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ORIGINAL RESEARCH

Cortical Activations During a Computer-Based Fraction Learning Game: Preliminary Results from a Pilot Study

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Abstract Advances in educational neuroscience have made it possible for researchers to conduct studies that observe concurrent behavioral (i.e., task performance) and neural (i.e., brain activation) responses to naturalistic educational activities. Such studies are important because they help educators, clinicians, and researchers to better understand the etiology of both typical and atypical math processing. Because of its ease of use and robust tolerance of movement, functional near-infrared spectroscopy (fNIRS) provides a brain-imaging platform that is optimally suited for such studies. To that end, the focus of the current research is to use fNIRS to help better understand the neural signatures associated with real-world math learning activities. For example, the computer game "Refraction" was designed as a fun and engaging method to improve fraction knowledge in children. Data collected in previous studies have identified significant correlations between Refraction play and improvements in fraction knowledge. Here we provide the results of a pilot study that describes participants' cortical activations in response to Refraction play. As hypothesized, Refraction play resulted in increases in parietal cortical activations at levels above those measured during spatial-specific activities. Moreover, our results were similar to another fNIRS study by Dresler et al. (J Neural Transm 116(12): 1689–1700, 2009),

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where children read Arabic numeral addition equations compared to written equations. Our results provide a valuable proof-of-concept for the use of Refraction within a large-scale fNIRS-based longitudinal study of fraction learning.

Keywords Neuroscience · Neuroimaging · NIRS · Education · Mathematics · Educational neuroscience

1 Introduction

Understanding the relationship between changes that occur in children's brains in conjunction with changes in performance on real-world math learning tasks may provide valuable insight into the math learning process for children of all abilities (Butterworth and Kovas 2013). Multiple classroom-based studies have identified computer-based approaches to math instruction that provide the learner with specific spatio-temporal visual and auditory stimulation that facilitates math learning (Bodner and Shaw 2004; Hu et al. 2004; Moyer-Packenham et al. 2013). Such studies are often conducted longitudinally, which enables investigators to identify signatures of learning that occur in real-time (i.e., individual learning sessions), as well as long-term effects of individual teaching regimens.

Studies of the brain's response to math learning have typically provided cross-sectional examinations of the maturation of arithmetic skills over large time spans (e.g., Ansari et al. 2005; Kawashima et al. 2004; Kucian et al. 2008; Rivera et al. 2005). In one such study, Rosenberg-Lee et al. (2011) identified significant changes in the brain's response to arithmetic between the narrow developmental span of 2nd and 3rd grades. Specifically, within a separate cohort of 2nd and 3rd grade children, a shift from frontal to parietal activation during grade-appropriate addition and subtraction tasks was identified. Similarly, using a longitudinal design, Kesler et al. (2011) identified significant changes in frontal-parietal activation following just 6 weeks of intensive (i.e., 1 h per day, 5 days a week) interaction with an adaptive, computer-based math-teaching tool that focused on number sense and general problem-solving skills.

These studies demonstrate that changes in brain activation patterns during basic math processing occur throughout development, and may be observed within weeks after the beginning of a training regimen. However, functional changes (i.e., changes in brain activation patterns) in the brain may also be observable at much shorter durations as well, and documentation of such changes may provide valuable insight into the math learning process. Unfortunately, methodological restrictions and high operation costs of common neuroimaging techniques such as functional magnetic resonance imaging (fMRI) limit the feasibility of longitudinal studies that include frequent scans of a large cohort of participants. Ecological validity in such studies is often compromised, and neural changes that occur across smaller epochs are missed. Alternatively, functional near-infrared spectroscopy (fNIRS) provides a low cost and robust neuroimaging platform that may be used to observe the brain's response to naturalistic math learning activities. For instance, in a study reported by Dresler et al. (2009), fNIRS was used in a primary school setting with a large cohort of 90 children (4th grade n = 46, 8th grade n = 44). Their results demonstrated significant differences in frontal and parietal activation when the children read Arabic numeral addition equations compared to written equations. As these data were collected in only 1 week's time, this study demonstrates fNIRS' ability to enhance the ecological validity of neuroimaging studies, while highlighting its efficiency.

While future longitudinal studies of math learning will benefit from the methodological flexibility of fNIRS, it is important that current studies identify tasks that are suitable (i.e., a valid educational tool that is both fun and challenging) for such longitudinal applications. Here, we employ the computer-based fraction learning game "Refraction" (Center for Game Science 2013; Martin et al. 2012), which requires players to combine math (i.e., fractions) and spatial (i.e., screen navigation) skills in order to successfully complete a series of game stages. Refraction[1] has been shown to enhance task performance following game play (Baker et al. 2013), although no investigation to date has investigated its effect on the brain. To that end, we present the data below as an initial proof-of-concept that reliable cortical signatures of math processing may be identified with fNIRS during Refraction play.

2 Methods

2.1 Participants

We recruited a total of ten students (female n = 5) from a large public university. All participants were actively enrolled undergraduate (n = 6) or graduate (n = 4) students. Informed consent was obtained for all participants, and no compensation was given.

2.2 Activities

Success in Refraction requires the user to demonstrate both spatial and mathematical competence. In order to distinguish between the neural activations that occur in response to math compared to spatial processing, it was necessary to observe the brain's response to both math (i.e., fractions) and spatial (i.e., screen navigation) processing individually, as well as to the combined processing expected during Refraction play. To that end, we developed three individual activities (Refraction, spatial, and math), each of which is described in detail below, which enabled us to compare cortical activation patterns across activity type. See "Appendix" for a detailed description of each activity, including visual examples.

2.2.1 Refraction Activity

Refraction is a computer-based math game that requires knowledge and application of fraction problem solving to complete. The game provides the user with an interactive interface, in which they attempt to provide power to spaceships that are lost in space. Each level of the game provides the user with a single stationary screen in which the entire level is completed (see Fig. 1). A laser is presented on each level, along with a varying number of stationary obstacles (e.g., rocks) that must be navigated around, and a catalog of tools including "benders" (i.e., bend the laser 90° in any direction) and "splitters" (i.e., split the laser into smaller proportions) that are used to provide each spaceship with the proportion of the laser it needs to re-power. In order to successfully complete each level the user must spatially navigate the laser around each obstacle, and also calculate and correctly split the whole laser into the fraction needed to power the spaceship.

