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Joseph Baker  
*Stanford*

Patricia Seray Moyer-Packenham  
*Utah State University*

Stephen Tucker  
*University of Louisville*

Jessica Shumway  
*Utah State University*

Kerry Jordan  
*Utah State University*

Ron Gillam  
*Utah State University*

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The Brain’s Response to Digital Math Apps: A Pilot Study Examining Children’s Cortical Responses During Touch-Screen Interactions

JOSEPH M. BAKER
Stanford University, USA
jbaker2@stanford.edu

PATRICIA S. MOYER-PACKENHAM
Utah State University, USA
patricia.moyer-packenham@usu.edu

STEPHEN I. TUCKER
University of Louisville, USA
s.tucker@louisville.edu

JESSICA F. SHUMWAY
Utah State University, USA
jessica.shumway@usu.edu

KERRY E. JORDAN
Utah State University, USA
kerry.jordan@usu.edu

RONALD B. GILLAM
Utah State University, USA
ron.gillam@usu.edu

Functional near-infrared spectroscopy (fNIRS) is an easy to use neuroimaging technique that is portable and maintains a liberal tolerance to movement. As such, fNIRS represents an ideal tool to observe children’s neural activity as they engage in real-world classroom activities, such as the interaction
with digital math apps on an iPad. Here, we provide the results of an initial hypothesis-generating pilot study designed to assess patterns of cortical activity that occur when children interact with digital math apps, that contained virtual manipulatives, on a touch-screen device. Our results highlight cortical activity within the bilateral intraparietal sulci and dorsolateral prefrontal cortices as children interacted with three different digital math apps, but not during rest. Our results provide valuable proof-of-concept that fNIRS may be used to assess math-related cortical activity during children’s naturalistic use of digital math apps on a touch-screen device.

**Keywords:** fNIRS, virtual manipulative, digital math apps, math, educational neuroscience, development

The goal of educational neuroscience is to develop an understanding of brain function as it relates to learning, and to bridge the gap between basic brain science research and education. Far from trivial, the combination of neuroscience and education has the potential to unlock information that may greatly improve the educational process (Butterworth & Kovas, 2013). Here, we provide the methods and results of a pilot study designed to bring functional neuroimaging closer to the classroom, and to help researchers and educators alike understand how children’s brains respond to real-world math teaching tools. Specifically, we sought to take the initial steps towards determining whether children’s naturalistic interactions with computer-based math teaching tools elicit similar patterns of cortical activation as those identified in highly controlled fMRI-based studies (Arsalidou & Taylor, 2011), and whether these patterns may be assessed by functional near-infrared spectroscopy (fNIRS).

**The promise of educational neuroscience**

Why is functional neuroimaging not already used in educational settings? Perhaps the primary reason stems from the operational cost of common neuroimaging tools such as fMRI. The cost of fMRI, which is currently the “gold standard” of functional neuroimaging, is prohibitively expensive and must occur in highly specialized laboratories. Moreover, in order for usable images of the brain to be acquired using fMRI, very little movement
(i.e., < 2mm) is allowed. As a result, the activities that can be conducted within fMRI are often limited to basic calculation or numerical comparison paradigms that may be accomplished while laying prone, and as a result may lack a degree of ecological validity. Despite these limitations, studies using fMRI have established that many forms of math and number processing elicit a robust profile of cortical activation throughout specific bilateral parietal and prefrontal brain regions (Arsalidou & Taylor, 2011). For instance, even passive viewing of math or number related material, such as that displayed during the Sesame Street children’s program, elicits cortical activation throughout the bilateral parietal cortex that is positively correlated with standardized math test scores (Cantlon & Li, 2013). While simultaneously capturing the brain’s response to a real-world example of how young children may interact with mathematics in the real world (i.e., via television), as well as the relationship between neural activity and math outcomes that is only possible to assess with functional neuroimaging, Cantlon and Li (2013) highlights the utility that brain imaging may provide for education. Importantly for the purpose of our pilot study, and discussed in greater detail below, the brain’s robust response to mathematics is also observable via optical imaging. This is important, as optical neuroimaging provides multiple methodological benefits that are amenable to use in real-world educational settings (Dresler et al., 2009).

