Title: Math on cortex – Underlying delta synchrony during naturalistic math demonstrations in math experts and novices

Hanna Poikonen, Samuel Tobler, Dragan Trninic, Cléa Formaz, Venera Gashaj, Manu Kapur
hanna.poikonen@gess.ethz.ch, tobler@imsb.biol.ethz.ch, dragan.trninic@gess.ethz.ch,
clea.formaz@gess.ethz.ch, venera.gashaj@gess.ethz.ch, manukapur@ethz.ch

Professorship for Learning Sciences and Higher Education,
Department of Humanities, Social and Political Sciences, ETH Zurich

Abstract: Neuroimaging studies show that expertise in math shapes brain functions. To understand the brain processes behind complex math tasks and manipulation of large abstract concepts, we need to study the brain with naturalistic stimuli. Such stimuli are, for example, long math demonstrations that evoke simultaneous and overlapping cognitive and metacognitive processes. In our EEG study, we compared math experts and novices while they actively processed long math demonstrations in sitting and standing. Experts had an enhanced delta (0.5-4 Hz) phase synchrony over the centro-parieto-occipital electrodes compared to novices. Internal concentration and engagement may play a role in such enhanced delta synchrony.

Introduction
Behavioral studies have shed light on cognitive mechanisms and concepts arising during mathematics and cognition. Brain research aims to understand, on a neuronal level, these mental transformations related to math processing. Thus far, neuroscientific studies in children, adults, and math experts have focused on relatively simple mathematical processing in the brain.

Until now, brain research of mathematical cognition is accomplished with very quick mathematical tasks such as single- or double-digit arithmetic, or a short sentence describing a mathematical concept (e.g. Amalric & Dehaene, 2019; De Smedt et al., 2009). All of these studies are made with a strictly still body posture, due to noise sensitivity of the imaging methods and artifacts caused by body movement. Problems may emerge when simplified models, based on such short and artificial tasks in isolated and static settings, are applied to complex psychological phenomena, like mathematical cognition. Complex cognitive phenomena are exceedingly difficult, perhaps impossible, to describe through the data of their building blocks alone, since these phenomena are greater than the sum of their parts (Zaki & Ochsner, 2012). Our study aims to contribute to the naturalistic leap in brain research of math, the path of which is already being developed by interesting studies, such as Dikker and collaborators (2017) on STEM learning in a classroom measured by EEG.

In our study, we focus on the brain processes of math experts and novices over three oscillation frequencies: delta, theta, and alpha. We study the cortical synchrony with EEG when the participants actively processed longer math demonstrations with a duration from 13 to 68 seconds. By active processing, we refer to the mental activity we do when we read notes, proofs, and worked examples. Therefore, active processing is not restricted to solving problems. The math demonstrations are presented in symbolics and geometric manner when the participants are sitting and standing. We expect the math experts to show stronger activation over the parietal electrodes than novices when processing math demonstrations (Grabner & De Smedt, 2012), possibly due to the expected activation of the domain-specific number network (Amalric & Dehaene 2019).

Methods
Participants
In the math expert (bachelor and master students in math or math-related disciplines) and novice (no university-level math studies) groups, there were 23 participants (6 female and 17 male; 6 female and 17 male, respectively).

The age of the participants ranged from 19 to 24 years (mean 21.0 years, standard deviation 1.82) among math experts and from 19 to 35 years (mean 23.6 y, std 3.89) among novices. All participants in both groups were right-handed. No participants reported hearing loss or history of neurological illnesses. The experiment protocol was conducted in accordance with the Declaration of Helsinki and approved by the local Ethics Commission.