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[1] Refraction may be found online at: http://centerforgamescience.org/?portfolio=refraction.

Fig. 1 Example Refraction level. The player must use a combination of laser benders and splitters (seen *on right*) in order to reduce the whole laser into thirds, and direct the reduced laser to the spaceship

Refraction has been shown to be useful for teaching students to solve fraction problems. Recent findings among a population of 4128 third-grade students indicated that repeated Refraction game-play significantly correlated with improved fraction performance (Baker et al. 2013; Martin et al. (2014) in preparation). The results of this study identified a significant change from pre- to post-level fraction problem solving success among 3rd grade students. Importantly, students' performance on a transfer test indicated that the fraction understanding gained from Refraction play generalized to a standardized fraction test.

2.2.2 *Spatial Activity*

It was important that the spatial activity performed by the participants be identical to the spatial actions performed in the Refraction game. To that end, the spatial activities used here were the same as those in the Refraction game, with the exception that splitting the lasers was not necessary to complete any level. Thus, the spatial activity required spatial reasoning without requiring processing related to fraction problem-solving. Greater activity in brain areas known to process math during Refraction compared to the spatial activity would provide important evidence that math activity may be separated from the spatial processing inherent in Refraction.

2.2.3 *Math Activity*

Similar to the development of the spatial activity described above, it was important to identify activation patterns related to math processing that occurred apart from spatial processing. Participants were given an assortment of Arabic numeral fraction addition and subtraction problems to solve on the computer. This enabled us to make activation comparisons between the math and Refraction activities to determine the degree to which neural response patterns differ within brain regions known to relate to math processing. Minimal differences in activation intensities between Refraction and math activities would indicate similar neural processing in response to both activities.

2.3 Brain Regions of Interest

The brain regions that relate highly with math and number processing have been well described elsewhere (Arsalidou and Taylor 2011; Menon et al. 2000). A meta-analysis by Arsalidou and Taylor (2011) highlighted significant parietal activation (i.e., left and right intraparietal sulci) during math and number processing. It is hypothesized that humans' ability to non-verbally represent and manipulate continuous quantities such as number and space emerges from regions within the right parietal lobe. Throughout development, and in particular with the onset of language, much of human's number processing begins to occur bilaterally, such that verbal math processing occurs in the left parietal region (Emerson and Cantlon 2014). The consistency among the research reported by Arsalidou and Taylor (2011) and others has led to the suggestion that numerosity perception is a primary sense (i.e., the number sense) that has been "hardwired" into the brain (see also, Dehaene 1997; Harvey et al. 2013). Also of importance for math processing are regions of the prefrontal cortex (PFC), which are thought to provide the working memory and attentional resources necessary to perform mathematics (Arsalidou and Taylor 2011). Together, these regions represent functional regions of interest to be targeted herein.

2.4 fNIRS Data Acquisition

Brain activation data were recorded with a continuous wave fNIRS system (ETG 4000, Hitachi Medical Co., Japan; see Plichta et al. 2006 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 3 × 5 optode caps. Each cap contained a total of 22 individual recording channels (seen in the numbered white boxes in Fig. 2). The caps were fastened to the participants' heads with elastic bands (see Fig. 2).

Optode cap placement was determined a priori, and was based on the brain regions of interest described above. In order to assure that each region of interest was captured by our probe cap placement, the 10–20 system was used to localization probe cap placement across participants (Okamoto, et al. 2004). The 10–20 system relies on individual head size

Fig. 2 Example optode patch placement

to localize brain regions. Namely, "10" and "20" refer to the fact that each location in the 10–20 system is either 10 or 20 % of the total distance between anatomical landmarks. First, naison-to-inion measurements along the midline were made for each participant. The point at exactly 70 % of the total distance from the naison identified the mid-point of the parietal lobe (i.e., Pz). Next, points were marked on a string of yarn to indicate each participants' naison, inion, and Pz locations respectively. In this manner, the string could be readjusted along the midline to the naison and inion points throughout the cap placement procedure so that Pz could be readily identified. The middle optode in the parietal cap was placed directly over Pz for each participant. In order to maintain placement of the pre-frontal probe cap, the middle column of optodes was placed along the midline, and the inferior edge of the cap was placed directly above the brow (see Fig. 2).

2.5 Procedure

Following receipt of informed consent, each participant was seated in front of a 15″ MacBook Air. Each activity (e.g., math, spatial, and Refraction) was described to the participants prior to beginning the task. For half of the participants, a brief practice period was given for the Refraction activity. The participants were told that each activity would occur in a random order, and that they should attempt to solve each activity as quickly and accurately as possible. Next, the fNIRS optodes were placed on the participant's head and the scan was started.

For each participant, each activity was repeated 10 times. The order of each activity was randomized prior to data collection, and the resulting order was used for each participant (i.e., pseudorandomization). Participants were given a total of 120 s to complete each activity trial. Each trial was followed by a 20 s rest period, during which participants were asked to sit quietly, close their eyes and clear their minds. Trials that were successfully completed prior to the 120-second time limit immediately progressed to the rest period prior to beginning the next trial. The average time to complete the entire session was 28.79 min (*SD* = 4.54 min, range = 23.2–36.5 min). Participants required an average of 9.07 min (*SD* = 1.93 min, range = 6.47–12.15 min) to complete the Refraction levels, 2.74 min for the spatial levels (*SD* = 0.76 min, range = 1.15–3.72 min), and 5.7 min for the math activities *(SD* = 2.68 min, range = 3.1–11.3 min).