The role of fNIRS in educational neuroscience

Functional near-infrared spectroscopy (fNIRS) is a portable neuroimaging technique that uses light projected into the brain to measure oxygen concentrations in the blood of the brain. As a region of the cortex becomes active, the oxygen molecules that are attached to the hemoglobin within that region are absorbed. Next, freshly oxygenated blood is sent to that region in order to support the brain activity. Similar to the BOLD signal recorded by fMRI, the interaction of oxygen and hemoglobin is known to be a reliable indicator of neural activity (Cui, Bray, Bryant, Glover, & Reiss, 2011). By measuring the oxygen concentrations multiple times a second (e.g., 10Hz), it is possible to map the *hemodynamic response* of different brain regions in response to mathematics. While cost-effective and easy to use, fNIRS is highly tolerable to movement, making it usable during a wide range of naturalistic math teaching tasks (Baker, Martin, Aghababyan, Armaghanyan, & Gillam, 2015). Finally, fNIRS is capable of imaging the regions of the brain that are highly involved in math cognition (Dresler et al., 2009).
In a recent meta-analysis of 53 neuroimaging data sets investigating the brain’s response to mathematics, all of the studies reported identified significant activation in the cortex of the parietal and pre-frontal brain regions (Arsalidou & Taylor, 2011). Within the parietal regions specifically, the left and right intra-parietal sulci are integrally involved in number and math cognition. The basic cognitive abilities that underlie mathematics, such as non-verbal number and visuo-spatial processing, may occur primarily within the right intra-parietal region. Throughout development, and in particular with the onset of language, verbal numerical processing and mathematics begin to occur bilaterally, within the left and right intraparietal sulci (IPS). As children become proficient with mathematics, brain activity during grade-appropriate math problem-solving occurs primarily in the left IPS (Emerson & Cantlon, 2014).

While regions of the parietal lobe are directly related to math and number cognition, the prefrontal cortex is commonly involved in a variety of higher-level cognitive control abilities associated with executive functioning, including the attention and working memory processes that occur during many educational tasks including, but are not limited to, mathematics. For example, activation of prefrontal cortex has been shown to be related to performance on number conservation tasks (Poirel et al., 2012), mathematical problem-solving (Anderson, Lee, & Fincham, 2014), literacy (Jasińska & Petitto, 2014), and language skills (Wang & Holland, 2014).

While these studies provide invaluable insight into the brain regions responsible for math and number cognition, the fMRI-based tasks used to demonstrate this relationship suffer from the ecological validity constraints discussed above. As a result, the generalizability of these results to real-world math education environments is hampered. While many of the same cognitive processes are likely at work during naturalistic math tasks, the extent to which real-world math processing mirrors these results remains ill-defined.

In an example of the use of fNIRS in an educational setting, Dresler and colleagues (2009) imaged the parietal and prefrontal cortex of 90 primary (4th grade n=46, n female=19) and secondary (8th grade n=44, n female=13) school children as they engaged in real world math problem solving. Engaging in mental calculations resulted in significantly greater blood oxygen concentrations within the parietal regions of their brains compared to simply reading number words. Notably, the authors of this study scanned all 90 of their participants over the course of two weeks, and all scans were carried out in the children’s school. Thus, while their results support the findings of similar studies conducted with fMRI, this study demonstrates the flexibility of NIRS to be used in an educational setting.
Digital math apps as a stimulus for math-based educational neuroscience

fNIRS has the potential to greatly influence educational neuroscience by providing a platform for naturalistic neuroimaging, and that may be used within educational settings. However, before a large-scale study may take place, it is important that pilot studies be conducted so that appropriate stimuli and procedures may be established. For example, in the future, researchers may be interested in using fNIRS to document the changes in brain response patterns that occur within individual children as they learn math over the course of a school year. In a longitudinal study such as this, wherein each child undergoes multiple imaging sessions, it is important that the educational activity that the child engages in throughout each scan be relevant to the math topic of interest, while remaining challenging and fun for the child across the duration of the study. Digital math apps, that contain virtual manipulatives, provide an optimal candidate for such activities.

