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Using a brain-computer interface (BCI) in reducing math anxiety: Evidence from South Africa

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A B S T R A C T

Prior studies have indicated that learning mathematics is highly associated with attitudes towards mathematics and emotions like math anxiety. Over the years, strong empirical evidence has emerged, showing that math anxiety has a significant negative effect on mathematics performance. Interestingly enough, some researchers have shown that math anxiety can be trained and reduced. However, the proposed interventions have mostly focused on teachers as oppose to students, while the existing physiological approaches like cognitive behavioural therapy require administration by trained professionals. With recent advancements in technology, low cost commercial brain-computer interface (BCI) devices that can capture human emotions in real time have been developed and can have a potential use in training and reducing math anxiety. In this study, the objective was to determine if using a BCI mathematics educational game can help students to effectively reduce math anxiety. To attain this objective, a within-subjects longitudinal research design with eight data gathering waves was adopted as the primary methodology to ascertain changes in the participant's level of math anxiety across two sessions that took place on separate days. Analysis of data captured across two training sessions with a BCI mathematics educational game showed that math anxiety can be effectively trained and reduced with a BCI. In addition, the results showed that math anxiety has a significant negative impact on mathematics performance which is congruent with prior studies. These findings provide a novel way in which a low cost non-invasive BCI device can be used for educational purposes.

1. Introduction

Understanding the relationship between emotions and learning has gained enormous grounds over the years. Prior research (Sabourin & Lester, 2014; Sun & Pyzdrowski, 2009) has indicated that emotions play a vital role in fostering the cognitive functions that are important for learning. Empirical evidence indicate that positive emotions such as engagement and concentration can enhance learning (Kanfer & Ackerman, 1989; Pekrun, Goetz, Titz, & Perry, 2002; Sabourin & Lester, 2014), while negative emotions such as frustration, anxiety, and boredom have an adverse effect on learning (Meyer & Turner, 2006; Sabourin & Lester, 2014). The development of low cost commercial off-the-shelf BCIs has provided great opportunities for studying and understanding human emotions. A BCI is a communication system for controlling an electronic device (e.g. a computer) based on user evoked bio-potentials. These BCIs are becoming an essential component in understanding how affective computing can enhance education. One important educational discipline in which affective computing can play a vital role is in mathematics education.

Learning mathematics is strongly associated with attitudes towards mathematics and emotions like math anxiety (Jansen et al., 2013; Sun & Pyzdrowski, 2009). Ashcraft and Krause (2007) define math anxiety as a "feeling of tension, apprehension, or fear that interferes with math performance" (p.243). The findings of most studies (Ashcraft & Krause, 2007; Jansen et al., 2013; Zakaria, Zain, Ahmad, & Erlina, 2012) have clearly indicated a significant negative relationship between math anxiety and mathematics performance. According to Zakaria et al. (2012) math anxiety is an important physiological dimension of learning that every educator must try to identify in his/her students. However, math anxiety is still very dominant around the globe. For example, about 93% of Americans experience some form of math anxiety

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(Furner & Duffy, 2002; Scarpello, 2007). Studies in South Africa (Hlalele, 2012; Mutodi & Ngirande, 2014) have noted that while the country faces a serious crisis of mathematics education, affective components of learning such as math anxiety have been overlooked. These researchers further documented that there is a very high level of math anxiety among learners in South Africa. As such, one way of addressing the maths crisis in South Africa is by developing approaches to reduce the high levels of math anxiety.

Studies (Cates & Rhymer, 2003; Kazelskis & Reeves, 2002; Lim & Chapman, 2013; Mattarella-Micke, Mateo, Kozak, Foster, & Beilock, 2011; Medeiros & Leclercq, 2007) in cognitive psychology and mathematics education have measured math anxiety using subjective measures such as the Fennema-Sherman Mathematics Anxiety Scale (FSMAS) and objective measures such as physiological arousal. Physiological arousal can be measured in real-time with a BCI device which could be useful in measuring and controlling anxiety levels. According to Sun and Pyzdrowski (2009) teachers can use several strategies in the classroom to reduce maths anxiety, however, when students are faced with math anxiety on their own, they often do not know what to do. One effective means through which students learn mathematics independently is through mathematics educational games (Abdullah, Bakar, Ali, Faye, & Hasan, 2012; Devlin, 2011). Combining mathematics computer games with the potential of the BCI device in providing real-time neuro-feedback on physiological arousal can act as a technological solution for effectively monitoring, training, and reducing math anxiety.

