

NeuroMat - A Brain+Foot Embodied Interface to Support Children with ADHD and Learning Disabilities: An Exploratory Study

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ABSTRACT

Prior research suggests that physical activity aids students with children affected by attention deficit hyperactivity disorder (ADHD) who are more likely to exhibit high levels of inattentive, hyperactive, and impulsive behaviors that result in difficulties in academic and social settings. Because of the lack of alternative treatments, the symptoms of ADHD are typically treated with medication. Physical activity has been shown to enhance classroom attention and overall performance, and neurofeedback used as a treatment for ADHD can successfully reduce negative behavioral symptoms. In this exploratory paper, we present the design, implementation, and initial evaluation of the NeuroMat, a device to enhance the attention of persons with ADHD through an adaptive user interface with an embodied, foot-controlled interface and real-time neurological feedback. NeuroMat combines cognitive training in mathematics with real-time neurofeedback in a device that enhances attention in elementary school students to improve academic performance. Our initial evaluation of 39 elementary students from Southwestern United States provides preliminary evidence that attention and academic performance are enhanced using NeuroMat. Given the substantial cost of ADHD treatment and management, this inexpensive and relatively effective system like NeuroMat can be used in classroom settings especially in economically developing countries.

Keywords: *Assistive educational technologies; ADHD; Cognitive disabilities; Special Education*

INTRODUCTION

Attention deficit hyperactivity disorder (ADHD) is a neurobehavioral disorder frequently diagnosed in early childhood (as early as three years old) and often lasting through adolescence and into adulthood. People with ADHD demonstrate difficulties in focusing and paying attention to specific activities, understanding the effect of actions, and acting with consideration about the consequences of actions, and generally expose behavior that might be impulsive and overly active. Prior research suggests that physical activity aids students with ADHD in classroom success (Azrin et al., 2006; Bell et al., 2010; Panksepp, 2007; Pellis et al., 2010; Six & Panksepp, 2012). The practicality of engaging students with ADHD in physical activities before a regular classroom has been questioned by researchers (Rief, 2005), as it is challenging to integrate into a class.

In this paper, we propose an inexpensive, non-intrusive, portable infrastructure that uses neurofeedback to increase attention and the effects of play on concentration for persons with

ADHD. Students engage in embodied physical activities (Dourish, 2001; Klemmer et al., 2006) while participating in learning tasks and overcoming barriers to integration. Our system, *NeuroMat* (initially referred to as the Digital Mat project), supports *cognitive learning* (via a focused task that adaptively changes based on performance and attention) and *neurofeedback* (where attention is continually measured while performing the cognitive learning task) while the user is actively moving the entire body. Additionally, the platform implements multiple real-time feedback mechanisms (audio, visual, haptic) to indicate performance. With *NeuroMat*, we aim to increase the attention of ADHD children while learning or practicing basic mathematical concepts. Math is a significant barrier for all children but is an even larger problem for children with ADHD (Lucangeli & Cabrele, 2006). This initial user study discussed herein indicates promising results.

The remainder of this paper is organized as follows. Our background section discusses the challenges of educating students with ADHD, neurological feedback devices, and prior related work. We then discuss the design and implementation of the *NeuroMat* system, followed by an initial evaluation. We conclude our paper by discussing the results, identifying the *NeuroMat* design as a promising interface to support ADHD-affected students in several domains.

BACKGROUND

Our background covers research into supporting students with ADHD, using neurological feedback devices in the context of supporting ADHD learners, and an investigation of prior research related to our own.

Educating Students with ADHD

Over time, we have witnessed sharp changes in the number of diagnosed cases of ADHD; since the first ever ADHD National survey (initially conducted in 1999), the literature has demonstrated a clear increasing trend in the estimated incidence of ADHD (possibly as a result of improved societal awareness and diagnostic instruments. Research shows that the prevalence of ADHD in the United States for youth in the 4–17 range has been about 4.1 million (Visser et al., 2013). While the causes of ADHD are still controversial (Thapar et al., 2013), the impacts of its symptoms on a child's ability to focus, function, and coexist in an educational environment are clear. Both inattentive behavior and hyperactive-impulsive behavior (the two predominant traits of ADHD) are antithetical to the need for concentration and discipline that are required to achieve satisfactory performance in learning and in the classroom. This is particularly severe in learning disciplines where sustained attention is critical (e.g., mathematics and sciences).

