



**HAL**  
open science

## Neuroscience, Technology and Learning: Areas and Issues for Interdisciplinary Progress

Paul Howard-jones, Michela Ott, Theo van Leeuwen, Bert de Smedt

► **To cite this version:**

Paul Howard-jones, Michela Ott, Theo van Leeuwen, Bert de Smedt. Neuroscience, Technology and Learning: Areas and Issues for Interdisciplinary Progress. 2011. hal-00722961

**HAL Id: hal-00722961**

**<https://telearn.archives-ouvertes.fr/hal-00722961>**

Submitted on 6 Aug 2012

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**The 2nd STELLARnet Alpine Rendez-Vous in the French Alps, 27th to 31st March 2011**

White Paper arising from the workshop on:

**Neuroscience, Technology and Learning: Areas and Issues for Interdisciplinary Progress**

**Paul Howard-Jones** (University of Bristol, UK)

**Michela Ott** (CNR- National Research Council, Italy)

**Theo van Leeuwen** (Twente University, Netherlands)

**Bert de Smedt** (Katholieke Universiteit Leuven, Belgium)

## 1. Introduction and motivation

This workshop was originally proposed by the STELLAR theme team NTEL (Neuroscience and Technology Enhanced Education). The NTEL theme team comprised Paul Howard-Jones (University of Bristol, coordinating), Bert de Smedt (Katholieke Universiteit Leuven, Belgium), Michela Ott (CNR National Research Council, Italy) and Theo van Leeuwen (Twente University, Netherlands). From May 2010 to May 2011, NTEL was funded by STELLAR to explore the issues and opportunities that may be generated by combining what we know about the brain with the affordances of modern learning technology.

This workshop aimed to bring together TEL researchers and specialists in neuroscience to:

- To identify areas of understanding where technology enhanced learning may benefit from neuroscience and
- To discuss how interdisciplinary research capacity in this area can be developed.

The workshop was by invitation-only, with priority given to active researchers in the TEL field who expressed interest in using findings from neuroscience to inform their research. Additionally, workshop attendance was appropriately balanced to provide sufficient expert opinion from neuroscience, psychology and education.

### *Programme:*

#### Monday March 28th

- 8.30 - 9.00 Introduction to the workshop and from participants
- 10.30 -11.00 Coffee
- 10.30 -11.15 Key note presentation (Dan Schwartz)
- 11.15 -12.15 Converging Areas I: Presentations by NTEL team
- 12.30 - 1.30 Lunch
- 13.30 - 16.30 *Snow activities*
- 16.30 – 18.00 Converging Areas II: Circulation/discussion of participants' research questions  
Small group discussion on  
Question 1: "Where will neuroscience meet TEL research?"
- 18.00–18.30 Coffee Break
- 18.30–19.15 Small group discussion on:  
Question 2: "What are the barriers to progress?"
- 19.15- 20.00 Discussion groups report back on each question  
Plenary Discussion

#### Tuesday March 29th

- 8.30 - 9.00 Summing up some of the issues/barriers etc
- 9.00 -10.30 Presentations by NTEL team on a "Levels of Analysis" approach
- 10.30 -11.00 Coffee break
- 11.00 -12.15 Small group discussion on:  
Q3: "How can we develop interdisciplinary research capacity in this area?"  
Discussion groups report back on question; Plenary Discussion
- 12.30 - 1.30 Lunch
- 13.30 - 15.30 *Snow activities*
- 15.30 - 16.00 Theme Team sum up some key opportunities identified

16.00 - 17.00 Where do we from here?

Mutual interests, common goals, collaboration between participants

**2. Workshop Description**

As can be seen from the programme above, the structure of workshop avoided an emphasis on individual presentation, in order to maximise opportunities for interdisciplinary dialogue between members of the diverse communities of neuroscience and TEL. In order to support discussion, a detailed 10,000 word review was circulated 3 weeks prior to the meeting that had been prepared by the NTEL theme team. This review reported on recent neuroscience findings that might be considered relevant to research within TEL. This document, together with additional reviews by members of the NTEL theme team on literacy and numeracy, was also posted on the NTEL web-site ([www.neuro-tel.net](http://www.neuro-tel.net)). Additionally, a presentation was provided by Prof Dan Schwartz on his personal U.S. perspective on possibilities in this emergent area, and 2 individual presentations were provided by Paul Howard-Jones (University of Bristol) and Theo van Leeuwen (Twente University, Netherlands) that summarised the discussion document and allowed for clarification of its concepts.

