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The effect of transcranial direct current stimulation (tDCS) on learning and performing statistical calculations

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The aim of this study was to determine whether the intraparietal sulcus plays a role in statistical calculations. Three conditions were employed, two experimental and one control. The control group was connected to the low current brain stimulator but did not receive any stimulation. The two experimental groups received either a 1 or 2 mA stimulation. There were no differences between those receiving either the larger stimulation or the lower stimulation compared to those not receiving any stimulation. The null hypotheses were supported and no differences were found between control and experimental groups. It was found that 1 mA scored significantly better than 2 mA on statistical calculation when stimulating the left dorsal lateral prefrontal cortex using the negative electrode.

The past 12 years have shown a significant increase in the use of low current electrical stimulation, tDCS (transcranial direct current stimulation), in an effort to promote brain functioning (Hecht, Walsh, & Lavidor, 2010; Jacobson, Koslowsky, & Lavidor, 2012; Marangolo et al., 2011; Wirth et al., 2011). Researchers have studied a range of brain functions using tDCS including: decision-making (Hecht, Walsh, & Lavidor, 2010); language production (Wirth et al., 2011); cognition (Jacobson, Koslowsky, & Lavidor, 2012); and speech apraxia (Hecht, 2010). These studies indicate that the stimulation of specific brain regions through anodal stimulation (positive electrode) has shown to increase neuronal long-term potentiation, LTP (Jacobson et al., 2012). By contrast, cathode stimulation (negative electrode) has resulted in reduced functioning of the neurons, or long-term depression, LTD (Jacobson, Koslowsky, & Lavidor, 2012; Marshall, Molle, Siebner, & Born, 2005). Findings also indicate that repeated anodal stimulation (positive anode) has produced longer term effects. Brain functions not investigated at length to-date are calculations and reasoning (Kadosh, Soskic, Luculano, Kanai, & Walsh, 2010).

The intraparietal sulcus, IPS, has been one area associated with mathematical calculations (Ashkenazi, Henik, Ifergane, & Shelef, 2008; Cantion, Brannon, Carter, & Pelphrey, 2008; Cappelletti, Barth, Fregni, Spelke, & Pascual-Leone, 2007; Dormal, Andres, & Pesenti, 2007). Dormal et al. (2007) noted that bilaterial IPS, left and right, have been associated with mathematical calculations. The left IPS has been found to be critical in numerical calculations and was identified through transcranial magnetic stimulation, TMS, studies (Cappelletti et al., 2007; Dormal et al., 2007). Holloway and Ansari (2009) found that the right IPS was associated with abstract numerical reasoning which was identified through brain imaging. Kadosh et al. (2010) conducted one of the few studies that attempted to determine the impact of tDCS on math calculations. They used tDCS and stimulation of three areas of the brain with either anodal or cathode stimulation. The researchers combined tDCS administration with training in automatic numerical processing. Using a low current, 1.0 mA in administering the tDCS, they stimulated the right parietal lobe, right, IPS, with a positive current (anode current stimulation). They found that anodal stimulation of the right parietal lobe (intra-parietal sulcus) resulted in improved numerical performance compared to the sham (control) condition.

Other regions of the brain may be involved in math/statistical calculations, particularly brain functions that involve connectivity and interact during such tasks as math/statistical calculations (Friston, 2009; Sik et al., 2005). The left DLPFC is associated with working memory and potentially is involved with math/statistical calculations. Zaehle, Sandmann, Thorne, Jancke, and Herrmann (2011) described working memory as "a set of basic mental operations that define the ability to hold an item of information transiently in mind, in order to recall, manipulate and associate this information to incoming new information" (p. 2). Silk et al. found that there is interaction between frontal lobes and parietal lobes during math tasks, visuospatial manipulation.

There has been minimal research into the impact of tDCS on brain function governing calculations and reasoning. There is significant potential to use tDCS to identify brain regions associated with math/statistical calculations. Identification of these brain regions associated with math/statistical calculations may lead to the use of tDCS and other methods to increase math/statistical performance.

Our research hypotheses were, first, anodal stimulation of the left intra-parietal sulcus, P3 (two levels of stimulation intensity, high and low) would increase performance on statistical calculations compared to a control group (sham condition). Second, the higher level of current stimulation, 2.0 mA, would result in significantly better performance on statistical calculations compared to a lower level of brain stimulation, 1.0 mA (anode and cathode stimulation). We used the following format in this study. First, participants in the experimental groups received the tDCS direct current brain stimulation followed by instruction in calculating a statistical procedure they had not seen before. The intended outcomes were that exposure to brain stimulation would increase long term neuronal potentiation and in so doing, enhance the likelihood that participants learning the selected material.