The use of educational games for enhancing mathematics skills has shown an enormous potential. However, researchers (Kebritchi, Hirumi, & Bai, 2010; Mitchell & Savill-Smith, 2004) have highlighted that there is still a high shortage of empirical studies to support the effectiveness of mathematics educational computer games. Also, some existing empirical studies have yielded mixed results (Godfrey & Stone, 2013; Laffery, Espinsosa, Moore, & Lodree, 2003), and most novel computer games (e.g. BCI based games) are yet to be tested. The existing empirical evidence has focused on post-game mathematics test for evaluating the impact of the game while little has been done on actually evaluating the impact of the games on the affective components of learning (e.g. anxiety, frustration, engagement etc.), which the players experience during gameplay.

This is a gap that needs to be filled since affective components of mathematics such as math anxiety have been established to explain the differences in math skills from early childhood to adulthood (Ramirez, Gunderson, Levine, & Beilock, 2013; Zakaria et al., 2012). Lyons and Beilock (2012) emphasized that educational interventions that focus on controlling negative emotional responses to math stimuli (e.g. math anxiety) will be more effective than simply providing additional mathematics training. Several studies (Gresham, 2007; Hendel & Davis, 1978; Tooke & Lindstrom, 1998) have shown that math anxiety can be reduced through training and education; however, the studies have mostly focused on teachers rather than students. Furthermore, a few studies (Karimi & Venkatesan, 2009; Schneider & Nevid, 1993; Sharp, Colthar, Hurford, & Cole, 2000) have adopted psychological interventions to provide an emotional response approach to reducing math anxiety. For example Sharp et al. (2000) showed that relaxation training significantly reduced math anxiety; Karimi and Venkatesan (2009) using cognitive behavioural group therapy (CBGT) also showed that it significantly reduced math anxiety; while Schneider and Nevid (1993) showed that stress management training and systematic desensitization lowered the math anxiety of college students. While these studies provide promising results, implementation in a larger context is difficult as the programs need to be administered by trained professionals who are often scarce especially in developing countries. In this light, this study looks at a psychological approach to learning that incorporates recent technology and can be administered by the students themselves or their parents/guardians in training, controlling and reducing their math anxiety levels. As such, this study has as main focus to determine if using a BCI mathematics educational game can help students to effectively reduce math anxiety.

2. Overview of BCI technology

Wolpaw and Wolpaw (2012) define a BCI as a communication system in which the commands or messages sent by an individual to the external world do not pass through the normal output channels of brain communication such as peripherals (e.g. speech) and muscles (e.g. gestures). Instead, a BCI device uses any bio-potentials that are under the conscious control of the user (Gnanayutham & George, 2006). Bio-potentials are electrical signals that originate from the brain and nervous system (Colman & Gnanayutham, 2013). BCIs establish a direct connection between the brain and an electronic device (Kübler & Müller, 2007). This direct communication between the brain and a computer is achieved by decoding brain signals into commands that can be understood by the computer. BCIs can either be invasive or non-invasive. Invasive BCIs require surgical removal of a section in the skull where the brain underneath needs to be accessed, while non-invasive BCIs decode brain signals using scalp recordings (EEG-based BCIs)[1] and as such do not require any surgery or medical care. Fig. 1 shows an overview of how the components of a BCI system function together.

This study will make use of the Emotive EPOC BCI which is a low cost non-invasive EEG-based BCI that has gained popularity in recent years. Researchers (Badcock et al., 2013; Duvinage et al., 2013; Taylor & Schmidt, 2012) have adopted the Emotiv EPOC to examine several BCI paradigms; however, little has been done with regards to its potential for educational purposes. The Emotiv EPOC neuro-headset comes with a control panel equipped with three detection applications namely: the Cognitiv Suite (captures cognitive actions for BCI-like control), Expressiv Suite (captures user's facial expressions), and the Affectiv Suite (captures information on the user's emotional states). All these application suites capture user information in real-time. Only anxiety data from the Affectiv Suit is reported for the purpose of this study.

3. Computer games and mathematics education

Digital educational games have been widely used over the years as a means for enhancing the mathematics skills of learners. According to Oblinger (2006) computer games have been recognized as important tools for mathematics education because they provide an effective and fun learning environment. Over the past decade, many researchers and academics have started to pay special attention to the impact that computer games could have on improving mathematics performance in schools (Ke & Grabowski, 2007; Kim & Chang, 2010; Oblinger, 2006). However, many studies have failed to find consensus on the impact of computer games on mathematics skill development. Some studies (Bokyeong, Hyungsung, & Youngkyun, 2009; Bragg, 2012; Burguillo, 2010; Kebritchi et al., 2010; Lopez-Moreto & Lopez, 2007; Shin,

[1] EEG stands for electroencephalography and refers to the measurement of electrical waves generated by the brain.