2.6 Data Analysis

2.6.1 Non-technical Overview

In order to conduct data analysis, the collected data were filtered to remove interfering noise, revealing the signals of interest more clearly. Interfering noise included signals related to respiration, heartbeat, and blood pressure changes. Standard signal-processing and statistical techniques were applied to remove the noise and t-tests were conducted on the filtered data to reveal significant effects in activity (Refraction vs. Spatial, Refraction vs. Math, & Spatial vs. Math). In the figures below the statistical significance is represented by t-values, which are indicated on a gray-scale "heat map". That is, comparisons that are highly significant, and which have a correspondingly large t-value, are displayed as white, while non-significant comparisons are darker in color.

2.6.2 Technical Details

First, the raw fNIRS data were low-pass filtered to remove structured noise (i.e., autocorrelation) caused by physiological processes such as respiration, blood-pressure changes, and heartbeat (Worsley and Friston 1995). Next, the data were high-pass filtered with a cutoff of 128 s using a set of discrete cosine transform (DCT) functions to remove low frequency noise (Ye et al. 2009). The processed data for each participant were individually analyzed using a general linear model approach (GLM) optimized for event-related fNIRS designs (see Plichta et al. 2007 for detailed review). For each activity type the known onsets and durations of each trial were used to extract the oxygenated hemoglobin observations that occurred concurrently, and were then used to calculate standardized beta-weights. The value of the resulting beta-weights provided an indicator of the degree of neural activation during each activity (Plichta et al. 2007). This procedure was completed for each recording channel individually. Next, channel-wise beta-weights for each participant were combined for each group-level analysis. In order to identify significant differences in neural activation patterns across activity types, paired-sampled *t* tests were used to compare the group-level channel-wise beta-weights for each activity pairing (e.g., Refraction vs. Spatial, Refraction vs. Math, & Spatial vs. Math).

3 Results

The paired-sample *t* test results for each activity comparison are displayed graphically in Figs. 3, 4, 5. These heat maps provide t-values in the form of a gray scale range from black ($t = 0$) to white ($t =$ highest value in each comparison). Thus, white segments of each map represent large differences in brain activity between the conditions within each comparison. Each of the 22 fNIRS recording channels for each optode cap are superimposed on top of each map. Refer to Fig. 2 for optode patch and channel locations.

3.1 Refraction Versus Spatial Activities

Our results identified greater cortical activations within parietal and pre-frontal brain regions previously shown to be associated with math and number processing when participants engaged in Refraction compared to purely spatial activities. In particular, compared to spatial tasks, Refraction game play elicited greater activity within the fNIRS recording channels that coincided with the left (Fig. 3a, channels 1, 6, 10) and right (Fig. 3a, channels 8, 9) anterior intraparietal sulci. Increased activation can be seen in the form of white-colored circles atop channels 6 and 8 of the parietal optode patch. This result is important, as it supports our hypothesis that observable cortical activation patterns related to math processing may be identified during Refraction play, and that these patterns are not due to spatial processing alone. Within the PFC (Fig. 3b), activity differences were identified in the left dorsolateral region (i.e., channels 5, 6, 10), which has also previously been implicated in math processing. Moreover, an increase in activity in the right middle prefrontal (i.e., channels 3, 4, & 8) and middle dorsal prefrontal (i.e., channel 20) regions, suggests an increase in working memory and attention processes during Refraction compared to spatial activities.

3.2 Refraction Versus Math Activities

The differences identified in the left and right parietal regions between the Refraction and spatial activities reported above were not identified when we contrasted the Refraction and math activities (see Fig. 4a). Instead, cortical activation in the left parietal region was similar for both activities, indicating that Refraction and mathematics elicited similar