The literature has highlighted the potential benefits of physical activity and stimuli (Azrin et al., 2006; Bell et al., 2010; Panksepp 2007; Pellis et al., 2010; Six & Panksepp, 2012) in enhancing classroom attention and overall subject-level performance such as mathematics (Bailey, 2009). The combination of physical activity with a reward mechanism or other form of positive reinforcement has also been repeatedly demonstrated to be effective in increasing attention and focus in subjects with ADHD (Abramowitz & O'Leary, 1991; Crain, 2005). These combined results encouraged research exploring the role of recreational physical activities in building attentiveness and calmness during learning activities (Azrin et al., 2007; Cooley, 2007).

Neurological Feedback Devices

Devices that measure neurological signals, such as electroencephalography (EEG), have been used both in the diagnosis and treatment of ADHD (Chabot et al., 2001; Clarke et al., 2001a; Loo & Barkley, 2005). EEG is noninvasive and provides excellent temporal resolution (measures changes in brain activity in milliseconds). The spatial resolution sometimes makes it difficult to determine precisely where the EEG signal is coming from. Early studies using EEG found that

children with ADHD exhibit EEG abnormalities such as excess slow wave activity compared to children without ADHD.

EEG signals are a mixture of several different frequency bands that can be decomposed into separate single frequencies. When examining EEG data, clinicians look at activity within a specific frequency band. Each particular band is associated with specific behavioral characteristics, and therefore, in conjunction with a characterization of patient behavior, EEG can be used as a diagnostic tool for ADHD. These frequency bands, associated behavior, and their relation to ADHD is as follows (Loo & Barkley, 2005):

1. Delta (< 4 Hz; Hz = cycles per second): Sleep, unconscious; increased in some ADHD, normal or decreased in others.
2. Theta (4–7 Hz): Drowsiness, unfocused; increased in frontal and central area of brain in ADHD, continues into adulthood.
3. Alpha (8–12 Hz): Eyes closed, relaxed, but alert; mixed findings, perhaps depending on age and gender.
4. Beta (> 13 Hz): Mental activity, concentration; decreased in some but not all ADHD children, may normalize in adults.

EEG data for persons with ADHD is most commonly characterized by increased theta and diffused decreased beta activity (Chabot et al., 2001; Chabot & Serfontein 1996; Clarke et al., 2001a; Clarke et al., 2001b; Loo & Barkley, 2005). Some have suggested that the theta/beta ratio is consistently different than normal in those with ADHD, is associated with cortical arousal, and remains stable over time (Clarke et al., 2001b; Monastra et al., 2001).

Because beta activity is associated with concentration, the theta/beta ratio is often used to measure attention in persons with ADHD (Cho et al., 2002; Johnstone, 2013; Wang et al., 2007). When using EEG in treatment of ADHD, the patient is trained to decrease their slow wave and increase their fast wave brain activity through an interface that displays the EEG frequency bands. Using EEG as an alternative treatment to medication has been shown to decrease negative behaviors associated with ADHD, although some argue that many of these studies are fundamentally flawed (Loo & Barkley, 2005). In our work, we use the NeuroSky Mindset to measure attention levels using EEG; this device has been shown to accurately measure attention (Crowley et al., 2010; Haapalainen et al., 2010; NeuroSky, 2009a; NeuroSky, 2009b; Rebolledo-Mendez et al., 2009) and has been used successfully in several neurofeedback devices (Mostow et al., 2011; Xu et al., 2011; Yasui 2009).

Related Work

Although the body of work pertaining to the benefits of cognitive training and neurofeedback to increase attention in persons with ADHD is large, the body of research that implements technology using these methods is significantly smaller. Much of this work incorporates using cognitive learning in conjunction with neurofeedback in a system to increase attention and performance. Few of these systems explicitly utilize the aspect of play or motion as an aid to increase attention in addition to neurofeedback as our system does.

The work of Cress et al. (2010) on using a digital dance mat to train kindergarten students is the most relevant to our research. This work aims to increase the basic numerical skills of kindergarten children through a digital dance mat that requires movement of the entire body to respond to a magnitude comparison task. The dance mat embodies the theory that there exists a connection between cognition and action (Lakoff & Johnson, 1999). With the dance mat, they implement an

architecture that combines number perception and motion, tested with 19 kindergarten children. Compared to a PC-based implementation of the same task, children using the dance mat made significant improvements in accuracy or correctness with reduced reaction times. Fischer et al. (2011) conducted a similar study using the digital dance mats and obtained similar results.