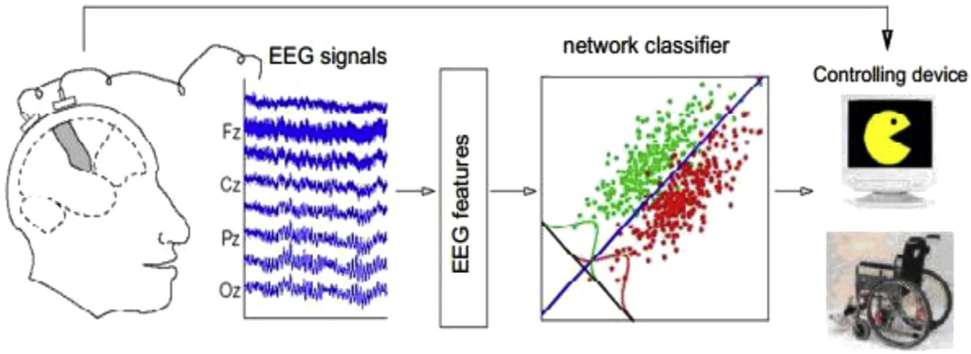

Fig. 1. Schematic view of BCI system components. Source: Karlovskiy & Konyshev, 2007.

Sutherland, Norris, & Soloway, 2012) have found significant evidence to support the use of computer games for mathematics education, while others (Lim, Nonis, & Hedberg, 2006; Nusir, Alsmadi, Al-Kabi, & Sharadgah, 2012; Vos, Van der Meijden, & Denessen, 2011) have had mixed results or no impact. These studies have, however, focused primarily on the post-game mathematics test results without evaluating the possible effect that emotions during the game play could have on influencing the mathematics outcome. As such, a key affective component like math anxiety which accounts for significant difference in math performance has been neglected.

4. Math anxiety and mathematics performance

Most students who are weak in mathematics always worry a lot in the process of solving mathematics problems and this aspect of worrying is the key factor that makes them perform poorer (Mohamed & Tarmizi, 2010). Generally, people tend to forget mathematics equations and lose confidence when they are experiencing math anxiety. The findings of most studies (Ashcraft & Krause, 2007; Jansen et al., 2013; Ramirez et al., 2013; Zakaria et al., 2012) have clearly indicated a negative relationship between math anxiety and mathematics performance. As math anxiety increases, the level of math performance decreases. Tapia and Marsh (2002) further indicated that students who have low levels of math anxiety are more confident, excited, and highly motivated to learn mathematics more than students with high levels of math anxiety. Jansen et al. (2013) established that mathematics performance only increases with more practice. This explains why people with high math anxiety tend to perform poorer in mathematics as the anxiety causes them to avoid solving mathematics problems as established by Zakaria et al. (2012). It is therefore of prime importance to identify students with high math anxiety and try to help them build their confidence in solving mathematics problems.

The relationship between math anxiety on mathematics performance has been consistent for both 'trait math anxiety' (Ganley & Vasilyeva, 2011; Miller & Bichsel, 2004) and 'state math anxiety' (Beilock, Rydell, & McConnell, 2007; Brodish & Devine, 2009). Trait math anxiety refers to the general tendency of feeling anxious about mathematics while state math anxiety is a measure of anxiousness during a mathematics testing situation. In a longitudinal study comprising of 113 grade two and three children, Vukovic, Kieffer, Bailey, and Harari (2013) established that math anxiety was responsible for significant difference in mathematics performance. Ramirez et al. (2013) using 164 grade one and two children found that there was a negative relationship between math anxiety and mathematics achievement. The relationship showed that children with high levels of math anxiety had poorer mathematics achievement than those with low math anxiety.

Fig. 2. Screen shot of the Math-Mind Game.

Cates and Rhymer (2003) used the FSMAS to classify students according to low and high math anxiety levels and then administered the two groups with a timed mathematics test comprising of basic operations like addition, multiplication, division and subtraction. The findings from the study revealed that students with high math anxiety performed poorer in all the different mathematic operations.

One way in which math anxiety affects mathematics performance is by interfering with the functioning of the working memory, which is a key cognitive function that significantly affects mathematics performance. Vukovic et al. (2013) highlighted that mathematics anxiety affected how some students used working memory resources in solving mathematics problems. Ramirez et al. (2013) also explicated that math anxiety in first and second graders negatively affected students working memory resulting in lower mathematics performance.

5. Methodology

5.1. Participants

This study adopted a convenience sampling in recruiting participants. A prerequisite for participating in the study was for the participant to be between the age group of 9–16 years inclusive. Parents/guardians of learners were contacted to find out if they were interested in allowing their children to participate in the study. Through this process, 36 children were available as participants. The majority of the participants were female (52.8%). The youngest participant was 10 years old and the eldest was 16 years. The average age of the participants was 14.06 years with a standard deviation of 2.08.