Virtual manipulatives are defined as “an interactive, technology-enabled visual representation of a dynamic mathematical object, including all of the programmable features that allow it to be manipulated, that presents opportunities for constructing mathematical knowledge” (p. 5) (Moyer-Packenham & Bolyard, 2016). Research has shown that math apps that contain virtual manipulatives have moderate positive effects on mathematics learning that are consistent across grade levels, mathematical topics, and study durations (Moyer-Packenham & Westenskow, 2013). Interactions with touchscreen based devices results in greater motivation (Riconscente, 2011), increased learning performance and efficiency (Moyer-Packenham, Shumway, & Bullock, 2015), and embodiment of interaction types that influenced learning (Paek, 2012; Paek, Hoffman, Saravano, Black, & Kinzer, 2011). A recent meta-analysis by Clark, Tanner-Smith, and Killingsworth (2016) shows the important impacts of digital games on student learning when compared with non-game conditions. Well-designed games, whose educational objectives are well-integrated with gameplay, are effective at motivating students and producing learning gains (Boyce, 2014; Habgood, 2011).

Here, we provide the results of a pilot study that used fNIRS to image the brains of children engaged in math education activities with digital math apps that contained virtual manipulatives. The overarching research question in this study was: Within brain regions known to be associated with mathematics, what signatures of cortical activity are present when children interact with digital math apps, that contain virtual manipulatives, on a touch-screen device? As we discuss, our results provide valuable proof-of-concept for fNIRS-based studies investigating math processing using digital math apps, and set the stage for future large-scale studies in this important vein.
METHODS

Participants

Researchers recruited ten second-grade students from a pool of children who had participated in previous research projects at the university and whose parents had indicated that they would like to be contacted for future studies. The ages of the students ranged from 7.4 to 8.5 years old. The majority of students were Caucasian, and three of the ten students qualified for free/reduced lunch at school. One child in the study received special education services. Parents reported that all 10 children had touch-screen devices in the home. Eight of ten participants had 1-4 devices and two participants had five or more devices in the home. There were six participants who used the devices every day, ranging from 30 minutes to 10 hours per week. Half of the participants used mathematics apps 1-3 days per week, while four participants reported never using mathematics apps. One participant used mathematics apps every day.

Description of the Math Apps

Participants interacted with three digital math apps on iPads: Montessori Numbers: Base-10 Blocks (100-999), Motion Math: Zoom (levels 2+), and LetsTans Kids.

Montessori Numbers: Base-10 Blocks (100-999). Montessori Numbers (see Figure 1) presented participants with a virtual place value chart and virtual ones, tens, and hundreds blocks to use to form a target number less than 1000. The app limited block placement to specific sections (e.g., ones only in the ones area), wherein the app automatically stacked the blocks placed by the user. Symbolic number tiles displayed the quantity represented in blocks and changed according to the addition or removal of blocks. The app bundled sets of ten identical blocks, regrouping them into their appropriate place value. All narration functions were disabled. The app used single-touch input, requiring tapping, dragging, or flicking motions for different interactions.
Figure 1. Screenshot of Montessori Numbers: Base-10 Blocks (100-999).

**Motion Math: Zoom (levels 2+).** To complete Motion Math: Zoom (see Figure 2), participants placed target numbers on a number line using multi-touch input. Animals of varying sizes corresponded to labeled intervals on the number line (e.g., rhinos for hundreds, dogs for tens, frogs for ones). Participants placed numbers on the number line by swiping or dragging to move the number line left of right, or zooming in or out to change the interval magnitude (i.e., ones, tens, hundreds, thousands, etc.) by bringing together or pulling apart two fingers, then tapping the bubble containing the number to allow it to drop to its correct place on the number line. The app responded to correct attempts by “popping” the bubble, thus releasing the number to fall into the corresponding empty space on the number line. The app responded to incorrect attempts by causing the bubble to shake instead of pop. The app provided visual and auditory scaffolds when the participant proceeded slowly.
Figure 2. Screenshot of Motion Math: Zoom (levels 2+).