Cho et al. (2002) present a virtual reality (VR)-based classroom that implements cognitive training and neurofeedback to increase attention of persons with ADHD. They create a simple virtual classroom with few distractions and the subject has an avatar that is the only “person” in the classroom. Subjects are given two types of cognitive training exercises. One is intended for quick response (short attention span) and the other aims to enhance sustained attention. Neurofeedback is used in the sustained attention tasks to adaptively select task level of difficulty. Using 20 test subjects, they show that their VR system significantly enhances attention in persons with ADHD.

Another notable work investigates the effect of Concept Mapping software use for students with ADHD, when they learn descriptive writing at the secondary level education (Riga & Papayiannis, 2015). The authors conclude that use of Concept Mapping software in writing activities benefits the students with ADHD but with a caveat: the technology must attract the attention and interest of the students and it must be deeply embedded in the teaching process.

Additional work aims to develop various systems or platforms that use EEG to enhance performance through neurofeedback (Mostow et al., 2011; Wang et al., 2007), but these are not intended for persons with ADHD or learning disabilities. Other prior work has sought to support people with ADHD without using neurofeedback and/or embodied interaction. Specifically, Weisberg et al. (2014) use tangible interaction to support morning routines, a challenge for children with ADHD. Malinverni et al. (2014) use full-body interaction with a Microsoft Kinect to engage social skills. To support students with special needs, Puccini et al. (2013) recommend designing to engage learners through multiple modalities and providing continuous feedback during learning, principles which we adopt in the design of NeuroMat.

NEUROMAT

The NeuroMat interface is developed by one of the authors of this study and is intended to be used for cognitive training to increase attention and thereby result in improved learning for children and, potentially, adults. Although it has been designed to also be used as a neurofeedback training device to treat the symptoms of ADHD, in this paper, we use the NeuroMat to increase attention and improve learning in basic mathematics. NeuroMat requires that users move in order to respond to mathematics questions. It provides attention-based neurofeedback to help students become mindful of their mental state and uses EEG data to help drive question difficulty. We have initially created a single NeuroMat system that we use for testing and evaluation and developed an application area for it: basic mathematics.

The NeuroMat is designed to be low-cost, portable, and used in a special-education classroom with little supervision by the teacher. Users can be quickly trained to use the system and can thereafter easily work independently. NeuroMat is an integrated hardware and software system with four components: a main computer, a neurofeedback device/headset, a haptic feedback wristband, and a pressure-sensitive mat. Figure 1 (see below) provides a system diagram describing the system as a whole.

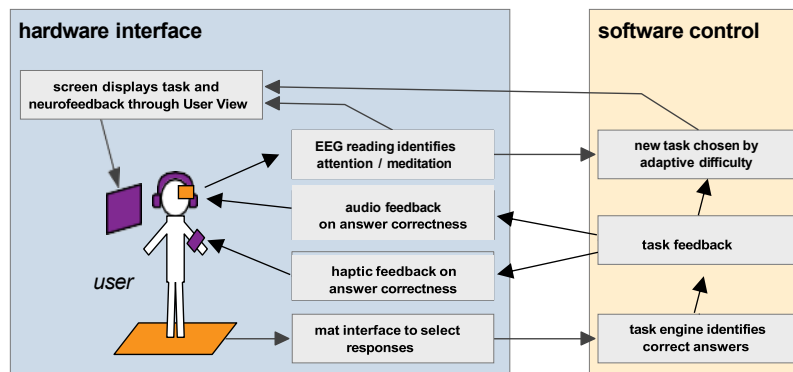


Figure 1: System diagram for NeuroMat interface

Motivation

NeuroMat brings together a number of components to create a cohesive experience for ADHD-affected learners. We developed the feedback mechanisms (visual, audible, haptic) based on prior research suggesting that multiple feedback mechanisms support learning-challenged students (Puccini et al., 2013). Further, since we can identify neurofeedback that best supports ADHD-affected students, we can provide this information to them as well, to help them understand their own mental states. Our use of embodied interaction, having students engage their bodies to select answers to questions, was driven by prior research showing that physical activity helps ADHD students to concentrate. Finally, we selected basic mathematics as a learning domain because our own interviews with special education teachers indicated that this was an area students found challenging, a point supported by prior research (Lucangeli & Cabrele, 2006; Zentall, 2007).