ICLS2022 Proceedings 1005 © ISLS
Stimulus

Participants watched 16 math demonstrations in a pseudorandomized order knowing that after watching them, they are asked to explain them to the experimenter. After each demonstration they were asked three self-evaluation reflections to which they answered by pressing a button in a 4-button response box. Each set of trials contained 4 excerpts of the same presentation style (symbolic or geometric) in two conditions (sitting or standing). One out of 8 math demonstrations is shown in Figure 1, both in a symbolic (Figure 1A) and in a geometric form (Figure 1B). The self-evaluation reflections (SER), which were presented after each demonstration, were the following: I had enough of time to follow the math demonstration (SER1), I was familiar with the math demonstration (SER2), I understood the math demonstration (SER3), and I found this math demonstration engaging (SER4). The options for the answers given via the response box were the following: 1 = Completely disagree, 2 = Somewhat disagree, 3 = Somewhat agree, and 4 = Completely agree.

Each math demonstration consisted of several slides, varying from 4 to 12 slides (6.9 slides on average) depending on the complexity of the demonstration. The total duration of math demonstrations varied from 13 seconds to 68 seconds (33.1 seconds on average). The timing of each slide was fixed and was defined based on a previous online screening with math experts and novices who did not participate in the actual study.

Figure 1

One out of 8 math demonstrations shown in symbolic (A) and geometric (B) form. The first slide (image in the middle) was the same in both symbolic and geometric presentation and was not used in the data analysis.

Equipment and procedure

The stimuli were presented to the participants with the MATLAB version R2019b via PsychToolbox version 3. The total length of the experiment material was approximately 15 minutes. The data were recorded using Ant Neuro eegomy electrode caps with active 128 EEG channels and 4 external electrodes for eye movements.

Data analysis

The average of all the EEG electrodes was set as a reference meaning taking the average of the signal at all EEG electrodes and subtracting it from the EEG signal at every electrode for every time point. The data were treated with independent component analysis (ICA) decomposition with the runica algorithm of EEGLAB to detect and remove artefacts related to eye movements and blinks. The data were split into the frequency bands of 0.5-4 Hz (delta), 4–8 Hz (theta), and 8–13 Hz (alpha) with high-pass and low-pass filtering.

We calculated the phase synchrony values (PSV; Tass et al., 1998) of the EEG data to the math demonstrations. The PSV value was calculated for 5-second segments with 50% overlapping for each math demonstration excluding the first two seconds and last second of the presentation. We conducted the synchrony analysis over the 12 electrodes of F3 (5), Fz (6), F4 (7), FCz (42), Cz (46), CP3 (48), CP4 (49), P1 (51), Pz (56),
P2 (52), PPO1 (92) and PPO2 (93; the 128-channel Ant Neuro EEG cap gap). Many of these fronto-parieto-occipital electrodes are traditionally used in EEG studies of mathematical cognition and show modulations in oscillation over memory retrieval, procedural strategies, and math training (e.g. De Smedt et al., 2009; Grabner & De Smedt, 2012).

The statistical analyses were conducted with MATLAB. The statistical analysis, repeated-measures ANOVA with a between-subject factor Group (Experts and Novices) and within-subject factors Posture (Sitting and Standing for math demonstrations), and Stimulus (Symbolic and Geometric), was conducted separately for each electrode pair (66 electrode pairs), each frequency band (delta, theta, and alpha). pGG indicates the Greenhouse-Geisser adjusted p-values of the repeated-measures ANOVA. For false discovery rate (FDR) correction, we employed a q-value threshold of 0.05. In the results section, we report only the statistically significant results in which both the pGG and the pFDR are < 0.05.

Results

Behavioral results
Self-evaluation reflections are an important indicator of how well the participants understood the math demonstrations (SER3) and how deeply they felt engaged with each demonstration (SER4). We also screened familiarity (SER2), and whether the participants had sufficient time to follow the steps of the demonstrations (SER1). For SER1, SER3 and SER4 experts reported significantly higher scores than novices, pGG=8.2e-06, pGG=8.2e-06, and pGG=0.0042, respectively. For SER2, there was no group difference, pGG=0.63.