**LetsTans Kids.** LetsTans Kids (see Figure 3), presented participants with five colored shapes and an empty frame in which to arrange the shapes, set on a grid background. Using single-touch input, participants dragged the shapes into the frame. The app guided tile placement by adjusting the tile position to align with the grid. The app did not allow reflection or rotation. Along the lower right side of the screen, icons allowed access to different features, including a circular arrow serving as an undo function, a light bulb icon providing access to a limited number of hints, and a timer to track elapsed time. A pop-up message accompanied the correct completion of a task. Acknowledging this message led to the display of another task. The app did not provide solution-related feedback during the solving process.
Figure 3. Screenshot of LetsTans Kids.

Description of fNIRS and localization of regions of interest

All brain activation data were collected with a continuous-wave fNIRS system (ETG 4000, Hitachi Medical Co., Japan) (Plichta et al., 2007). fNIRS uses light projected into the cortex of the brain to measure changes in blood oxygenation, which provides an indicator of neural activity. By observing the relative concentration of blood oxygenation at a rate of 10Hz, fNIRS provides an indicator of functional changes in cortical brain activity (see Plichta et al., 2007 for detailed description).

A total of 44 recording channels (i.e., 16 source and 14 detector optodes) were divided equally over each participant’s pre-frontal and parietal brain regions by two 3x5 optode caps. Each cap contained a total of 22 individual recording channels. The caps were fastened to the participant’s head with elastic bands (see Figure 4). Throughout the procedure we assessed each child’s comfort through conversation. The caps could be easily adjusted so that the children remained comfortable throughout the entire session. Optode arrangement and placement was determined a priori, and was focused around the parietal and prefrontal regions integral to math process-
The internal 10-20 system was used to assure that each ROI was captured by our probe placement, and to help localize probe placement across participants (Okamoto et al., 2004). The middle optode in the parietal cap was placed directly over the midpoint of the parietal lobe (Pz) for each participant. In order to maintain placement of the pre-frontal probe cap, the middle column of optodes were placed along the midline, and the inferior edge of the cap was placed directly above the brow.

**Figure 4.** fNIRS optode patch placement.

**Procedure**

The study took place in two different room settings: a “briefing room” and a “fNIRS room.” When the participant arrived to the research center, the facilitator first escorted the participant and the parent to the briefing room. Here, the parent completed informational surveys and consent forms, and the facilitator briefed the children on the apps to be used in the study. Two of the apps were familiar to the children (Montessori Number and Motion Math Zoom) and one app was not familiar (LetsTans Kids). The children briefly looked at the two familiar apps to remember how they worked. The facilitator explained and modeled the LetsTans Kids app, and the children tried one of the puzzles (Puzzle #200) for practice to ensure that they understood how to work the app.

Next, the facilitator accompanied the child and parent to the fNIRS room, where the interaction sessions occurred. The fNIRS room was
equipped with the ETG-4000 fNIRS device described above behind a partition, and a desk at which the participant sat to interact with the apps (see Figure 5). The facilitator sat next to the child and positioned a GoPro Camera on them to capture close-up views of their interactions with the apps on the iPad. The facilitator explained to the participant that she should take her time with each of the activities on the apps throughout the session, and encouraged each participant to relax and have fun with the apps. The fNIRS cap was then placed on the child, and the scan was started in conjunction with the start of the child’s interaction with the apps.