Hardware

The NeuroMat hardware includes a consumer-grade EEG headset, a mat for foot-based interactions, and a haptic feedback wristband, in addition to the computer on which the mathematics tasks are displayed.

EEG Headset

We use the NeuroSky eSense System (NeuroKey, 2009a; NeuroSky, 2009b) as our brain-computer interface (BCI) that uses EEG signals to measure brain activity. The NeuroSky headset uses a proprietary algorithm to convert the EEG signal frequencies to an Attention and Meditation rating. The higher the Attention rating, the more focused the subject is, the more brain activity is occurring in the beta frequency range. Meditation is a state of low brain activity (Delta through Alpha), where the subject is relaxed with little focus. Based on prior research, we expect ADHD students to function best when their EEGs show activity in the beta range (Loo & Barkley, 2005).

Foot-Based Interactive Mat

The 0.9m × 0.9m × 3mm black rubber mat is equipped with pressure sensors under each of the four squares (red, green, blue, yellow, and (rectangular) white) as shown in Figure 2, based on the design of a Dance Dance Revolution input pad (Andrews, 2007). The output from these sensors is read by a microcontroller that determines which square is activated (explained below); this information is passed as input to the computer to be used in the cognitive training exercise, which is solving a basic math problem.

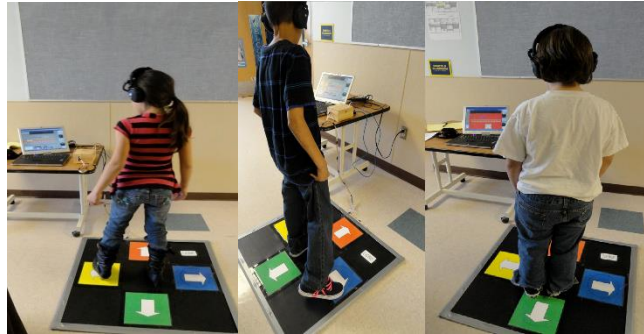


Figure 2: Children using the NeuroMat system to undertake mathematics tasks.

In Figure 2, the children are wearing the NeuroSky headset and standing on the mat interface; the User View is showing on the screen in front of them.

The mat comprises four colored squares that enable the user to control the direction of the cursor on the number line displayed on the computer screen. It also has a white Done rectangle that is tapped by the user to communicate to the computer that an answer is complete. Under each of the shapes (squares and the rectangle) there is a force-sensitive resistor (FSR) with a square, 4.5cm × 3.8cm sensing area. Each FSR is connected to 5V on one end and to a digital input pin on the microcontroller on the other end.

An FSR will vary its resistance depending on how much pressure is being applied to the sensing area. The harder the force, the lower the resistance. When no pressure is being applied to the FSR its resistance is greater than 1Mohm. This FSR can sense applied force anywhere in the range of 100g–10kg.

Haptic Feedback Wristband

The vibration motor used for haptic feedback through the wristband is a tiny vibratory motor with a 2–3.6V operating range. These units shake vigorously at 3V. All moving parts are protected with a housing to provide user safety.

Software

The interactive software component includes a set of education tasks for the user to perform using the mat while the system monitors the user's attention. There are presently six levels of difficulty. Levels 1–3 implement addition problems; levels 4–6 implement subtraction. The system initializes to a default difficulty of 3.

Dynamic Difficulty Adjustment

Using the NeuroSky headset, we are able to provide the user with constant feedback about her/his mental state. The User View (Figure 3) provides the user with a bar graph of her/his attention level. *Attention* is a state of alertness and is characterized by high frequency brain activity, as determined by the NeuroSky eSense system. Attention levels are tracked while the user is solving problems and is stored in a database for later analysis.