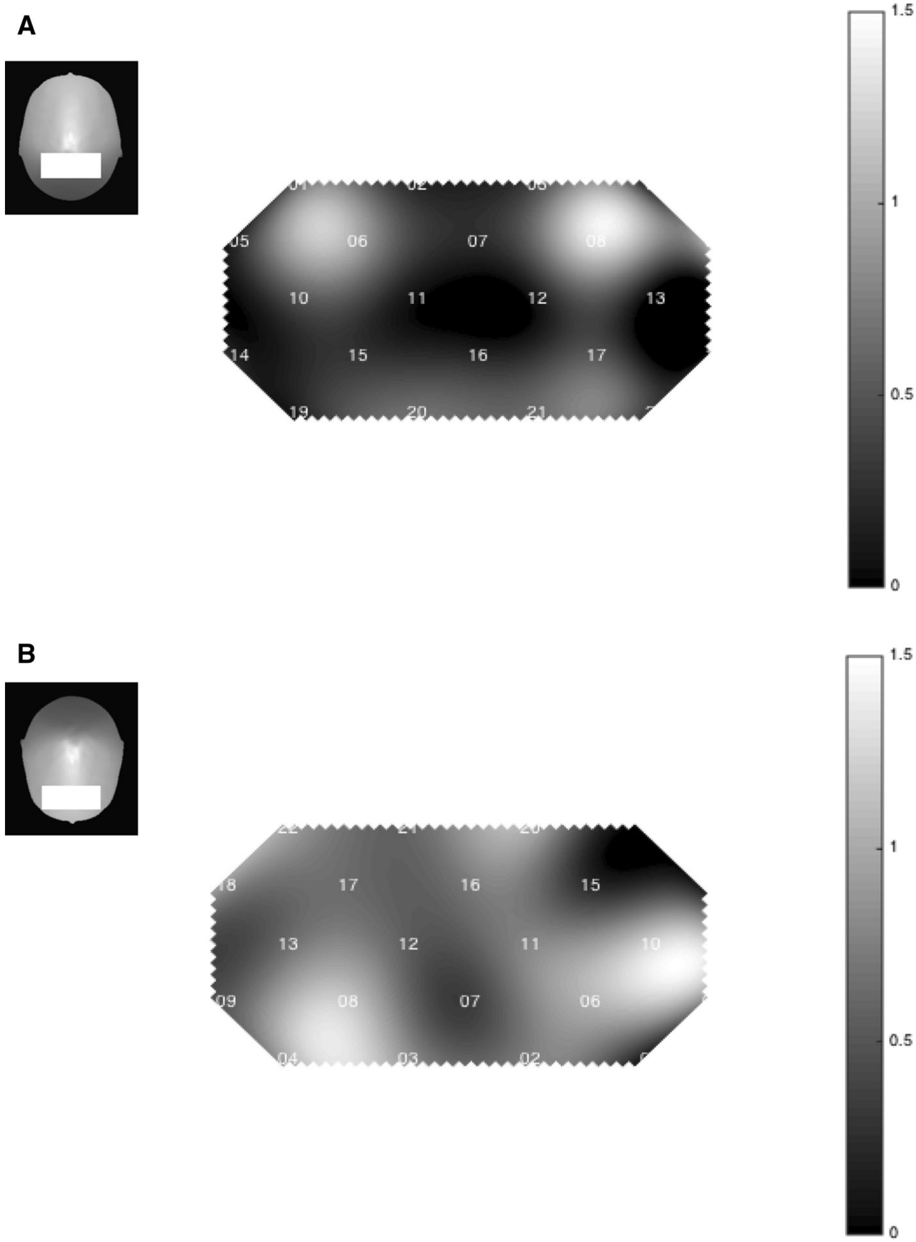


Fig. 3 Refraction versus Spatial activity t-value heat map. The inset image in the *top left* corner displays the cap arrangement on the head. **a** Parietal Optode Patch, **b** Prefrontal Optode Patch. Both scales range from t = 0–1.5. *Bright white* regions indicate greater activation for Refraction compared to the Spatial activity

levels of cortical activation within brain regions known to be related to verbal math and number processing. An increase in activity within the right anterior parietal region (Fig. 4a, channel 3, 7, 8, 12) suggests that non-verbal numerical and spatial processing may be greater during Refraction play compared to Arabic math problem solving. Conversely, the

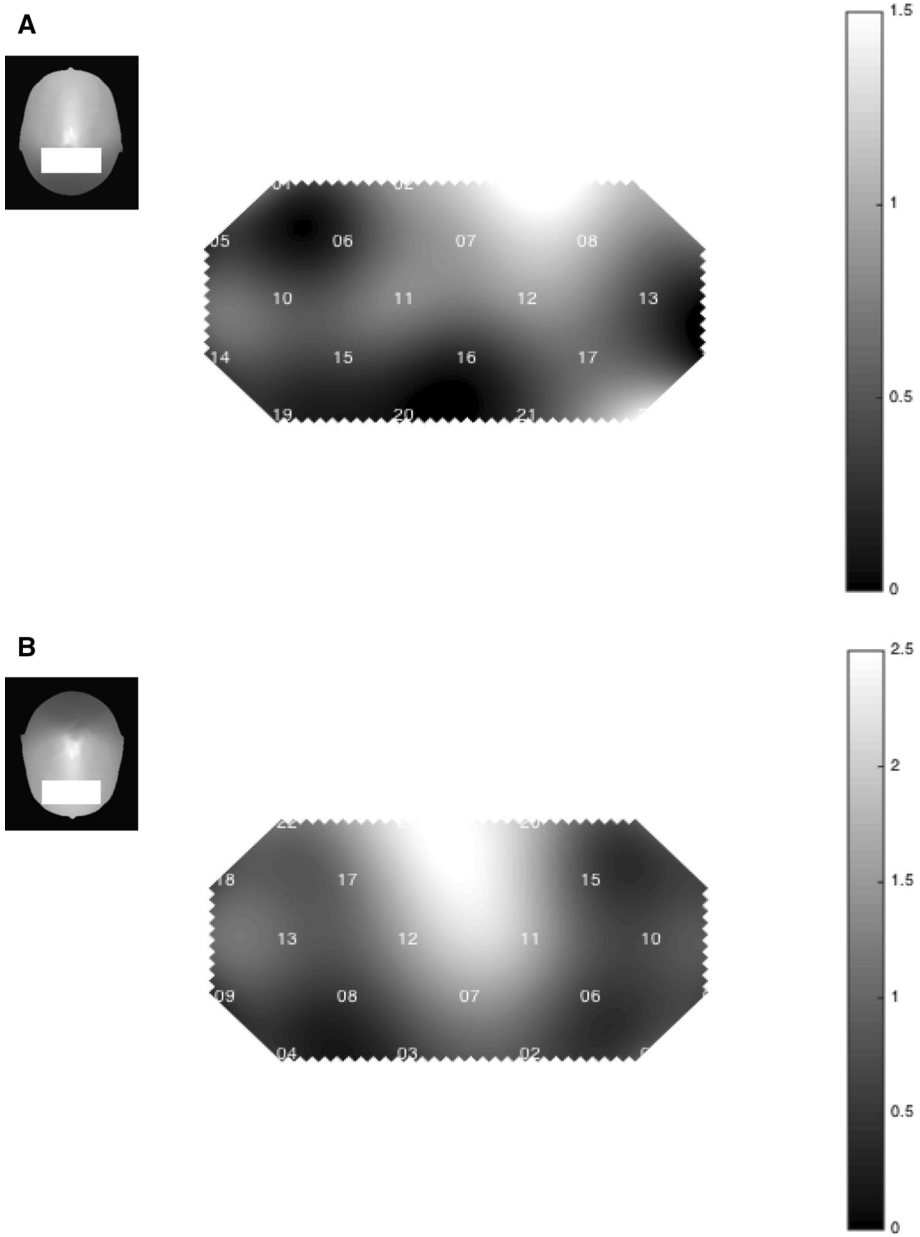


Fig. 4 Refraction versus Math activity t-value heat map. The inset image in the *top left* corner displays the cap arrangement on the head. **a** Parietal Optode Patch, **b** Prefrontal Optode Patch. The t-range from the parietal patch ranges between t = 0–1.5. The range for the prefrontal patch ranges from t = 0–2.5. *Bright white* regions indicate greater activation for Refraction compared to the Math activity

Refraction activity caused significantly greater cortical activation in the middle pre-frontal cortex compared to Arabic math problems. This effect may be attributable to an increased working memory load during Refraction compared to Arabic numeral mathematics.