In this way, the workshop was able to focus on generating a set of key issues to overcome, and a set of opportunities for progress that took the form of new grand challenges for STELLAR.

Participants were:

Dan Schwartz	Stanford, US
Anja Ischebeck	University of Graz, Austria
Tamara van Gog	Erasmus University of Rotterdam, Netherlands
Elisabeth Friedrich	University of Graz, Austria
Niklas Ravaja	Helsinki University, Finland
Theo van Leeuwen	Twente University, Netherlands
Di Levine	BECTA, UK
Carlo Perrotta	Futurelab, UK
Riccardo Berta	University of Genoa, Italy
Tony Fisher	University of Nottingham, UK
Diana Laurillard	London Knowledge Lab, UK
Paul Howard-Jones	Bristol University, UK
Michela Ott	CNR- National Research Council, Italy
Frank Fischer	LMU Munich, Germany
Charles Fadel	CISCO, U.S.
Pierre Dillenbourg	EPFL, Switzerland

*Examples of where the workshop identified neuroscience with relevance to TEL*

Neuroscience is shedding light on a range of developmental disorders and neuroscientists themselves have already been actively involved in developing technology-based educational interventions that seek to apply some of this emerging knowledge. Technology may help provide adaptive training for a range of disorders. Butterworth and Laurillard have highlighted several attractions of applying our emerging knowledge of dyscalculia in educational digital technology<sup>1</sup>. They point out that digital implementation can be practice-oriented (providing easily-accessed and unsupervised repeated practice), can be age-independent, needs-oriented (e.g. providing alternative

input/output modes for learner also suffering from slight dyspraxia or reading difficulties), meaningful (e.g. they can link the physical to the abstract in ways not possible in the physical world, such as when a learner 'zooms into' a 1–10 number line to discover decimal numbers) and they can offer private, unthreatening interaction and feedback in an endlessly patient fashion. These potential advantages of integrating our scientific understanding with technology are relevant in attempts to remediate a broader range of developmental disorders. Although claims about the general effectiveness of commercial programmes must be carefully scrutinised<sup>2</sup>, neuroimaging can also provide insights in cases where successful results are reported. For example, a dyslexia intervention using commercially available language training software reported partial remediation and improved reading, with ameliorated disrupted function in brain regions associated with phonological processing and additional compensatory activation in other regions<sup>3</sup>. When the cognitive and neural data converges in this way, we can be more confident in the underlying theoretical models and the effectiveness of the intervention.

Historically, neuroscientists have focused more upon abnormal than normal development and this helps explain why the first examples of neuroscience in TEL have been aimed at ameliorating developmental disorders. However, understanding from neuroscience has increasingly wider implications for TEL, with relevance to a range of mainstream TEL concepts. Although a preference for a particular learning style does not appear helpful in educational terms, we have seen (in Box 3) how some types of digital **personalization** can influence emotional engagement. Neuroscientific techniques may also provide insights into **individual differences** on a range of factors that can inform how technology might be tailored to suit particular types of learner. These factors may include ability, but also gender and age. One study has highlighted gender differences in how individuals respond to video games<sup>4</sup>, which have been cited as an informative and engaging context that educators may wish to understand learn from<sup>5</sup>. In another example, the type of feedback which is optimal for our brain to learn appears dependent upon our maturity. Here, in a study of a computer-based rule search and application task, brain imaging data suggested a qualitative difference in how children and adults use performance feedback, with a transition around 11-13 years old towards an increased influence of negative feedback on performance adjustment<sup>6</sup>. Understanding how our ability to self-regulate develops through to adulthood may also provide insights and reasonable expectations (rather than constraints) about the **self-regulated learning** of children at different ages. Recent research shows how a range of factors that are critical to successful self-regulated learning (processing speed, voluntary response suppression, and working memory) mature across different age groups<sup>7</sup>, and this development is linked to an understanding of structural changes that occur in the brain until early adulthood<sup>8</sup>.