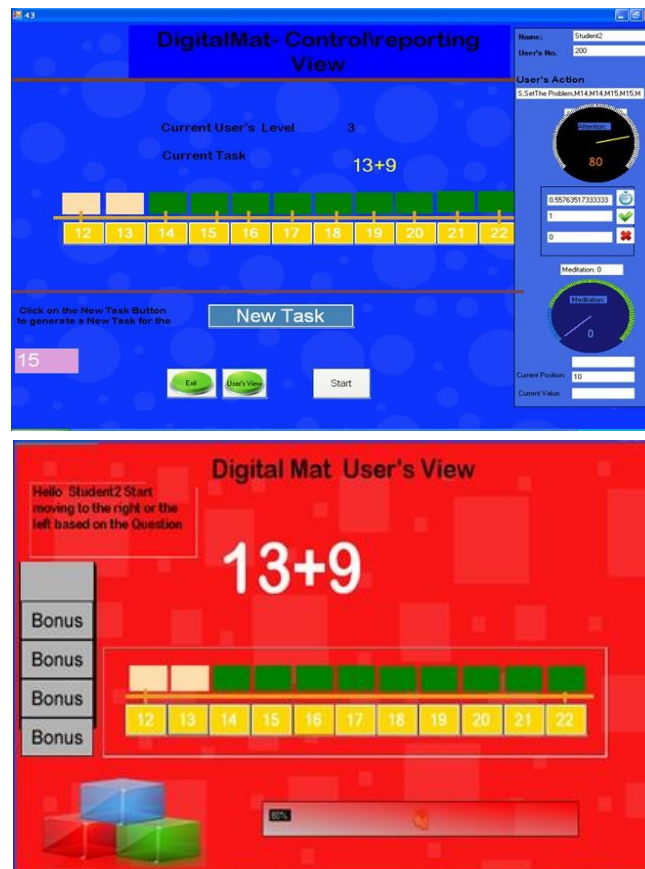


Figure 3: The NeuroMat Instructor View (IV) (top) and User View (UV) (bottom).

In Figure 3, the IV is used to configure the UV to select the current mathematic task for the student; it provides constant feedback about the user's current mental state. The UV is the view that students see while using NeuroMat. It includes the current question (center in white), the number line from which the user selects a response (the set of green and yellow boxes in the center), and the user's current attention level (the red meter at the bottom).

For the instructor, the Instructor View shows both attention and meditation, visualized as analog gauges. *Meditation* is relaxed state characterized by slow (low frequency) brain waves. The analog feedback gauges in the Instructor View were eliminated on the User View screen after initial testing due to the high level of distraction it caused for the users.

As the user progresses, her/his level of difficulty is dynamically adapted according to the algorithm in Table 1. If the user performs well by answering questions correctly and/or exhibiting a high level of attention, the level of difficulty is automatically increased. The difficulty level is similarly decreased when the user answers incorrectly and/or has a low level of attention. The algorithm is based on the hypothesis that users who are engaged and/or having difficulty will have a high attention, while users who are disengaged will have a low attention rating.

Table 1: Difficulty progression algorithm for NeuroMat mathematics tasks based on user neurological state and correct answers

	correct answer	incorrect answer
high attention	increase 1 level	decrease 1 level
low attention	increase 2 levels	decrease 2 levels

Embodied Interaction

Upon start-up, the Instructor Screen is presented to the instructor. As in Figure 3, since the level of difficulty defaults to 3, addition is chosen as the default operation. The instructor may choose a new task to generate a new addition problem, then the instructor switches to the User View (Figure 3) so the student can begin using the NeuroMat interface.

When the system switches to the User View (Figure 3), the task (in the case of the figure, an addition problem) is displayed above a number line on the screen. To solve a problem, the user steps on the colored squares on the mat, left or right, until the cursor highlights the number on the number line that is the answer to the displayed problem. When the user believes he/she has the correct answer, s/he steps on the Done button to enter the answer. Feedback is given by audio cues through the headset (cheering for correct; buzzer for incorrect), visual cues through the computer screen (the square highlighting the answer on the number line is green for correct, red for incorrect), and vibration through the wristband for an incorrect answer. Note the Bonus buttons on the left of the screen. These are additional problems that the user can optionally choose to do without having to return to the Control Screen to choose a new task.

STUDY DESIGN

We performed an initial evaluation of the NeuroMat on a small sample of children diagnosed with ADHD and a larger sample of children diagnosed with various learning disabilities. The study was undertaken as part of an elementary school class. The experiment was conducted in accordance with the approved Institutional Review Board (IRB) at New Mexico State University and the parent consent is obtained as a part of the IRB process.

We decided to test the NeuroMat in an environment that was familiar to the test subjects, which limited the venue to a school setting. The design maximizes ecological validity, however, gaining access to public school students is difficult and, to date, we have only been able to test in a single special- education classroom. To fully understand the effects of NeuroMat on performance and attention, further, carefully designed experiments and a larger number of test subjects is required and will be performed in the future.