EEG results
EEG results related to the Group differences and their interactions are reported and discussed in this paper. The only statistically significant Group differences and their interactions occurred over the delta band (Table 1).

<table>
<thead>
<tr>
<th>Delta: 0.5 – 4 Hz</th>
<th>Electrode pair</th>
<th>pGG value</th>
<th>pFDR</th>
<th>Multiple comparison (Bonferroni)</th>
<th>Difference</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group main effect</td>
<td>Cz – PPO1</td>
<td>0.015</td>
<td>0.0097</td>
<td>0.12</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pz – P2</td>
<td>0.020</td>
<td>0.0067</td>
<td>0.14</td>
<td>0.056</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CP3 – P1</td>
<td>0.049</td>
<td>0.0080</td>
<td>0.10</td>
<td>0.051</td>
<td></td>
</tr>
<tr>
<td>Group*SitStand interaction</td>
<td>Cz – Pz</td>
<td>0.014</td>
<td>0.00035</td>
<td>0.11</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cz – P1</td>
<td>0.020</td>
<td>0.00035</td>
<td>0.11</td>
<td>0.052</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CP4 – PPO1</td>
<td>0.049</td>
<td>0.00048</td>
<td>0.11</td>
<td>0.052</td>
<td></td>
</tr>
</tbody>
</table>

Discussion
In our study, we compared math experts to novices when they were actively watching long and complex math demonstrations in an EEG laboratory in sitting and standing body posture. Our main finding is that the math experts have a stronger delta phase synchrony over the centro-parieto-occipital electrode pairs than novices when watching math demonstrations. Our results refer to enhanced internal concentration (Harmony, 2013), and/or activity related to the number network in experts in comparison to novices (Amalric & Dehaene, 2019).

Internal concentration
When processing long and complex math demonstrations, internal concentration is crucial bringing the focus to the task at hand. Simultaneously, brain processes related to other external stimuli or task-irrelevant internal thoughts need to be suppressed. Harmony and colleagues (Harmony, 2013) showed that left parietotemporal
cortices have an increased activation on the delta band (3.9 Hz) during an arithmetic calculation in comparison to control tasks. After other results from their laboratory, Harmony and colleagues (2013) reasoned this increase in the delta band to occur due to enhanced internal concentration required to solve the arithmetic problem. Also in our study, the enhanced delta phase synchrony in experts over the centro-parieto-occipital electrodes may reflect their deeper internal concentration in comparison to novices. The self-evaluation reflections would also support this interpretation since experts reported stronger engagement and a better understanding of the math demonstrations than novices.

**Sitting and standing body posture**

Most of the group differences in delta synchrony in experts and novices occurred during both body postures, sitting and standing. However, some synchrony differences, expanding to the right hemisphere, emerged only during the standing position. To our knowledge, our study is the first one that investigates complex math in a standing body posture. Visuospatial working memory seems to function faster and more precisely when standing than when sitting down (Dodwell et al., 2019). However, sustained upright posture seems to require constant attentional engagement (Woollacott and Shumway-Cook, 2002). In our study, potential attentional interference between standing and math tasks appears to challenge math novices more than experts, who might have more automatic mathematical processing and thus require less attentional effort (Jeon et al., 2019).

**Conclusions**

Our novel study setting with long and complex math stimuli revealed enhanced delta synchrony in math experts in comparison to novices over the centro-parieto-occipital electrodes. Over some electrode pairs, the group differences were shown only when standing but not while sitting. Taken together, these results indicate a deeper internal concentration in experts and/or potentially a stronger activation of the number network in comparison to novices when actively processing math demonstrations. Our results encourage future study of the brain with naturalistic stimuli, such as long and complex math tasks, in naturalistic setting including different body postures to understand how the brain functions in the real world in which continuous and overlapping stimuli are encountered and interacted with, evoking several simultaneous sensory, cognitive and emotional brain processes.

**References**