5.2. Materials

The research edition of the Emotiv EPOC BCI device was used in this study. A BCI mathematics educational game called Math-Mind (Figs. 2 and 3) was developed by the researchers and used for the purpose of this study. The participants played the game while wearing the BCI headset. The Math-Mind game captured real-time brain activity with the Emotiv EPOC BCI and provides visual feedback to the user when anxiety levels increased in an attempt to help the user control the anxiety levels. The Math-Mind game was developed using XNA 4.0 and was administered to the participants using a Core i3 Acer Laptop with 4Gig RAM. The participants completed a pre-test questionnaire which captured demographic information and information relating to their math anxiety levels based on the widely used FSMAS math anxiety scale.

5.3. Design and procedure

This study adopted a short-term longitudinal research approach in which each participant was expected to complete two sessions. A longitudinal research design was chosen because it was necessary to collect data from the same sample at two or more different points in time so as to determine how the participants managed and controlled their anxiety levels with the BCI neuro-feedback. It should be noted that a key aspect of a longitudinal design is the time factor. However, time factor is not only measured based on the duration of the study. Researchers (Karapanos, Martens, & Hassenzahl, 2009; Singer & Willett, 2003) have argued that one way of measuring time in a scientific study is to look at it in terms of the number of data gathering waves. This typically looks at how many data gathering waves occur in a single session or across several sessions which could all span in the same day or across several days. Tullis and Albert (2013) adopted a similar view in explicating how learnability can be measured in usability studies. Prior literature and empirical findings suggested that scientific longitudinal studies should have at least three data gathering waves in order to effectively capture change (Karapanos et al., 2009; Karapanos, Zimmermann, Forlizzi, & Martens, 2010; Singer & Willett, 2003). These approaches have been successfully used in many scientific studies. For example, Rieger (2009) demonstrated that change process in a longitudinal study could be sufficiently observed within a 2.5 h session with several data gathering waves. Combaz et al. (2013) used two BCI session with each session lasting between 1 and 2 h (if the participant was not tired) in order to evaluate change process with regards to BCI performance and cognitive workload of two spelling BCI applications.

Fig. 3. Screen shot of Math-Mind game with real time feedback indicating a high level of math anxiety in the game player.

Based on this argument, this study adopted an approach with two sessions per participant that took place on two separate days. Each session had four data gathering waves for math anxiety, with a break (distracter task) after the second data gathering wave. The participants had to play two levels (level one and level five) of the Math-Mind Game. The two levels have different difficulties based on the mathematics problems they present. The game had four key math problems which were addition, subtraction, division and multiplication. During each session, the participants played each of the two levels twice with data captured each time a level was played. Feedback to the participant was provided after the task was completed to see his/her overall level of math anxiety during the task and to provide advice on how to control math anxiety in the next task. A schematic view of the research procedure is presented in Fig. 4 below.

6. Results and discussion

Out of the 36 participants who took part in the study, only 25 completed the two sessions. However, because four data gathering waves took place during the first session, full data for all participants will be used when analysing data relating to the first session. This is because each session was carried out in a way that allowed for effective capturing of changes in math anxiety. As such, when analysing information that spans across the two sessions, only the data for the 25 participants who completed both sessions will be used. This information will be clearly indicated with each analysis.

6.1. Training math anxiety

The math anxiety findings from the FSMAS are presented in Table 1 below.

The FSMAS components in Table 1 are composed of both positively worded (1–4) and negatively worded (5–8) questions. In computing the overall math anxiety score, the negatively worded questions are reversed so that a higher score indicates a high level of math anxiety. The overall mean math anxiety score is 2.2 which indicate that the level of math anxiety is moderate among most of the participants in the study. This score is slightly lower than that of previous studies in South Africa (Hlalele, 2012; Mutodi & Ngirande, 2014). However, these studies used a larger sample with most of their participants above 16 years. It is imperative to acknowledge this difference in age groups as prior studies (Baloğlu & Koçak, 2006; Mutodi & Ngirande, 2014; Woodard, 2004) have indicated a significant relationship between math anxiety and age. This relationship is confirmed in this study by the significant positive correlation between age and overall math anxiety score indicating that math anxiety increases with age. This is probably because older students have been exposed to more difficult mathematics problems than younger students. Contrary to prior studies (Devine, Fawcett, Szucs, & Dowker, 2012; Ho et al., 2010; Jain, & Dowson, 2009; Mutodi & Ngirande, 2014; Yüksel-Şahin, 2008) gender and grade did not show a significant relationship with the overall math anxiety score. Nonetheless, the findings are in line with other studies (Birgin, Baloğlu, Çatlıoğlu, & Gürbüz, 2010; Dede, 2008; Tapia, 2004) that have also found no significant relationship between math anxiety and gender. However, the correlation results between component 2 of the FSMAS and gender provides significant evidence that female learners are more likely to refrain from taking more maths courses than male learners which is again consistent with prior studies (Devine et al., 2012; Yüksel-Şahin, 2008).