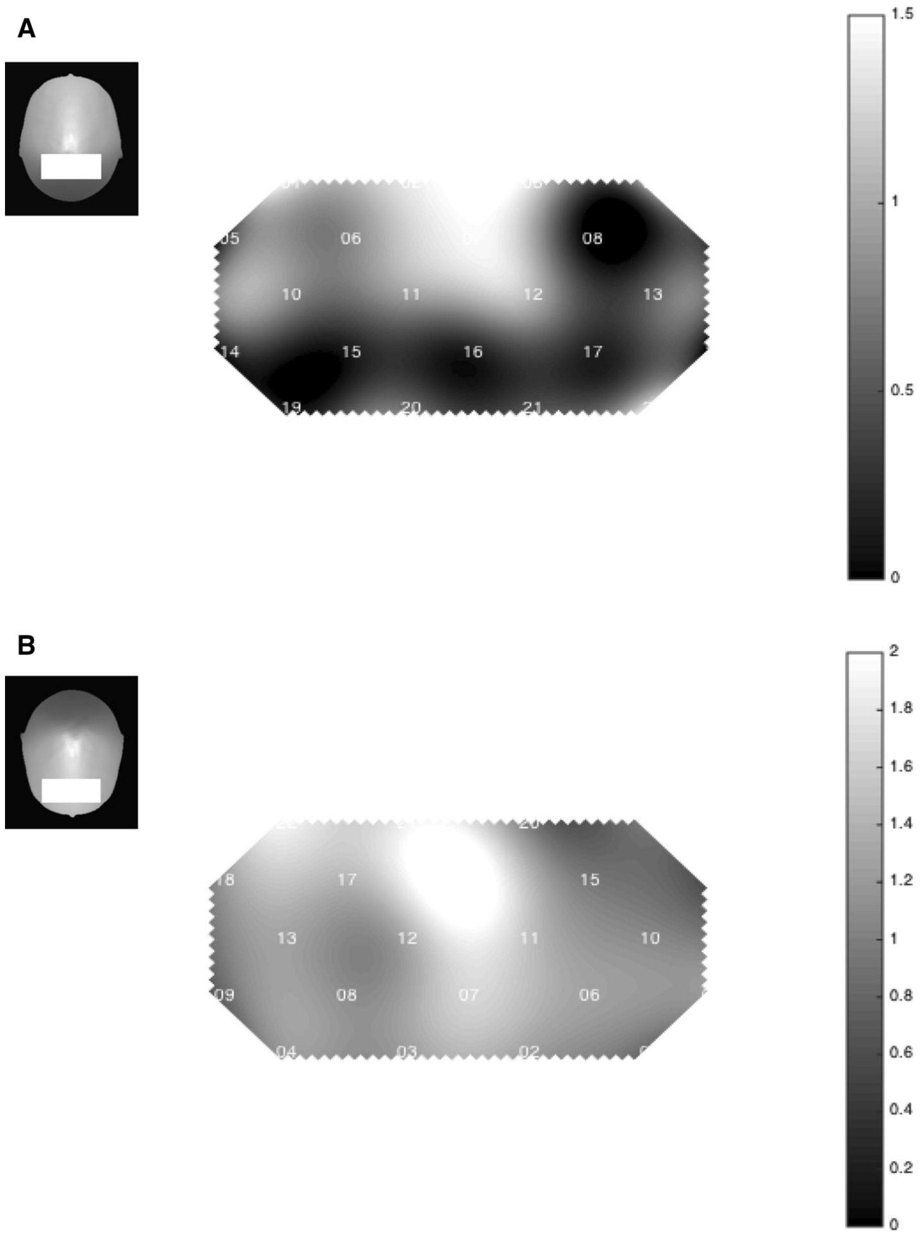


Fig. 5 Math versus Spatial activity t-value heat map. The inset image in the *top left* corner displays the cap arrangement on the head. **a** Parietal Optode Patch, **b** Prefrontal Optode Patch. The t-range from the parietal patch ranges between t = 0–1.5. The range for the prefrontal patch ranges from t = 0–2. *Bright white* regions indicate greater activation for Math compared to the Spatial activity

3.3 Math Versus Spatial Activities

Our results identify greater activity within the left and middle anterior parietal cortex during mathematics compared to spatial activities (see Fig. 5a). This result was expected, given the known relation between the left parietal region and verbal math processing. However, the right parietal region has been implicated in both spatial and non-verbal number processing. Because the Arabic math problems that we employed included elements of spatial processing (e.g., mathematical calculation of proportions requires spatial reasoning along with number processing), moderate amounts of right parietal activity during Arabic math problem solving was expected. Our results suggest that the activity in the right parietal region during Arabic mathematics was similar to the activity that occurred during the spatial activities. Within the prefrontal region, the math activity evoked significantly greater cortical activation related to working memory in the middle prefrontal cortex. Moreover, a general increase in activation during the math activity was seen over most other regions of the PFC as well, which was expected given the greater need for working memory and attentional processes during arithmetic compared to spatial activities.

4 Discussion

Our results demonstrate that Refraction play elicited neural activation in cortical brain regions commonly associated with math processing. In particular, cortical activations in the left parietal region were greater for Refraction than spatial activities, and were similar to the activations elicited during Arabic mathematics. Activations in the right parietal region, which has previously been associated with both non-verbal number and spatial processing, were greater during Refraction than both the spatial and Arabic math activities. Moreover, cortical activations in the prefrontal region, which is commonly associated with working memory and attention, were greater for Refraction than both spatial and Arabic math activities.

Taken together, our results suggest that cortical activations related to Refraction play are similar to those that result from traditional math activities commonly employed in studies of math cognition. While our results should be interpreted with caution for reasons outlined below, they do provide valuable proof-of-concept that Refraction may be used as a training stimulus throughout longitudinal fNIRS-based neuroimaging studies of math learning. Importantly, our results allow for the development of hypotheses that may be explored in a future large-scale investigations designed to further elucidate the behavioral and neural components of naturalistic math learning.

