como completamente espontaneo y no susceptibles a la intervención del docente:

No todos los niños/alumnos/adultos los encuentran tan fácil ser creativos, entonces cuando vas a la escuela, no puedes esperar que ellos nada más improvisen, nada más porque nosotros lo podemos hacer. Esta en nosotros como maestros, entonces, diferenciar.

Temas sobre la dificultad en combinar el lenguaje y las perspectivas de ciencia natural con pensamiento educacional se mantuvo silencioso hasta esta discusión final, como algunos aprendices se les dificulto encontrar los términos apropiados para la cual expresar sus pensamientos:

Aprendiz: Creo que es despertador (1) mi curiosidad, y (2) algunos revelaciones previas sobre el ambiente y los efectos que tiene en las personas, y de lo que son capaces de hacer y como-y esta es la única manera que puede pensar de cómo decirlo, como puede psicológicamente manipular [risa]-¡a la mejor hay una mejor manera de decirlo!

Otra [sugiriendo]: "…afecta el cambio"

Aprendiz: Esa es la única… [Risa], pero puedes ver a e influir el ambiente y [así] la manera de pensar de las personas, y como cambiar eso y sacar lo mejor de las personas haciendo eso.

En conclusión

En conjunto, durante esta corta intervención, los maestros aprendices mostraron un progreso en su atención para, y entendimiento de, creatividad cognitiva en el salón de clases. Este progreso paso a través de las etapas que incluyeron:

(1) Un alto inicio de un grado de entusiasmo.
(2) Un floreciente de comportamiento inicial y neuromitos convenientemente prescriptivos.
(3) Una realización desalentadora que las cosas eran más complejas y requerían atención a la cognición.
(4) Incremento en la meta-cognición, con la neurociencia ayudando a “biologise”, y “concretar” y conceptos profundos.
(5) Conceptos emergentes, lenguaje y capacidad reflectora que permite una reflexión profunda, sensible e ideas alrededor de prácticas personales en contextos específicos, en términos de mente y cerebro.

El esfuerzo de aprendices por entender sus propias experiencias de aprendizaje/creatividad en términos subyacentes del proceso cognitivo parecía un importante paso en el desarrollo relacionado con las ideas dentro de sus practicas docentes. Aprendices buscaron aplicar su nuevo entendimiento en una variedad de áreas, incluyendo efectos ambientales y temas alrededor de la planificación de actividades tales como la secuencia de eventos y proporcionando para individuales diferencias. fMRI y otras investigaciones involucrando imagen puede ser muy efectivo en la participación no especialista con el pensamiento sobre la mente y el cerebro aunque, con este poder de participar, también surgió peligros consiguientes de mitos alentadores como la frenología simplista. También se encontró que casos de estudios neurocientíficos tenían el papel de ayudar a maestros aprendices a entender la mente y el cerebro, aunque su apropiado como una herramienta más general de enseñanza en el área de educación puede necesitar más profunda consideración ética.

Aquí habíamos reportado un estudio exploratorio se enfoco en el proceso por el cual conceptos pedagógicos pueden ser co-construidos a través de la neurociencia y la educación. No hemos reportado ningún detalle en los conceptos desarrollados (véase Howard-Jones 2008) y estos no habían sido formalmente evaluados. Si tales ideas son, como habíamos esperado, un mejoramiento en los muchos “cerebro-basados” ideas de aprendizaje presentemente siendo marcados, muchos temas todavía tendrían que ser considerados para determinar su valor, dos de las cuales merecen ser mencionados aquí. El primero, conocimiento científico del cerebro y la mente siempre serán ideas parciales y pedagógicas que dibujaron en tales conocimientos siempre requerirá continua actualización y mejoramiento. Por ejemplo, a los aprendices se les alentó usar los encuentros de las investigaciones para ganar ideas reflexivas en el comportamiento creativas de los alumnos. Pero, los estudios fMRI de “normal” función cognitiva presentado a los aprendices fue llevado acabo con los adultos, mientras que el proceso cognitivo y neural de los niños puede diferenciar significativamente de los de adultos. Como la investigación sobre la mente y el cerebro progresan, estas diferencias inevitablemente necesitaran ser considerados en términos de sus implicaciones pedagógicas. Relacionados con tales consideraciones, aprendices juzgaron el entendimiento que habían ganado para ser útil y aparecía mejorar la habilidad para reflejarlo en su practica, pero su valor en términos de mejorar la practica todavía requiere de más investigación. Tentativamente sugerimos que los conceptos desarrollados a partir de un proyecto como el nuestro puede aportar una contribución útil y estimulante para las investigaciones sistemáticas de docentes en su propia práctica. Tales investigaciones, las cuales ayudan a docentes desarrollarse como aprendices reflexivos, son consideradas en ellos a ser un importante ingrediente de enseñanza y aprendizaje efectivo (Hofkins 2007).

En nuestro proyecto, ideas sobre la mente y el cerebro exitosamente destaco un mensaje general sobre como la creatividad involucra un modo generativo de pensar que es esencialmente diferente al modo predominante analítico en la educación de las escuelas. Por otro lado, como se les enseño a los aprendices, es claro que la creatividad individual siempre será un viaje cuyo destino se desconoce. Cada viaje creativo es una experiencia única, así como todo cerebro es único en términos de su estructura y funcionamiento. Por estas razones en si, neurociencias no puede completamente explicar o desmitificar la creatividad cognitiva y la experiencia. Aunque, usando un proceso de co-construcción que atiende a perspectivas educacionales y científicas puede producir nuevas maneras de pensar y hablar sobre la creatividad y, de esta manera, nos ayuda a reflexionar sobre las decisiones del diario que hacemos como educadores cuando fomentamos la creatividad en nuestros estudiantes.

Reconocimiento

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