**Figure 5.** Set-up of fNIRS room.

The fNIRS scan began with a 30-second rest period. After the rest period, the participant interacted with the three digital math apps for three minutes each, with 45 second rest periods between each app. Apps were presented in the following order: Montessori Numbers, Zoom, LetsTans Kids. The facilitator opened and closed each app for the participant but remained silent as the participant interacted with the apps. After interacting with the final app, there was a final rest period of 30 seconds. After the interaction session ended, researchers removed the fNIRS equipment from the child and debriefed the parent and participant.
Data analysis

Oxygenated hemoglobin was used for all analyses. First, all data were high- (0.5Hz) and low-pass (0.01Hz) filtered in order to remove noise due to biological processes (e.g., respiration, heart-beat, etc.) and signal-drift due to inherent constraints in signal measurement. The filtered data were then analyzed using a general linear model approach (see Plichta 2007 for detailed review). In short, individual standardized coefficients (i.e., beta weights) were estimated for each math activity and rest, and were based on the properties of the fNIRS signal that were generated while the child engaged in each activity. The value of each coefficient provides an indicator of the cortical activity that occurred as the children engaged in each app and within each fNIRS channel.

The coefficient estimation procedure described above was conducted for each participant individually, and each channel-wise beta weight was grouped together for group analyses. One-sample t-tests were then conducted to determine if the activation observed during each activity differed from zero. Notably, repeated testing of the null hypothesis results in an inflated risk of committing a type I error (i.e., false positive). In an effort to overcome this risk, it is common practice to implement a correction procedure (e.g., false discover rate), which effectively reduces the probability of committing a false positive due to repeated testing. However, as this was a pilot study intended to generate hypotheses for future tests, and because our sample size was kept appropriately small for pilot testing (N=10), we did not conduct such correction procedures.

In the section below, we outline the results of each activity comparison. The results of each t-test are shown as colors on a heat map of the prefrontal and parietal NIRS optode patches. Greater activations (i.e., larger t-values) are shown as “hot” colors, and their location provides an indicator of functional regions of interest for future studies using similar math activities.

RESULTS

Parietal results

We hypothesized that increases in cortical activation would be identified in regions of the brain corresponding to the left and right intraparietal sulci. As hypothesized, this pattern of activity was observed for all three digital math apps, but it was not present during rest (see Figure 5 showing...
the parietal activity heat maps). That is, within each digital math app heat-map, three distinct hot-colored (i.e., bright yellow) patches are visible on the middle left (i.e., left IPS), upper right (i.e., right IPS) and bottom right (i.e., right angular gyrus) portions of each heatmap. As discussed above, each of these regions are known to be involved in math and number processing, as well as visuospatial cognitions that are related to mathematics.

Interestingly, these results closely mirror the patterns of neural activity that have been observed during basic math tasks previously employed in studies of math processing using fMRI. This suggests, with respect to the current pilot study, that similar patterns of cortical processing emerge when children engage in naturalistic math tasks during an fNIRS scan. Notably, activity during the rest periods elicited a different pattern of activation. That is, the left and right regions of the parietal lobe, which were consistently active during math play, were not active during rest. This pattern suggests that these regions were not always active, and that sitting quietly and not actively engaging in interaction with math apps reduces the cortical activity in these regions.

<table>
<thead>
<tr>
<th>Montessori</th>
<th>Math Motion</th>
<th>LetsTans Kids</th>
<th>Rest</th>
</tr>
</thead>
</table>

Activation was consistently high within the left and right parietal regions during each activity. This activity profile is not present during rest. The range of t-values in each heatmap was -3 (dark blue) to 3 (bright yellow).

**Figure 5.** T-value heatmaps displaying cortical activation patterns in the parietal brain region for all participants combined (N=10).

**Prefrontal results**

Similar to the parietal results above, based on previous research within both fNIRS and fMRI, we hypothesized that regions of the PFC would be active during each digital math app while maintaining minimal activity during rest. Data from the current pilot study support this hypothesis, and highlight high levels of activity in bilateral regions of the dorsolateral prefrontal cortex (see Figure 6). As described above, working memory and attention
processes needed to complete each digital math app may have driven these patterns of results. Notably, the left dorsolateral PFC, in the lower right region of each prefrontal heatmap, demonstrated increased activation in the “LetsTans Kids”, “Math Motion”, and somewhat within the “Montessori” app. This pattern of results is expected, given this region’s common involvement during math processing. Finally, similar to the parietal results from this current pilot study, data suggest that comparatively little activity was present in children’s PFC during periods of rest. Again, this pattern of results is expected, given similar patterns identified in previous studies. In addition, as stated above, these results suggest that fNIRS is capable of identifying reductions in PFC activity when children stop playing with the apps.