However, perhaps of greater value is the ability of technology to adapt dynamically to the changing needs of the learner, based on an automatic assessment of their responses. Indeed, the potential of combining TEL and neuroscience in **adaptive educational systems** has been highlighted in the UK as an area of research deserving future investment. An example of where scientific research has been integrated with an adaptive educational system is "Graphogame" - a non-commercial system developed at the University of Jyväskylä (Finland) which introduces the association of graphemes and phonemes to young children according to the frequency and consistency of a grapheme in a given language<sup>9</sup>. In this game, online algorithms analyze a child's performance and rewrite the lesson plans "on the fly" depending on which specific confusions the learner shows<sup>10</sup>. The difficulty of the content is also adjusted so that the challenge matches the learner's ability. Using fMRI and EEG together (allowing both good spatial and temporal resolution in measurements), it has been shown that the practise with the game could initiate print-sensitive activation in a critical component of the mature reading network located in the left occipitotemporal cortex, termed the "visual word-form system"<sup>11</sup>. Knowing that this occipito-temporal print sensitivity is established during the earliest phase of reading acquisition in childhood, suggests that a crucial part of the later reading network

first adopts a role in mapping print and sound. Such results provide insight into how the software succeeds in supporting literacy, how/when it should be implemented and how neuroscience can be used to inform TEL design. McCandliss<sup>10</sup>, reflecting on this and other studies, suggests “Given that adaptive educational computer programs are being developed in tandem with imaging studies of how such innovations drive changes in brain activity, new possibilities may emerge for educational and neuroscience research efforts to inform one another in increasingly rapid cycles.”

It has been known for some time that illustrating text can enhance memory<sup>12</sup>, with pictures of objects appearing more memorable than their names. This effect has provided an important justification for the type of **multimodality** that can be provided by technology. Such approaches might be further informed by evidence that additional brain activity is produced by multimodal stimulus over and above that produced by experiencing each mode separately<sup>13</sup>. In this study, participants were scanned while exposed to auditory and visual characteristics of tools (hair-dryer, hammer etc) and the additional activities related to simultaneous exposure to both types of sensory cue were associated with making links between visual and auditory features. This automatic recruitment of additional processing might suggest we should necessarily observe improved memory for multimodally presented stimuli. However, this is not always the case. Simply presenting cues in two modes does not guarantee improved long-term memory (although it can decrease the load on working memory). The effectiveness of multimodal presentation as a memory/learning strategy appears to rely on whether it encourages in-depth processing of the type related to educational objectives<sup>14</sup>. Andreano et al. recently studied the effects of increasing the immersive nature of a virtual reality environment, with the hypothesis that this should increase activity in regions associated with learning<sup>15</sup>. This study showed that adding auditory cues to a virtual reality environment (comparing unimodal with multimodal) increases activation in the hippocampus, a region strongly associated with memory formation and having no sensory function, thus supporting the notion that multimodality is an important aspect of virtual reality that can support learning. The educational use of **tangibles** may also be informed by fresh understanding from neuroscience. For example, topics involving shape have been principally taught through the medium of vision, but there is increasing evidence for shape information being easily transferable between vision and haptics. A recent imaging study suggests that the relationship between audio and visual processes, which may be considered complimentary in their differences, may not resemble the relationship between haptic and visual processes, which may be considered more similar. Indeed, object recognition by touch and vision activate several overlapping and closely-related brain regions (see Fig. 1). In this study, the researchers observed “enhanced effectiveness”, in neural terms, of combining haptic and visual stimulus<sup>16</sup>. That is, the multisensory gain with a combination stimulus was greater when its unisensory components were themselves associated with greater neural activity.

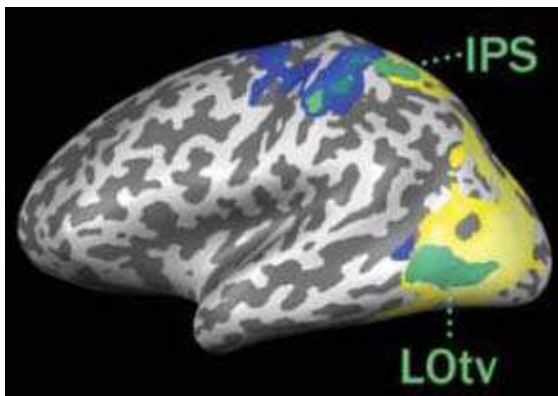


Fig 1 Regions of the brain that activate for visual and haptic object recognition overlap. Tangibles both types of information about shapes and these appear to enhance each other’s neural effectiveness