To evaluate NeuroMat, we tested using two groups of subjects: (1) 3 elementary school children (grades 2 and 3) who have ADHD and are currently being treated with medication to control their symptoms (ADHD Condition), and (2) 36 elementary school children (grades 3–5) who have a diagnosed learning disability (LD Condition). The ADHD and LD diagnoses for these students were determined by the evaluations performed by the educational diagnosticians working for the school district. This information was verified using the school records provided by the school. The study was conducted in a special-education classroom at a local elementary school during school hours. Students in the ADHD Condition represent all ADHD-diagnosed students in the school.

For our study, students undertook a suite of 10 basic math problems, both addition and subtraction. The problems were selected by teachers from the existing curriculum, ensuring they aligned with

grade-level learning objectives. All the students are initially asked to solve these 10 basic math problems using paper and pencil. They are subsequently asked to solve the *same* 10 basic math problems, but in a different order than the paper one using NeuroMat. Students were provided with instructions prior to each testing condition inclusive of practicing with NeuroMat to ensure they understand how to use the system. During both tests (paper and NeuroMat), level of attention is recorded every second using the NeuroSky eSense System. Correctness of the answers is recorded by computer software during the use of NeuroMat along with the level of attention and the time at which students answer the problems. The paper problems are graded for correctness after completion. Both correct and incorrect results were cross-checked across the two testing methods to ensure consistency.

RESULTS

The analysis of study data shows an increase in both attention and correct task answers in all conditions when using the NeuroMat interface instead of the traditional paper and pencil. Figure 4 shows the average attention of the ADHD students and LD students when solving the 10 test problems using paper versus using the NeuroMat. As shown, the average attention of the ADHD subjects increases from 42% using paper to 66% using the NeuroMat; LD students show a lesser increase from 43% to 58%. This preliminary evidence based on descriptive statistics suggests that participants are more attentive while using the NeuroMat interface when compared to performing the same math problems using pencil and paper.

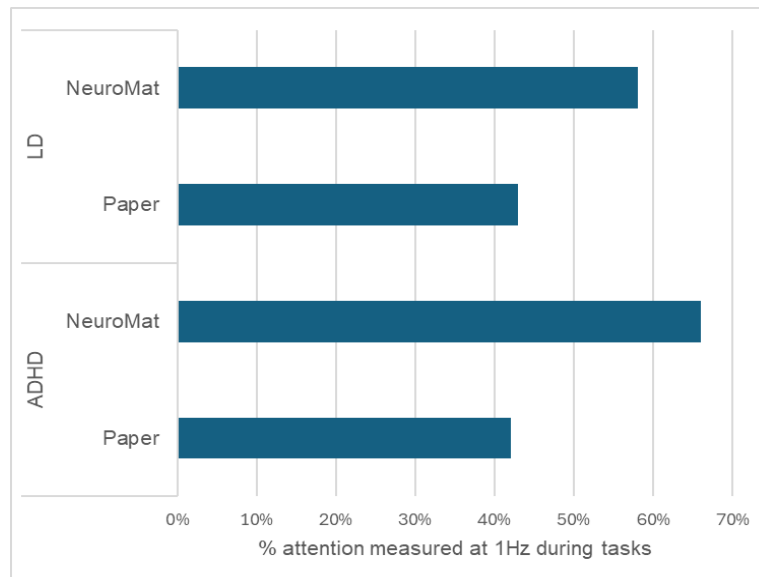


Figure 4: The average attention values for participants, grouped by condition

We also observe gains in the number of math problems that students answered correctly. Figure 5 shows that ADHD students increased their mathematics performance from 25% to 75% when using NeuroMat; again, with the LD students, the gain was less pronounced, but increased from 36% to 76%.