4.1 Practical and Theoretical Implications

The promise of educational neuroscience is to positively influence education for children of all abilities (Butterworth and Kovas 2013). Far from trivial, the results of such studies have significant practical and theoretical implications. As we develop a more firm understanding of how the brain responds to real-world math education, teachers may begin to make use of such findings, thus improving the educational method. For example, the identification of increased brain activations in response to particular aspects of a math-teaching tool may help educators design and implement more effective instructional tools. Indeed, children's psychophysical sensitivity to number, which is related to success in mathematics, is enhanced when redundant information about numbers is provided (Jordan and Baker 2011). It has been hypothesized that computer-based math learning tools may exploit such features, thus enhancing the learner's math-related psychophysical representations and improving math learning (Moyer-Packenham et al. 2014). Neuroimaging studies such as ours may help elucidate how the brain responds and adapts to math teaching tools, and how these adaptations coincide with changes in task performance.

Furthermore, neuroimaging studies such as ours may help uncover important correlations between a child's patterns of behavioral responding on math learning games and the patterns of brain activity they exhibit. "Big data" studies, which use the power of modern computing technology to mine the wealth of data collected when children play interactive math learning games such as Refraction, allow for in depth interrogation of each child's game play strategy and the resulting performance. The addition of brain activation information into such big data applications may yield unprecedented insight into the brain activation patterns that commonly relate to poor compared to high performance on such games. Taken together, such studies would provide educators with powerful information that may help triangulate the optimal teaching strategy for each child.

From a theoretical perspective, neuroimaging studies as participants are engaged in functional learning activities have the potential to re-write what is currently understood about how the brain processes mathematics. As discussed above, the seminal studies describing the brain's response to mathematics were conducted using fMRI. As a result, participants in these studies were forced to lay prone inside a large magnet bore and restrict all movement as much as possible. The ecological validity of such studies was severely diminished, and as a result, our understanding of how the brain responds in the real world remains largely unknown. Future applications of educational neuroscience using methodological approaches similar to ours may uncover surprising aspects of human cognition that have been missed due to the inherent constraints of many neuroimaging techniques.

4.2 Future Directions

In order for the practical and theoretical applications discussed herein to occur, it is important that future research studies expand and improve on our method. Moreover, multiple advances in fNIRS neuroimaging are currently being developed that may also have far-reaching implications for educational neuroscience. For example, real-time neurofeedback approaches using fNIRS have shown promise in improving executive functioning abilities in patients with attention deficit hyperactivity disorder (ADHD). That is, children with ADHD and other executive functioning deficits often exhibit diminished cortical signatures of activation relative to neurotypical peers. By requiring participants to increase a visual representation (e.g., heat map) of their own real-time cortical activations related to executive functioning, behavioral signatures of executive functioning are enhanced. Future applications of these methods applied to math learning may have far reaching implications for math learning treatments within populations with math learning disabilities.

Furthermore, advances in fNIRS-based hyperscanning (i.e., simultaneous neuroimaging of two or more individuals engaged in social interactions) may uncover important interpersonal aspects of cognition that occur when children engage in math learning tasks together. Emergent research has demonstrated significant inter-brain coherence that occurs when participants engage in social interactions (Cui et al. 2012). Notably, increases in inter-brain coherence are known to coincide with enhanced behavioral performance. Given the highly social nature of the typical elementary school classroom, it is imperative that social cognition also be investigated in relation to math processing. Thus, future studies may employ a fNIRS-based hyperscanning paradigm throughout real-world group math activities with the hopes of identifying unique signatures of social- and math-related processing that together influence the math learning process.

4.3 Limitations

As mentioned above, because the current project was intended to serve as a pilot study for a large-scale fNIRS-based investigation of math learning using Refraction as a training stimulus, it is important that the current results be interpreted with caution. First, our statistical analyses were underpowered due to our small sample size, resulting in an inability to identify appropriate levels of statistical significance. Future studies must adjust for this by including larger samples of participants. Moreover, because of our low sample size, correction for Type I error due to multiple testing was not conducted. It is important that future studies employ an appropriate statistical correction procedure (e.g., false discovery rate correction) to account for false positive outcomes. Finally, it is likely that spatial processing may have been confounded in the subset of the Arabic math problems we employed. That is, some questions required the participants to navigate a number line to solve math problems (see "Appendix"). This activity likely evoked spatial processing, which would have been convolved within the math-processing signal captured by fNIRS. Future studies should take care to develop more appropriate control tasks that do not correlate so highly with the processes needed to complete the Refraction activity.

Aside from the statistical constraints of our current design, it is important that future studies more appropriately account for individual differences in the populations recruited for participation. For example, it is impossible to discern the underlying differences in brain activations across each activity. It is likely that individual differences in participants' baseline understanding of mathematics may have influenced the cortical signatures that we observed. Indeed, differences in the intensity and spatial distribution of math-based brain activations are related to differences in math proficiency (Cantlon and Li 2013). Thus, future studies should take care to thoroughly assess participants' understanding of the math domains they seek to test, and to incorporate such information into their brain activation analyses.

5 Conclusion

The results of the current study set the stage for future large-scale studies of math learning using a combination of fNIRS and Refraction. As we have demonstrated above, fNIRS provides a useful platform that may be used to observe the brain's response to naturalistic math learning tasks such as Refraction. Future studies may capitalize on the groundwork set by our findings, and may extend the application of fNIRS throughout different aspects of mathematics, as well as other educational domains. Given the high probability that these and other applications of neuroscience will positively impact education, the future of educational neuroscience is bright. Importantly, because the cost of imaging approaches such as fNIRS are low, and training to implement such technology is minimal, it is reasonable to believe that fNIRS and other similar tools may one day be adopted by individual schools to better serve their students. It is important that today's researchers work together to bring such a future to fruition.