YELLOW = activation due to visual object recognition

BLUE = activation due to haptic object recognition

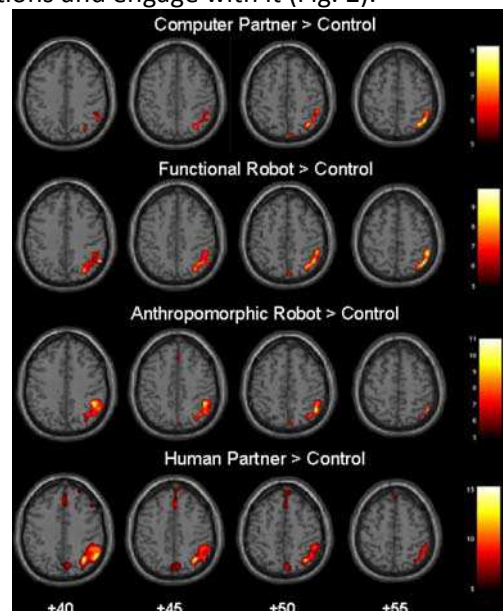
GREEN = overlapping activation regions





Advances in fMRI techniques are now allowing the neural substrates of social processes to be imaged. This is providing insights into the subtleties of how we engage with others in simple co-

operative tasks, which can contribute to our understanding of **collaborative learning**. A recent study identified the right pSTS as a key region for both social interaction and joint attention. By considering activations of this region in this and other studies<sup>17,18</sup>, the authors suggest that full joint attention requires more than just simultaneously gazing at the same object. Instead, two people must deliberately coordinate attention on the object, usually with the expectation that the object will be rewarding (for cooperative exchanges) and/or relevant (for communicative exchanging), and it is this behaviour that activates the pSTS. In other research, it has been found that several aspects of social interaction that may support collaborative learning, such as interactional synchrony, anticipation of other's actions and co-regulation of turn-taking, are associated with neural synchronisation between collaborators' brains as measured by EEG<sup>19</sup>. Brain research has also helped establish a better understanding of how trust between potential collaborators develops through reciprocity<sup>20,21</sup> and insights into such trust differs from that engendered through institutions<sup>22</sup>.

Understanding how our brain responds to other humans can also shed light on our response to **artificial agents** (tutors, competitors, collaborators), which may form an increasingly important part of the new learning technologies. New learning technologies that embody key elements of individual human tutoring while avoiding its extraordinary financial cost are likely to exploit what we understand about human processes of imitation, shared attention and empathy<sup>23</sup>. When we 'communicate' with non-human technology we may recruit brain regions usually involved with communicating with each other, particularly if this technology appears moderately human-like. A question tackled in a recent fMRI study was how human-like an artificial agent needs to be before we start attributing human intentions to them, i.e. a theory of mind. Although we have already seen that visual appearance is not a prerequisite (see Box 3) using networks usually associated with biological action, it does seem that visual appearance can play an important role. In a recent fMRI study, participants were asked to play a game against different type of opponent who, unbeknown to them, were all playing randomly<sup>24</sup>. Brain regions associated with theory of mind were activated in order of increasing human-like features (computer<functional robot<anthropomorphic robot<human). This suggests that cosmetic attempts to make technology more human-like may seriously influence our tendency to attribute human intentions and engage with it (Fig. 2).

Fig. 2 Regions associated with 'theory of mind' grow more active as the appearance of a technological opponent becomes more human-like, even when it is clearly not human (Krach et al 2008).



Interaction Partner				
Condition	Computer Partner (CP)	Functional Robot (FR)	Anthropomorphic Robot (AR)	Human Partner (HP)
Humanlikeness	no human shape; no perceivable button pressing	no human shape; button pressing with artificial hands	humanlike shape; button pressing with humanlike hands	human shape; button pressing with human hands