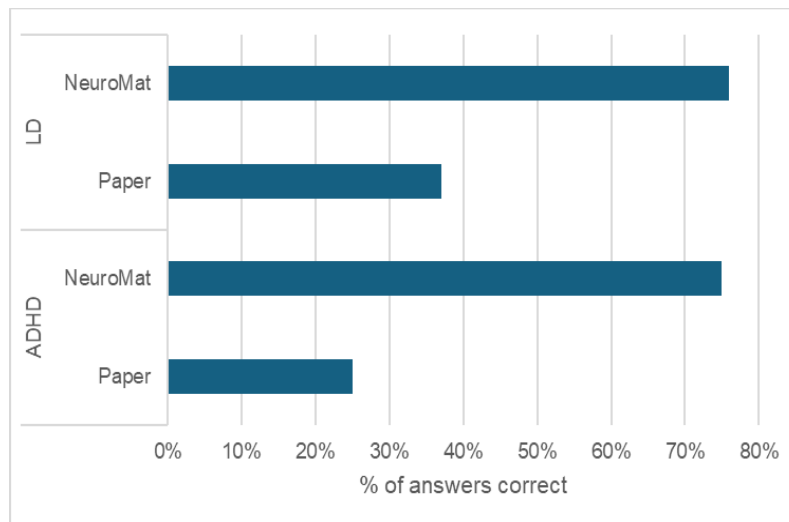


Figure 5: The average correct answers for participants, grouped by condition

The results show promise that the NeuroMat *may* help children with ADHD (and those with learning disabilities) increase attention and performance on cognitive tasks. Based on these results, we will move forward with further testing. However, to fully validate the effectiveness of the system, we must perform testing with a larger random sample size of ADHD and LD individuals and with a rigorously defined controlled experimental plan.

DISCUSSION

Children with ADHD often exhibit strong urge to move and tend to be motorically more active under various demands to their capacity working memory (Dekkers et al., 2021). Extant literature provides some evidence with respect to the positive therapeutic effect of exercise and physical activity on children with ADHD (Archer & Kostrzewa, 2012; Neudecker et al., 2019), even increasing their self-efficacy when performing tasks within a classroom environment (Hoy et al., 2024). The preliminary evidence from this study also shows that physical movements facilitate the students with ADHD to perform relatively better in math, when compared to stationary pencil-paper test environment. We speculate that students with ADHD channel their energy more positively when they are moving since physical activity is known to have a positive effect on cognition especially for processes demanding more executive control (Dishman et al., 2006).

Given that the treatment and management of ADHD pose significant cost to the societies (Chhibber et al., 2021), there is a great need for the development of inexpensive and effective interactive interfaces for ADHD children to develop their motor and cognitive skills. The novelty of the system investigated herein is its capability to bridge the gap between brain and behavior. It is combining the physical movement and the effect of neurofeedback on their behavior while they are actively engaged in learning task using the NeuroMat interface. A dynamic difficulty algorithm drives students toward tasks that best fit their mental needs using performance and neurofeedback. Children with ADHD are known to be very active and easily distracted; our system helps to reduce distraction and keep students engaged in mathematics tasks.

Implications for Design

The present system suggests that more action-oriented activities can be employed in the classroom

to support students with ADHD by using embodied forms of interaction.

Study Limitations and Need for Further Investigation

The present experiment represents only an initial evaluation of NeuroMat but shows promising results. However, a more rigorous controlled experiment based on random sampling is needed to generate statistical inferences. Furthermore, the restriction of working within the classroom prevented the use of counterbalancing, which would have made the experiment more robust. Further research will also deeply investigate how the attention measure is useful to students.

We plan to apply NeuroMat in a number of education domains, beyond basic mathematics. Our initial investigation suggests that the design is sound, and that other domains where we can drive question responses with physical interaction will be benefited by using NeuroMat.

CONCLUSION

We presented the design of and an initial evaluation of the NeuroMat, a system that combines embodied interaction with cognitive training and neurofeedback to enhance the attention and learning performance of children with ADHD and learning disabilities. We provided details on the design of the system, sufficient to support replication and wider research on the system. Our initial investigation, while not rigorous, suggests that students with ADHD and learning disabilities benefit from the design of the system.

In conclusion, this study indicates that the use of technology improves learning and thus supports the idea that multimodal devices can be important stipulations of learning to individuals with ADHD. The NeuroMat is non-invasive, portable, and safe for everyone. Furthermore, this study supports the idea that the inclusion of bodily movement may not only be helpful to represent math concepts but that embodied cognition also aids to their achievement. The adaptive software improved the focusing attention measured by the MindSet (BCI) and created an environment where users could learn efficiently. We conclude that the NeuroMat system decreases frustration, increases attention, and assists in comprehension for ADHD. Future work includes conducting a more extensive and rigorous evaluation of the device. We also plan to extend the cognitive training tasks to include more mathematical operations such as multiplication and division. Finally, we plan to examine how to use NeuroMat as an alternative to medication for the treatment of ADHD.

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