Appendix: Activity Descriptions

For the purposes of this study we used three different activities: mathematics, spatial negotiation, and Refraction. Each activity is described in detail below:

Mathematics: Each participant completed a number of mathematical problems that fell into one of five categories: fraction and decimal comparison (see Table 1, a); splitting (see Table 1, b), number line (see Table 1, c), fraction identification (see Table 1, d), and fraction addition (see Table 1, e).

Spatial levels: Each participant completed a series of spatial negotiation activities in which they were required to bend a whole laser into the target. These activities were identical to the Refraction activities described below, although they did not require the participant to spit the laser (see Table 2).

Table 1 Mathematics examples

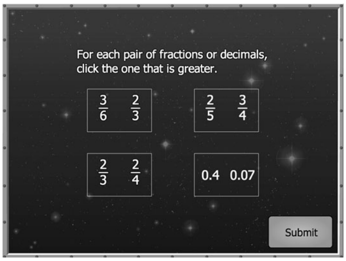
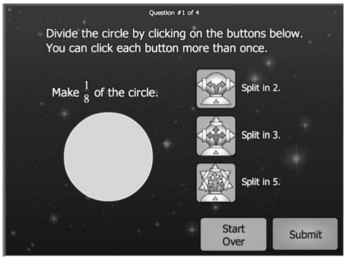
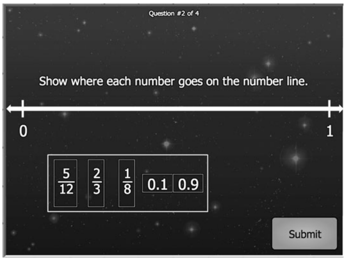
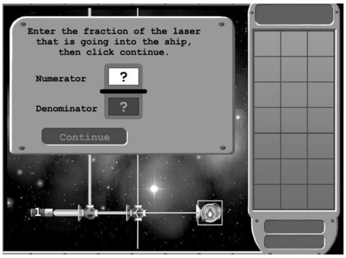
a. Fraction and decimal comparison  For each pair of fractions or decimals, click the one that is greater. 	This problem category assessed participant's ability to compare fractions and decimals
b. Splitting  Question #1 of 4 Divide the circle by clicking on the buttons below. You can click each button more than once. Make $\frac{1}{8}$ of the circle. 	This problem category assessed participant's ability to split a circle using their knowledge of fractions
c. Number line  Question #2 of 4 Show where each number goes on the number line. 	This problem category assessed participant's ability to order fractions and decimals on a number line
d. Fraction identification  Enter the fraction of the laser that is going into the ship, then click continue. Numerator ? Denominator ? 	This problem category assessed participant's ability to identify fractions

Table 1 continued

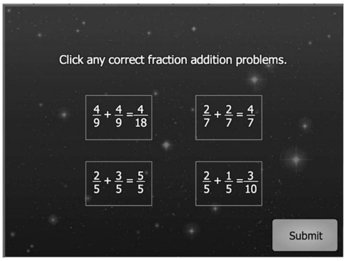
e. Fraction addition  Click any correct fraction addition problems. $\frac{4}{9}+\frac{4}{9}=\frac{4}{18}$ $\frac{2}{7}+\frac{2}{7}=\frac{4}{7}$ $\frac{2}{5}+\frac{3}{5}=\frac{5}{5}$ $\frac{2}{5}+\frac{1}{5}=\frac{3}{10}$ 	This mathematical level assessed participant's ability to add fractions together

Table 2 Spatial Negotiation examples

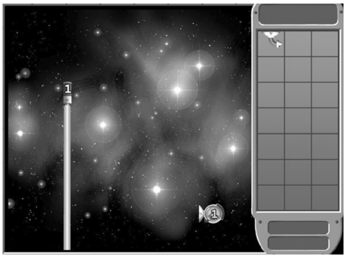
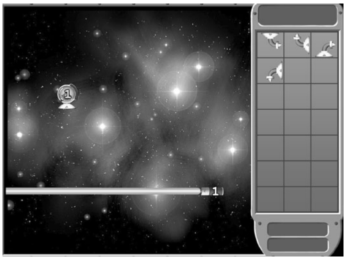
a.  	These activities acted as a control for the mathematical and Refraction activity, as they required the same physical movements to complete but did not require mathematical processing
b.  	

Table 3 Refraction examples

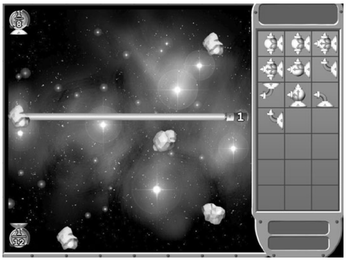
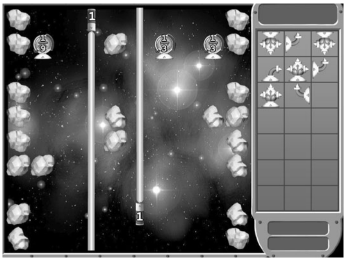
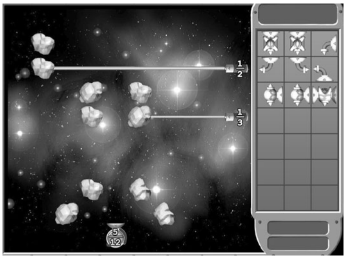
a.  	In this example, the participant must correctly place a series of laser "benders" and "splitters" in the path of the whole laser to correctly feed a 1/8 proportion of the laser to the top target and a 1/12 proportion to the bottom target

Table 3 continued

b. 	In this example, the participant must correctly split and bend two whole lasers to correctly feed 1/9, 1/3, and 1/3 proportions to each respective target
c. 	In this example, the participant must correctly bend, split, and combine two laser fractions to correctly feed a 5/12 proportion to the target

Refraction levels: The Refraction activities required a combination of mathematical and spatial processing to accurately complete (see Table 3).

References

Ansari, D., Garcia, N., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic number processing in children and adults. *NeuroReport, 16*, 1769–1773.