Through technology, we are now able to experience **mobile, ubiquitous and pervasive learning**, but biological contexts play an important role in understanding why such 24/7 experiences appear to be effective or not. Sleep plays an important role in memory, so when we learn influences how well we learn, with better recall following a period asleep than after the same period awake. Since technology now makes it easier for us search out, learn, communicate and apply knowledge all day and all night, this access can impact negatively on our sleep. For example, hormonal developmental influences produce a phase delay in the circadian timing mechanism of teenagers, but the use of mobile technology has also been shown to contribute to their sleep loss<sup>25</sup>. A recent study in the U.S., a recent study showed the average teenager indulging in around 4 activities involving technology after 9.00 pm, spending over an hour on each<sup>26</sup>. When we sleep after learning, the hippocampus in our brain rapidly integrates this information within distributed regions of the cortex<sup>27</sup>. Successive sleep-dependent reactivation of this hippocampal–cortical network leads to progressive strengthening of connections across the cortex, which over time, allowing these memories to become independent of the hippocampus and gradually integrated with other, pre-existing cortical memories. Therefore, not only does sleep support our recall of these memories but it also supports our ability to make links between these memories and older ones, which is important for our creative functioning. So, when access to technology impacts on our sleep habits, it can be detrimental to both our learning and our creativity. Moreover, activities involving close bright screens are able to delay the brain’s production of the hormone melatonin and so interrupt sleep-cycles in ways that a TV screen does not<sup>28,29</sup>.

Evidence that our learning has biological substrates is sometimes mistakenly used to support theories of biologically determined outcomes. Yet a core concept of modern neuroscience is the brain’s plasticity. Our educational experience influences the connectivity, function and structure of our brains. Even in old age, the brain remains plastic<sup>30,31</sup> and use of cognitive training by the elderly has been shown to improve and protect cognitive function. These successful attempts at **technology enhanced lifelong learning** include research that has focused on sufferers of Alzheimer's, who have used training derived directly from our understanding of how different regions of the brain are affected at the various stages of the disease (AD). This study showed maintenance of cognitive function for sufferers with severe symptoms compared with controls, and improvements in related behaviours (anxiety, depression, apathy, sleep disturbances) for those with mild to moderate symptoms (Yuanguas 2006). Many of the training programmes tested have been technology-based and it has been pointed out that technology offers particular advantages in these applications Fauconau(2010) et al.

Computer-based cognitive training (so called “brain training”) amongst the healthy has chiefly been found to improve performance on the training itself, rather than transferring to everyday application<sup>32</sup>. Once very important exception, however, is the training of working memory, which is a major constraint on our ability to learn new concepts. When young adults undertook a 19-day computer-based training program that focused on developing working memory for 30 minutes a day, it was found that not only their working memory, but also their fluid intelligence improved (i.e. their ability to solve problems in new situations). A convincing range of such results (including associated neural changes – see Fig 3) have led scientists to conclude that working memory can be trained<sup>33</sup>, and changes to prefrontal activations associated with working memory have been



identified<sup>34</sup>. This bodes well for those wishing to develop more effective “brain training” games – but so far the commercial response to these exciting developments has been slow.

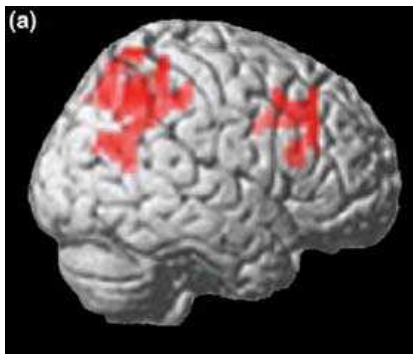


Fig 3 Increases in frontal and parietal regions after WM training (Olesen et al. 2004)

*Interdisciplinary Discussions*

It was noted that links existed between a range of concepts in TEL and neuroscience. The diagram below highlights some of these (fig. 4)

TEL	Neuroscience	
Screen design	Visual salience	
Tangibles	Visual/haptic processing	
Collaboration	Neural synchronisation	
Cognitive training	Tuning dopaminergic transmission	
Artificial agency	Mirror neurons	
Creative idea sharing	Automaticity suppression	

Fig. 4 Some potential links between concepts in neuroscience and TEL. The table is intended to highlight where interdisciplinary discussion might be fruitful in interrelating concepts, and is not intended to imply equivalence or any simple correspondence of ideas.