The next step was to examine if the math anxiety measured with the FSMAS was similar to the physiological arousal measure of math anxiety obtained from the BCI device. Similar to Cates and Rhymer (2003), the participants were classified into two groups (high and low math anxiety) based on their overall math anxiety score from the FSMAS. The median math anxiety score for all participants in the study was used as the separation point with participants classified as having low anxiety if they scored at or below the median, and high math anxiety if they scored above the median. Cates and Rhymer (2003) elucidate that this approach of using the median is superior to other approaches because it controls for any artificially inflated differences between groups often observed in methods that classify the groups based on the upper and lower quartile scores. After classifying the participants into high and low math anxiety groups, an independent sample *T*-test was

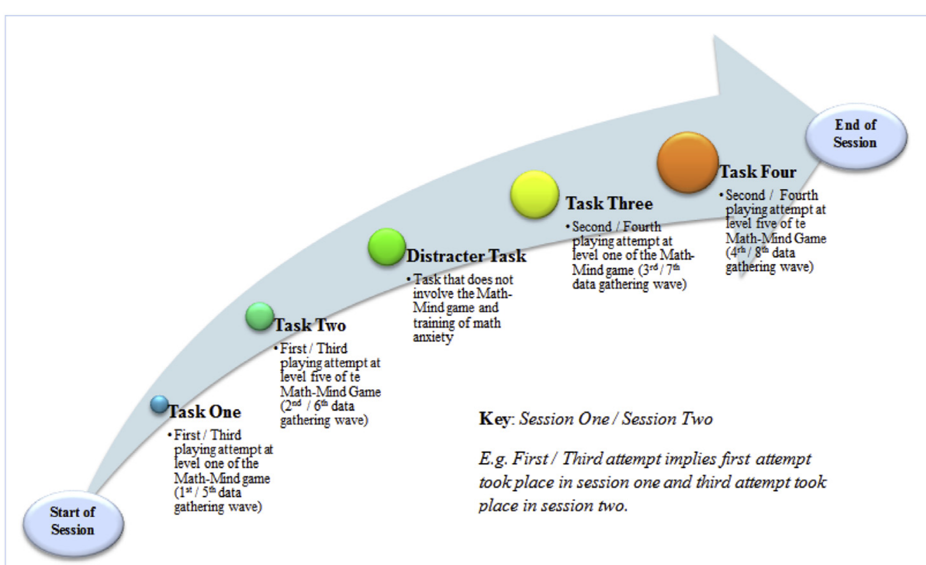

Fig. 4. Study design and task sequence for testing sessions one and two.

Table 1
FSMAS measures and relationship to Age, Gender and Grade.

Statements	Descriptive statistics			Correlation		
	Mean	Std. dev	Skewness	Age	Gender	Grade
1. Mathematics does not scare me at all.	1.62	0.922	1.13	0.326**	−0.097	0.155
2. It would not bother me at all to take more mathematics courses.	2.74	1.62	0.14	−0.216	0.333**	−0.264
3. I usually do not worry about my ability to solve mathematics problems.	2.24	1.44	0.86	0.327**	−0.166	0.357**
4. I have always been at ease during mathematics tests.	2.41	1.28	0.35	0.586***	−0.233	0.602**
5. Mathematics makes me feel uncomfortable and nervous.	3.91	1.29	−0.82	−0.337**	−0.301	−0.224
6. I always feel tense when I think of trying hard mathematics problems.	3.74	1.26	−0.52	−0.312	−0.260	−0.233
7. My mind goes blank and I am unable to think clearly when working mathematics.	3.85	1.44	−1.09	−0.248	−0.210	−0.221
8. Mathematics makes me feel uneasy and confused.	3.41	1.37	−0.29	−0.060	−0.043	0.018
Overall Math Anxiety Score	2.26	0.93	0.504	0.327**	0.092	0.251

***$p < 0.01$; **$p < 0.05$.

used to compare the differences in the BCI measured math anxiety for the first time the participants played each of the two game levels. Only the first time for each level was used because it was expected that by the second time a participant plays the same level, he/she has already received feedback on math anxiety from the first time with guidance on how to control anxiety. As such, the math anxiety score from the second gameplay would already have been influenced by prior biofeedback and training using the BCI. The results of the independent sample *T*-test are depicted in Table 2 below.

The results in Table 2 indicate that the high math anxiety group from the FSMAS had a higher mean BCI measured math anxiety compared to the low math anxiety group. The results are, however, not significant for level one of the Math-Mind game. This could possible account for the fact that level one math exercises are very easy and so exert a limited amount of math anxiety on most of the participants. Nonetheless, the results for level five of the Math-Mind game and the average for both levels are significant at the 5% level. This clearly depicts that the level of math anxiety measured with the FSMAS is significantly related to that measured with the BCI. This finding support the view of prior studies (Mattarella-Micke et al., 2011; Medeiros & Leclercq, 2007) that math anxiety can be measured in terms of physiological arousal.