Arsalidou, M., & Taylor, M. J. (2011). Is 2 + 2 = 4? Meta-analysis of brain areas needed for numbers and calculation. *NeuroImage, 54*, 2382–2393.

Baker, S., Petrick-Smith, C., Martin, T., Aghababyan, A., Popovic, Z., Andersen, E., et al. (2013). Learning fractions through splitting in an online game. Paper presented at the American Educational Research Association Annual Conference, San Francisco, CA.

Bodner, M., & Shaw, G. L. (2004). Symmetry math video game used to train profound spatial-temporal reasoning abilities equivalent to dynamical knot theory. In R. T. Sharp & P. Winternitz (Eds.), *Symmetry in physics: In memory of Robert T. Sharp* (Vol. 34, pp. 189–201). Providence, RI: American Mathematical Society.

Butterworth, B., & Kovas, Y. (2013). Understanding neurocognitive development can improve education for all. *Science, 340*(6130), 300–305.

Cantlon, J. F., & Li, R. (2013). Neural activity during natural viewing of Sesame Street statistically predicts tests scores in early childhood. *PLoS Biology, 11*(1), e1001462.

Center for Game Science (2013). Refraction [Softward}. Available from http://centerforgamescience.org/.

Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage, 59*, 2430–2437.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. New York, NY: Oxford University Press.

Dresler, T., Obersteiner, A., Schecklmann, M., Vogel, A. C. M., Ehlis, A. C., Richter, M. M., et al. (2009). Arithmetic tasks in different formats and their influence on behavior and brain oxygenation as assessed with near-infrared spectroscopy (NIRS): A study involving primary and secondary school children. *Jouranl of Neural Transmittion, 116*(12), 1689–1700.

Emerson, R. W., & Cantlon, J. F. (2014). Continuity and change in children's longitudinal neural responses to numbers. *Developmental Science, 18*(2), 1–13.

Harvey, B. M., Klein, B. P., Petridou, N., & Dumoulin, S. O. (2013). Topographic representation of numerosity in the human parietal cortex. *Science, 341*, 1123–1126.

Hu, W., Bodner, M., Jones, E. G., Peterson, M. R., & Shaw, G. L. (2004). Data mining of mathematical reasoning data relevant to large innate spatial-temporal reasoning abilities in children: Implications for data driven education. In *Society for neuroscience Abst 34th annual meeting*.

Jordan, K. E., & Baker, J. M. (2011). Multisensory information boosts numerical matching abilities in young children. *Developmental Science, 14*(2), 205–213.

Kawashima, R., Taira, M., Okita, K., Inoue, K., Tajima, N., Yoshida, H., et al. (2004). A functional MRI study of simple arithmetic: A comparison between children and adults. *Cognitive Brain Research, 18*(3), 227–233.

Kesler, S. R., Sheau, K., Koovakkattu, D., & Reiss, A. L. (2011). Changes in frontal-parietal activation and math skills performance following adaptive number sense training: Preliminary results from a pilot study. *Neuropsychological Rehabilitation, 21*(4), 433–454.

Kucian, K., von Aster, M., Loenneker, T., & Martin, E. (2008). Development of neural networks for exact and approximate calculation: A fMRI study. *Developmental Neuropsychology, 33*(4), 447–473.

Martin, T., Petrick-Smith, C., Forsgren, N.F., Aghababyan, A., Janisiewicz, P., & Baker, S. (2014). Learning fractions by Splitting: Using learning analytics to illustrate the development of mathematical understanding. (Mansucript submitted for publication).

Martin, T., Smith, C. P., Andersen, E., Liu, Y. E., & Popovic, Z. (2012). Refraction time: Making split decisions in an online fraction game. In American Educational Research Association Annual Meeting, AERA.

Menon, V., Rivera, S. M., White, C. D., Glover, G. H., & Reiss, A. L. (2000). Dissociating prefrontal and parietal cortex activation during arithmetic processing. *NeuroImage, 12*(4), 357–365.

Moyer-Packenham, P., Baker, J. M., Westenskow, A., Anderson, K., Shumway, J. F., & Jordan, K. E. (2014). Predictors of achievement when virtual manipulatives are used for mathematics instruction. *REDIMAT- Journal of Research in Mathematics Education, 3*(2), 121–150.

Moyer-Packenham, P., Baker, J. M., Westenskow, A., Rodzon, K., Anderson, K., Shumway, J., & Jordan, K. (2013). A study comparing virtual manipulations with other instructional treatments in third- and fourth-grade classrooms. *Journal of Education, 193*(2), 25–39.

Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., et al. (2004). Three-dimensional probabilistic anatomical crani-cerebral correlation via the international 10–20 system oriented for transcranial functional brain mapping. *NeuroImage, 21*, 99–111.

Plichta, M. M., Heinzel, S., Ehlis, A. C., Pauli, P., & Fallgatter, A. J. (2007). Model-based analysis of rapid event-related functional near-infrared spectroscopy (NIRS) data: A parametric validation study. *Neuroimage, 35*, 625–634.

Plichta, M. M., Herrmann, M. J., Baehne, C. G., Ehlis, A.-C., Richter, M. M., Pauli, P., & Fallgatter A. J. (2006). Event-related functional near-infrared spectroscopy (fNIRS): Are the measurements reliable? *NeuroImage, 31*, 116–124.

Rivera, S. M., Reiss, A. L., Eckert, M. A., & Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex, 15*(11), 1779–1790.

Rosenberg-Lee, M., Barth, M., & Menon, V. (2011). What difference does a year of schooling make? Maturation of brain response and connectivity between 2nd and 3rd grades during arithmetic problem solving. *NeuroImage, 57*, 796–808.

Worsley, K. J., & Friston, K. J. (1995). Analysis of fMRI time-series revisited-again. *NeuroImage, 2*, 173–181.

Ye, J. C., Tak, S., Jang, K. E., Jung, J., & Jang, J. (2009). NIRS-SPM: Statistical parametric mapping or near-infrared spectroscopy. *NeuroImage, 44*, 428–447.