Discussions identified a number of barriers to progress that would need tackling in efforts to integrate understanding from neuroscience into TEL research, arising from differences in:

- language, terms and concepts in the two fields
- professional aims (neuroscience is interested in determining new fundamental facts about neural processes, TEL seeks to generate practical demonstrations of benefit)
- methods and epistemology, and the types of validity that are sought
- research contexts (i.e. moving from controllable lab experiments to more ecologically valid but complex and less controllable “real world” scenarios)

### 3. Emerging Research Questions

In response to the discussion document, some participants had already noted a number of areas where neuroscience and TEL might inform each other, and they demonstrated these in the following (potential) research questions:

Charles Fadel:

How might neuroscience help refute "learning styles" and other techniques for accelerated learning – or help confirm them?

Tamara van Gog:

1. Would mirror neurons really play a role in learning from video-based or animation-based modeling examples in which tasks involving human movement are demonstrated to learners (which we hypothesized in a 2009, Educational Psychology Review article, might be a potential explanation for the fact that many animations about mechanical or natural phenomena are NOT more effective than a series of static pictures, while those involving human movement are)

2. Self-regulated learning: Adults are quite effective at monitoring their learning under certain instructional conditions; the findings regarding young children are mixed, an interesting question in my opinion would be whether this process relies on the same neural mechanisms in children and adults and how it develops?

And two more general questions:

3. Cognitive load measurement: EEG seems very promising, but what about fMRI for example?

4. I often get the impression that many people in the TEL community believe that technology makes kids effective multitaskers (doing homework with the television on while chatting on Facebook and following tweets), even though studies in cognitive psychology show that when it comes to learning, this is not effective at all; potentially, neuroscience research on attention and memory could make an important contribution (and one that might be more convincing for some) in this area as well

Tony Fisher:

1. How might neuroscience inform our pedagogical and technological choices when we look to exploit ICT tools, social networks etc as part of learning and teaching?

2. How does neuroscience help us to understand and foster attention, engagement and flow in learning?

3. What can we usefully say in ITE and teacher CPD about the intersection of TEL and findings from neuroscience?

Niklas Ravaja:

How do emotion- and cognition-related psychophysiological responses predict learning during a learning game?

Diane Levine:

1. Can technology help us to learn what to remember?
2. What can the neuroscientific evidence on 'rewards' tell us about the ways in which young people develop relationships with others online?
3. Is there a difference between cultural and biological evolution? And how much do culturally learned thinking skills explain human creativity in a globalised TEL context?
4. What sorts of metaphors are good for helping children and young people understand what we know about how brains work? And how can they use those working models to keep safe and happy online?
5. To what extent are we able to remember old solutions or strategies whilst generating new ones while using new technologies?

Lisa Friedrich

1. What games are suitable to be combined with neurophysiological measurements (e.g. can be modified to send appropriate trigger for EEG analyses)?
2. What approaches are there/ should be made for adaptive educational systems (e.g. what kind of measurements (EEG, ECG, skin conductance,...), criteria/threshold for adaptation, which games, impact/consequences/improvement)

Further discussion was focused on developing further Grand Challenges, as a means of demonstrating how opportunities at the confluence of neuroscience and TEL might arise.

### 4.1 Grand Challenge 1

- Substantially improving motivation and learning of students in European schools by systematically using game-based environments informed by our emerging understanding of the brain's reward system

Activities necessary:

- Basic research on understanding how the brains reward system responds to different types of feedback – and how that influences learning
- Use the neuro-computational algorithm, implement them into the game software to maximise engagement
- Design-experimentation on improving an exemplary game; including varying the content
- Bridging studies that study the game in the laboratory but also in the classroom with teachers included in this process.

- Scaling studies
- Involve industry, technologists, educators, neuroscientists to explore the interdisciplinary processes to build future research capacity

A Time frame of ~4 years would be necessary for this project. Measurable outcomes could be:

- improved engagement and achievement amongst targeted students

The generation of neurocomputational algorithms accurately predicting behaviour in a variety of game contexts, with their neural correlates

### 4.2 Grand Challenge 2

- Designing TEL environments to systematically inform all European teachers on main advances in Neuroscience and possible conclusions for teaching and learning in school.