Since the results from Table 2 indicate that the captured math anxiety by the BCI is valid, it is imperative now to evaluate if the participants used the neuro-feedback from the BCI to control and reduce their level of math anxiety as the different tasks progressed. A paired sample *T*-test (Table 3) was used to evaluate differences in the levels of math anxiety for the different tasks.

Pair one (pair two) indicates the comparison between the two attempts at playing level one (level five) of the Math-Mind game during the first session of the study. The *t*-test indicates a significant difference in the level of math anxiety for the two attempts indicating that there was a significant reduction in the level of math anxiety for the second attempt for each of the levels was played. This indicates that the feedback on math anxiety that the participant's received from the first task of each level helped them to train how to control math anxiety and effectively reduced it. This in turn shows that math anxiety can be trained within a single session thus supporting the view of Tullis and Albert (2013) that learnability can be measured over a single session with a break in-between the task.

Pair three (pair four) indicates the comparison between the two attempts at playing level one (level five) of the Math-Mind game during the second session of the study. The findings also indicate a significant reduction in the level of math anxiety for the second attempt the game was played in the second session (4th task) compared to the first time (3rd task). These findings align with the findings from the first session and thus support the view that a BCI device can be used to significantly train and reduce math anxiety.

Pair five (pair six) indicates the comparison between the two attempts at playing level one (level five) of the Math-Mind game for each of the two sessions. The findings indicate a significant reduction in math anxiety for the second session compared to the first session. Based on all six comparisons, it can be stated that neuro-feedback from the BCI on real time physiological arousal can be used to train learners in controlling and reducing their level of math anxiety. The findings also support prior studies (Gresham, 2007; Hendel & Davis, 1978; Karimi & Venkatesan, 2009; Schneider & Nevid, 1993; Sharp et al., 2000; Tooke & Lindstrom, 1998) which highlighted that math anxiety can be controlled and reduced. In the next section, a regression analysis is performed to determine if the measured math anxiety was related to mathematics performance.

6.2. Relationship between math anxiety and mathematics performance

This section presents the results on the relationship between math anxiety and mathematics performance following a set of linear regression models (Table 4).

In evaluating the impact of math anxiety on mathematics performance, this study acknowledged the fact that all the participants did not have the same level of computer experience, and as such, some level of anxiety could have been a result of computer anxiety. Existing

Table 2
Comparing FSMAS scores to Math Anxiety scores of the BCI.

	Mean anxiety values		*T*-test for equality of means	
	High math anxiety group	Low math anxiety group	*T*-value	*P*-value
Level one math anxiety	58.360	46.706	1.430	0.163
Level five math anxiety	59.193	36.658	2.376	0.024**
Average math anxiety	58.777	43.182	2.174	0.037**

**$p < 0.05$.

Table 3
Paired sample *T*-test for math anxiety across task.

	N	Mean anxiety values		*T*-test for equality of means	
		1st Task	2nd Task	*T*-Value	*P*-value
Panel A: session one					
Pair one	36	50.792	29.208	4.232	0.000***
Pair two	36	47.144	29.972	5.160	0.000***
Panel B: session two					
		3rd Task	**4th Task**		
Pair three	25	35.072	21.967	3.626	0.001***
Pair four	25	32.368	18.592	4.367	0.000***
Panel C: comparison across the two session					
		Session 1	**Session 2**		
Pair five	25	39.926	28.520	2.377	0.026**
Pair six	25	42.048	25.480	3.972	0.001***

***$p < 0.01$; **$p < 0.05$.

empirical evidence (Dupin-Bryant, 2002; Lee & Huang, 2014; Sam, Othman, & Nordin, 2005; Terujeni, Lavasani, Karamdust, & Hassanabadi, 2013) has indicated that prior usage and exposure to computers significantly reduces the levels of computer anxiety. As such, participants who had a low level of computer anxiety could possibly perform better in the game task than those with a high level of computer anxiety. This is because those with high computer anxiety will struggle more using the computer which might also influence the measured physiological arousal. Based on this assumption and the fact that prior computer experience is a proxy for computer anxiety (Dupin-Bryant, 2002; Terujeni et al., 2013), this study used the participants' prior exposure to computers as a control factor to ascertain the influence of math anxiety of mathematics performance.