<table>
<thead>
<tr>
<th>Montessori</th>
<th>Math Motion</th>
<th>LetsTans Kids</th>
<th>Rest</th>
</tr>
</thead>
</table>

Activation was high within bilateral superior prefrontal regions for each math activity. Consistently greater left dorsolateral activity was also observed for the Math Motion and LetsTans Kids apps. Activation during rest was comparatively lower and less spatially distinct. The range of t-values in each heatmap was -3 (dark blue) to 3 (bright yellow).

**Figure 6.** Heatmaps displaying cortical activation patterns in the prefrontal brain regions for all participants combined (N=10).

**DISCUSSION**

Mathematics apps are quickly becoming a ubiquitous aspect of children’s education. With over 500,000 apps available on iTunes and over 300,000 available on Android platforms, 72% of the top-selling apps target preschool/elementary aged children, and mathematics is the second most popular subject (13%) (Shuler, Levine, & Ree, 2012). Despite these impressive numbers, there is very little research on how children’s interactions with mathematics apps engage the brain. Notably, advances in fNIRS neuroimaging now make it possible for researchers to observe cortical activation patterns while children interact with these and other real world math teaching tools (Baker et al., 2015). This is important, as it represents an integral step towards the overarching goal of educational neuroscience, which is to bridge the gap between basic brain science research and education.
A better understanding of the neurocognitive signatures that emerge during children’s interactions with math apps may have tangible consequences on their education. For instance, development or selection of educational tools may be optimized based on the degree to which interaction with each tool elicits the expected or desired neural response. For struggling math learners in particular, interaction with an app that results in high parietal activity related to math processing along with low prefrontal activity related to working memory, may be preferred over a design that elicits heavy working memory processes. It is important that future studies address the degree to which such brain-based optimization may benefit behavioral outcomes. Furthermore, the use of fNIRS during naturalistic math activities may also provide a unique indicator of a child’s understanding of a math topic. That is, when children are first introduced to a math topic (e.g., addition/subtraction), much of their cognitive processing during these activities occurs in the prefrontal cortex. It is thought that this signature is evidence of significant working memory processes that are needed when a new topic is introduced (Delazer et al., 2005; Emerson & Cantlon, 2014; Rosenberg-Lee, Barth, & Menon, 2011). As the math topic is learned, much of the prefrontal activity is reduced and processing begins to occur within the parietal brain regions more predominately (Rosenberg-Lee et al., 2011). Importantly, parietal activation patterns during naturalistic interactions with mathematics correlates with behavioral performance (Cantlon & Li, 2013). Thus, the ability to observe this functional shift throughout real-world math learning may provide educators with a powerful tool to help identify struggling math learners. The results from the current pilot study suggest that fNIRS may be an optimal neuroimaging platform to address these exciting empirical questions.

CONCLUSION

It is important to interpret the current results with caution: As discussed above, results stem from a pilot study designed to generate hypotheses for future large-scale studies. As is common with pilot studies, sample size was small, which reduced the ability to make reliable statistical inferences. Furthermore, the statistical comparisons that were made were unadjusted for inflation of Type I error. Taken together, the limitations of the current study make it difficult to generalize results to a wider population.

Despite the limitations of the current study, our findings provide valuable proof-of-concept regarding the utility of fNIRS to observe math-related cortical activations in children as they engage with real-world math apps.
Because the elementary grades serve as a foundation for critical skills in secondary math, it is important to understand children’s experiences with math technologies. Students’ early math experiences have a long term effect on their math performance and success in later years (Geary, 2011; Geary, Hoard, Nugent, & Bailey, 2012, 2013). Digital math apps can be powerful learning tools (VanEck, 2015), because they provide an important avenue for positive math experiences in the early grades. Our hope is that these results lay the groundwork for future studies designed to elucidate the brain’s response to naturalistic math activities.

References