#### *Activities necessary*

- Define a curriculum with respect to concepts, methods, and findings of neuroscience with respect to learning and instruction (including the definition of a process to revise the curriculum in the light of advances in research). We need a working group comprising educ. Researchers, practicing teachers, teacher educators, and neuroscience researchers.
- Develop and evaluate a platform for bi-directional exchange (collecting and urging relevant areas of investigation – target group being neuroscientists and educational researcher – neuroscience in a nutshell /minimum level of knowledge not to fall under the influence of neuromyths / strong method focus. Need for a technical team in addition.
- Support the systematic implementation (including finding ways to engage the different groups, evaluation of these TEL environments; tap into funding; use ECER network; ministries of education.
- Empirical research: studies on scientific reasoning; change of perspective of use of rewards, interest, motivation

This Grand Challenge could be later generalised to include parents and policy makers as target groups. A suitable timeframe would be 2-3 years in order to meet the following measurable success criteria:

- vibrant community;
- development of research agendas;
- change in (neuro)scientific reasoning of teachers
- scale of participation(5000 teachers)

### 5. Researchers and Communities

Clearly, such projects as outlined above would require interdisciplinary teams for their successful promulgation:

*Educational experts* - able to identify content and participants, to help problematize research questions, guide issues of ecological validity, participate in evaluations

*Cognitive neuroscientists* – able to provide existing neural concepts and help theorize their application

*Psychologists* – able to provide existing psychological concepts linking brain and learning behaviour, able to provide essential data specifying participants

*TEL experts* (including commercial software providers) – able to theorise learner-technology interaction, help devise and construct prototypes and support exploitation of outcomes.

## References

- 1 Butterworth, B. & Laurillard, D. Low numeracy and dyscalculia: identification and intervention. *ZDM* **42**, 527-539, doi:10.1007/s11858-010-0267-4 (2010).
- 2 Strong, G. K., Torgerson, C. J., Torgerson, D. & Hulme, C. A systematic meta-analytic review of evidence for the effectiveness of the 'Fast ForWord' language intervention program. *Journal of Child Psychology and Psychiatry* **52**, 224-235, doi:10.1111/j.1469-7610.2010.02329.x (2011).
- 3 Temple, E. *et al.* Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from functional fMRI. *Proceedings of the National Academy of Sciences (USA)* **100**, 2860-2865 (2003).
- 4 Hoeft, F., Watson, C. L., Kesler, S. R., Bettinger, K. E. & Reiss, A. L. Gender differences in the mesocorticolimbic system during computer game-play. *Journal of Psychiatric Research* **42**, 253-258 (2008).
- 5 Gee, J. P. Learning and Games. *The John D. and Catherine T. MacArthur Foundation Series on Digital Media and Learning* -, 21-40, doi:doi:10.1162/dmal.9780262693646.021 (2007).
- 6 van Duijvenvoorde, A. C. K., Zanolie, K., Rombouts, S., Raijmakers, M. E. J. & Crone, E. A. Evaluating the negative or valuing the positive? Neural mechanisms supporting feedback-based learning across development. *Journal of Neuroscience* **28**, 9495-9503, doi:10.1523/jneurosci.1485-08.2008 (2008).
- 7 Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A. & Sweeney, J. A. Maturation of cognitive processes from late childhood to adulthood. *Child Development* **75**, 1357-1372 (2004).
- 8 Luna, B. *The Maturation of Cognitive Control and the Adolescent Brain*. (Springer-Verlag Berlin, 2009).
- 9 Lyytinen, H., Ronimus, M., Alanko, A., Poikkeus, A. M. & Taanila, M. Early identification of dyslexia and the use of computer game-based practice to support reading acquisition. *Nord. Psychol.* **59**, 109-126 (2007).
- 10 McCandliss, B. D. Educational neuroscience: The early years. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 8049-8050, doi:10.1073/pnas.1003431107 (2010).
- 11 Brem, S. *et al.* Brain sensitivity to print emerges when children learn letter-speech sound correspondences. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 7939-7944, doi:10.1073/pnas.0904402107 (2010).
- 12 Paivio, A. & Csapo, K. Picture superiority in free recall: imagery or dual coding? *Cognitive Psychology* **5**, 176-206 (1973).
- 13 Beauchamp, M. S., Lee, K. E., Argall, B. D. & Martin, A. Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron* **41**, 809-823 (2004).
- 14 Dubois, M. & Vial, I. Multimedia design: the effects of relating multimodal information. *J. Comput. Assist. Learn.* **16**, 157-165 (2000).
- 15 Andreano, J. *et al.* Auditory Cues Increase the Hippocampal Response to Unimodal Virtual Reality. *CyberPsychol. Behav.* **12**, 309-313, doi:10.1089/cpb.2009.0104 (2009).