In Model A (Table 4), it is seen that math anxiety has a significant negative relationship with mathematics performance. This indicates that high maths anxiety results in poor mathematics performance. The findings are consistent with prior studies (Ashcraft & Krause, 2007; Jansen et al., 2013; Ramirez et al., 2013; Zakaria et al., 2012) which also indicated a significant negative relationship between math anxiety and mathematics performance. The significance of the *F*-change value indicates that controlling for the effect of computer experience is vital as it has a significant influence on the model. The R^2-change (0.271) indicates that computer experience reduces the error of using math anxiety to predict mathematics performance by 27.1%. This shows that for session one a significant level of the anxiety could have been induced by computer experience as participants who had little computer experience had to struggle with the computer in addition to the mathematics exercises. The results also show that the participants with more prior computer experience scored better in the mathematics exercises of the Math-Mind game. This finding aligns with observations during the first session which showed that some of the participants failed to answer the questions on time because they were struggling with the mouse to click the correct answer. As such, they scored comparatively lower due to their computer competence and not their mathematics competence. This further supports the view of controlling for the effect of computer experience when evaluating how the measured math anxiety impacts on mathematics performance.

In model B, math anxiety also has a significant negative relationship with mathematics performance. The math anxiety beta value in model B is more than double that of model A indicating that math anxiety had a stronger relationship in model B than in model A. The *F*-change value is insignificant showing that computer experience did not significantly influence the findings in the second session. It is seen that the variance explained by computer anxiety is only 2.7% compared to 27% in model A. This indicates that by the second session, participants with little computer experience had already learned how to use the computer well in completing the exercises of the Math-Mind game. As such, there is little or no computer induced anxiety that could significantly affect the relationship between math anxiety and mathematic performance. This supports evidence form prior studies (Dupin-Bryant, 2002; Lee & Huang, 2014; Sam et al., 2005; Terujeni et al., 2013) which indicate that exposure to computers reduces computer anxiety.

In Model C, the change in math anxiety between the first and second sessions has a significant negative effect on the change in mathematic performance. This shows that a participant who significantly trained and reduced his level of math anxiety in the second session compared to the first session scored higher in the mathematics exercises and vice versa. Although this relationship is significant at the 5% level, the F-value for the overall model is not significant. So the effect of anxiety change across the two sessions on mathematics performance must be treated with caution.

Nonetheless, these results are expected based on the findings from model A and model B as it is seen that computer induced anxiety affected the measure of math anxiety in session one. As such participants with little computer anxiety could have recorded very high anxiety levels in session one compared to the participants with more computer experience. During the second session, the participants with little computer experience were therefore much likely to have a higher change in the level of math anxiety as their computer experience during the first session had reduced the level of anxiety induced by the computer competence. As such, the magnitude of the change in anxiety could not possibly reflect the exact change in mathematics performance when compared to the participants who had more computer experience prior to the first session. This argument is supported by the negative coefficient (-0.278) of computer experience in model C which indicates that participants with more prior computer experience had a smaller change in mathematics performance across the two sessions, than participants with little or no prior computer experience. This aligns with the findings presented in model A that people with more prior computer experience performed better in the math exercises.

7. Limitations of the study

Although this study adopted a systematic and well thought-out research design for evaluating the change process (in this case changes in math anxiety) as established by prior studies (Combaz et al., 2013; Karapanos et al., 2009; Karapanos et al., 2010; Rieger, 2009; Singer & Willett, 2003; Tullis & Albert, 2013), it is not without limitations. Firstly, the study adopted a within-subjects design with eight data

Table 4
Relationship between math anxiety and mathematics performance.

	Models					
	Model A		Model B		Model C	
Variables	Beta	T-Stats (*P*-value)	Beta	T-Stats (*P*-value)	Beta	T-Stats (*P*-value)
Constant		9.314 (0.000)***		17.874 (0.000)***		2.175 (0.041)
Math Anxiety	−0.328	−2.350 (0.025)**	−0.856	−6.777 (0.000)***	−0.435	−2.029 (0.045)**
Computer Experience	0.522	3.737 (0.000)***	−0.170	−1.347 (0.192)	−0.278	−1.298 (0.208)
Model parameters						
Total observations	36		25		25	
R^2	0.398		0.068		0.175	
Adjusted R^2	0.359		0.657		0.096	
F-value (sig.)	10.243 (0.000)***		23.051 (0.000)***		2.222 (0.133)	
R^2-change	0.271		0.027		0.066	
F-change (sig.)	13.966 (0.001)***		1.814 (0.192)		1.684 (0.208)	
Durbin–Watson Stats	1.539		1.342		1.556	

In Model A (Model B), the dependent variable is the overall mathematics score obtained in the first session (second session) while the explanatory variable is the average math anxiety for each of the corresponding sessions. In Model C, the dependent variable is the change in mathematics performance across the two sessions while the explanatory variable for math anxiety is the change in math anxiety across the two sessions. R^2-change and F-change indicate the effect of controlling for possible computer anxiety influenced by a participant's prior computer experience.
$^{***}p < 0.01$; $^{**}p < 0.05$.

gathering waves to ascertain changes in the participant's level of math anxiety across two sessions that took place on separate days. However, one cannot state with certainty the actual components of the application that significantly contribute to the reduction in the level of math anxiety. To address this situation going forward, future studies can utilize a control group that does not view the real time level of math anxiety from the BCI as well as visual feedback when the level of math anxiety increases from its current state. Also, a control for the overall level of math anxiety for each task presented at the end of the task can be examined to determine its effect on reducing math anxiety. Since this study was a proof of concept on using a BCI-based solution for training and reducing math anxiety, the general assumption adopted from existing studies (Ávila, Chiviacowsky, Wulf, & Lewthwaite, 2012; Chiviacowsky & Wulf, 2007) was that effective feedback will improve the participants learning on how to manage and control math anxiety. In order to improve the effectiveness of using a BCI-based solution for reducing math anxiety, future studies can investigate this association further by using different visual feedbacks and control groups to provide a more detailed insight on the subject.