- 16 Kim, S. & James, T. W. Enhanced Effectiveness in Visuo-Haptic Object-Selective Brain Regions with Increasing Stimulus Salience. *Human Brain Mapping* **31**, 678-693, doi:10.1002/hbm.20897 (2010).
- 17 Williams, J. H. G., Waiter, G. D., Perra, O., Perrett, D. I. & Whiten, A. An fMRI study of joint attention experience. *Neuroimage* **25**, 133-140, doi:10.1016/j.neuroimage.2004.10.047 (2005).
- 18 Materna, S., Dicke, P. W. & Thier, P. Dissociable roles of the superior temporal sulcus and the intraparietal sulcus in joint attention: A functional magnetic resonance Imaging study. *Journal of Cognitive Neuroscience* **20**, 108-119 (2008).
- 19 Dumas, G., Nadel, J., Soussignan, R., Martinerie, J. & Garnero, L. Inter-Brain Synchronization during Social Interaction. *PLoS ONE* **5**, doi:e12166 10.1371/journal.pone.0012166 (2010).
- 20 King-Casas, B. *et al.* Getting to know you: Reputation and trust in a two-person economic exchange. *Science* **308**, 78-83, doi:10.1126/science.1108062 (2005).
- 21 Miller, G. Neuroscience - Economic game shows how the brain builds trust. *Science* **308**, 36-36 (2005).
- 22 Boudreau, C., McCubbins, M. D. & Coulson, S. Knowing when to trust others: An ERP study of decision making after receiving information from unknown people. *Social Cognitive and Affective Neuroscience* **4**, 23-34, doi:10.1093/scan/nsn034 (2009).
- 23 Meltzoff, A. N., Kuhl, P. K., Movellan, J. & Sejnowski, T. J. Foundations for a New Science of Learning. *Science* **325**, 284-288, doi:10.1126/science.1175626 (2009).
- 24 Krach, S. *et al.* Can machines think? Interaction and perspective taking with robots investigated via fMRI. *PLoS ONE* **3**, e2597 (2008).
- 25 Van den Bulck, J. Television viewing, computer game playing, internet use and self-reported time to bed and time out of bed in secondary-school children. *Sleep* **27** 101-104 (2004).
- 26 Calamaro, C. J., Mason, T. B. A. & Ratcliffe, S. J. Adolescents Living the 24/7 Lifestyle: Effects of Caffeine and Technology on Sleep Duration and Daytime Functioning. *Pediatrics* **123**, E1005-E1010, doi:10.1542/peds.2008-3641 (2009).
- 27 Walker, M. P. in *Year in Cognitive Neuroscience 2009* Vol. 1156 *Annals of the New York Academy of Sciences* 168-197 (Blackwell Publishing, 2009).
- 28 Higuchi, S., Motohashi, Y., Liu, Y., Ahara, M. & Kaneko, Y. Effects of VDT tasks with a bright display at night on melatonin, core temperature, heart rate, and sleepiness. *Journal of Applied Physiology* **94**, 1773-1776, doi:10.1152/jappphysiol.00616.2002 (2003).
- 29 Higuchi, S., Motohashi, Y., Liu, Y. & Maeda, A. Effects of playing a computer game using a bright display on presleep physiological variables, sleep latency, slow wave sleep and REM sleep. *J. Sleep Res.* **14**, 267-273 (2005).
- 30 Boyke, J., Driemeyer, J., Gaser, C., Buechel, C. & May, A. Training-induced brain structure changes in the elderly. *Journal of Neuroscience* **28**, 7031-7035, doi:10.1523/jneurosci.0742-08.2008 (2008).
- 31 Lovden, M. *et al.* Experience-dependent plasticity of white-matter microstructure extends into old age. *Neuropsychologia* **48**, 3878-3883, doi:10.1016/j.neuropsychologia.2010.08.026 (2010).
- 32 Owen, A. M. *et al.* Putting brain training to the test. *Nature* **465**, 775-U776, doi:10.1038/nature09042 (2010).
- 33 Klingberg, T. Training and plasticity of working memory. *Trends in Cognitive Sciences* **14**, 317-324, doi:10.1016/j.tics.2010.05.002 (2010).
- 34 Olesen, P. J., Westerberg, H. & Klingberg, T. Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience* **7**, 75-79, doi:10.1038/nn1165 (2004).