Secondly, human emotions are a complex thing to study. This is because at a given point in time, several different emotions can be produced by an individual. So by singling out only one emotional component (math anxiety) this study is limited from determining the role other emotional components could play in the training and reducing of math anxiety. For example, researchers (Tractinsky, Katz, & Ikar, 2000; Wolfson & Case, 2000) focussing on multimedia learning platforms have shown that positive emotions are produced from different design aspects like layout, colour, sound etc. As such, such emotions can be produced by the game and thus play an unrecognized role in the results obtained in this study. Recent studies (Garcia-Molina, Tsoneva, & Nijholt, 2013; Pell et al., 2014) have also shown significant dependencies between human emotions (affective states) and cognitive functions. Therefore, controlling for the effect of cognitive functions like working memory and inhibitory control that have been shown to play a significant role in learning mathematics could better ascertain the relationship between math anxiety and mathematic performance and whether these cognitive functions have any influence on the training to reduce math anxiety. Nonetheless, researchers (Lyons & Beilock, 2012) using functional magnetic resonance imaging to examine brain activity have shown that math anxiety can be isolated as an individual emotion and studied.

8. Conclusion

The central aim of this study was to determine if a BCI-based mathematics educational game could be used to reduce math anxiety in students. Math anxiety has been widely acknowledged as a critical factor with a significant negative impact on mathematics performance (Ashcraft & Krause, 2007; Jansen et al., 2013; Zakaria et al., 2012). With most countries around the world suffering from "math crisis" (Pausigere, 2013; Schoenfeld, 2005); it becomes imperative to identify the factors that account for the poor mathematics performance such as math anxiety and find ways of controlling them. Interestingly, prior studies (Gresham, 2007; Hendel & Davis, 1978; Karimi & Venkatesan, 2009; Schneider & Nevid, 1993; Sharp et al., 2000; Tooke & Lindstrom, 1998) have indicated that math anxiety can be trained and reduced. This study adds to the evidence from prior studies by indicating following a repeated measure *T*-test that math anxiety can be trained and reduced with the aid of a BCI-based mathematics educational game. The results also showed that the level of math anxiety captured with the widely used FSMAS was similar to that captured with the BCI. This is a novel finding as BCI devices have been known to have a great potential for educational purposes, however, little empirical evidence exists to support these arguments. Also, unlike prior cognitive psychological methods of reducing math anxiety that need to be administered by a trained professional, the BCI math-mind game can be used with little or no technical support by the students or their parents/guardians. This thus provides a home based solution for reducing math anxiety especially as the cost of consumer BCI devices have significantly dropped over the years.

The results in this study also indicated a significant negative relationship between math anxiety and mathematics performance. The findings are congruent with other studies that have also shown that high math anxiety results in poor mathematics performance. In addition, it was seen that when using a computer based system to capture math anxiety, it is vital to control for the effect of computer anxiety especially when all the participants do not have the same level of competence in computer usage. This study showed that computer induced anxiety significantly affected mathematics performance during the first session of the study, however by the second session, all the participants where already proficient in using the computer for playing the math-mind game and it was seen that the effect of computer anxiety completely diminished. As such, computer proficiency is therefore a key factor that needs to be controlled in studies that utilize computers for achieving educational goals.

Lastly, this study replicated the findings of prior studies (Baloğlu & Koçak, 2006; Mutodi & Ngirande, 2014; Woodard, 2004) that established a significant relationship between age and the overall math anxiety of students. Furthermore, this study is congruent with prior studies (Birgin et al., 2010; Dede, 2008; Tapia, 2004) that failed to find a significant relationship between gender and math anxiety, however, the results contradict those of researchers (Devine et al., 2012; Ho et al., 2010; Jain, & Dowson, 2009; Mutodi & Ngirande, 2014; Yüksel-Şahin, 2008) that have argued that math anxiety is significantly related to gender. Nonetheless, this study showed evidence that some components of math anxiety and not the overall math anxiety has a significant relationship with gender. Lastly, future studies could compare the BCI-based intervention for math anxiety with existing methods like the CBGT to determine the most appropriate method for reducing math anxiety in school children.

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