Method

Participatns

Participants were recruited from four undergraduate sections of an upper division educational statistics course. There were 200 students in four sections of the educational statistics class. A researcher attended a class in each section, briefed the students about the research, and requested participation. Students were given written explanation of the study and information about contacting a researcher if they chose to participate. The course instructor offered extra credit to students who elected to participate in research studies as part of the course requirements. An initial screening for medical problems was made, e.g. any major cardiovascular or neurological problems (e.g., seizures). Any student reporting any of the above medical problems was excluded from participation. Also, participants were screened for use of prescriptions such as medications for attention deficit/hyperactivity disorder. Eight student volunteers reported either a medical problem or took prescription medication, e.g. Adderall for ADHD, and consequently were excluded from the study. Forty-two participants completed the study. This resulted in 14 participants in the control (sham condition), 15 in the 1 mA condition, and 13 in the 2 mA condition. Students covered basic statistical calculation in the statistics course, but did not cover non-parametric statistics. Once students agreed to participate they were randomly assigned to one of three groups: Group 1, control group or sham condition (only pre-stim, 1.0 mA for 30 seconds); Group 2, low current stimulation, 1.0 mA; and Group 3, high current stimulation, 2.0 mA.

Administration of the tDCS, low level direct current to the scalp, was achieved through the Soterix Medical 1 X 1 transcranial Direct Current (tDCS) Low-Intensity Simulator. All direct current was administered to the scalp using a saline-soaked (.9% saline) pair of 5 cm x 7 cm (35 cm^2) sponge pads. The two saline soaked pads had one anodal electrode (positive) and one cathodal electrode (negative) inserted into each of the sponges.

Three graduate research assistants were trained in administering the stimulation and they received instruction in the safe use of the equipment. Written procedures for administering each approach with the three conditions were provided to the research assistants.

Procedure

We used a posttest only research design with random assignment to one of three groups: two experimental and one control. The control group, Group 1, was connected to the tDCS stimulator, the sham condition, based on the exact same montage and procedures used with the other two groups (experimental groups). No stimulus other than the pre-stim tickle at the beginning of the session was administered to the control condition participants. Control condition participants were set up with the sham condition for 20 minutes. The sham received an initial "pre-stim tickle" a short electrical current, 1 mA, for 30 seconds. The intention of the pre-stim tickle is to give control participants a feeling they are receiving an intervention. One experimental condition, Group 2, experienced a 20 minute administration of 1 mA and Group 3, involved the administration of stimulation at 2.0 mA current for 20 minutes. Each condition, control, 1mA, and 2 mA involved one single administration.

For the all three conditions, the anodal electrode was placed over P3 based on the 10-20 international system for EEG electrode placement. For participants who were in the two experimental conditions (administration varies intensities of current) the intent was to stimulate the area of the P3 which has been associated with calculations and reasoning (Walker et al., 2007). This anodal electrode is associated with increasing the maximum potentiation for neuronal firing and increasing cortical excitability (Stagg & Nitsche, 2011). The cathodal electrode was placed over the dorsal lateral prefrontal cortex (DLPFC), F3 (10-20 international system for EEG electrode placement) which is associated primarily with fine motor coordination (Walker et al., 2007) and selective attention (Gladwin, Uyl, Fregni, & Wiers, 2012).

After the 20 minute stimulation or sham each group viewed a four and a half minute instructional video on calculating a non-parametric statistic, the Kruskal-Wallis. The video demonstrated how to state both the null and alternative hypothesis. It also demonstrated calculating the critical value and the actual calculation of the Kruskal-Wallis. The video showed the formula and provided an example of the calculation. Participants had an opportunity to view the video as many times as they chose, e.g. they may have chosen to watch the video multiple times or one time. To capture the time on task, we recorded the time spent viewing the video. In addition to the video, participants had paper and pen available for taking notes. After viewing the video each participant was given a single statistical problem, calculating a Kruskal-Wallis non-parametric statistical calculation. The statistical problem concerned comparing three different drinks for caffeine content (colas, teas and coffees). The dependent variable was assessed through successful completion of the calculation. In addition to recording the time spent watching the instructional video the time spent completing the calculation was also recorded.

Measures

The dependent variable involved measuring successful completion of a calculation, a non-parametric-Kruskal-Wallis. Scoring was completed on each respondent by two of the researchers who blindly evaluated each response (did not know the experimental condition prior to scoring). Scores ranged from 0 to 5. Respondents were awarded: one point for the correct hypotheses statement (e.g. null and alternative hypothesis); identification of the critical value for Kruskal-Wallis; and the correct interpretation of the outcomes. Two points were awarded for successful calculation of the Kruskal-Wallis. Two researchers independently scored each participant's calculation of the Kruskal-Wallis. Inter-rater reliability was established first by calculating total agreement, it was found that the raters had total agreement on 86 percent of the scores. A Kappa also was calculated on inter-rater agreement and it was found to be .82. Finally, the two raters reviewed the six scores which they were in disagreement and determined a final score for each.

We also collected data on time viewing the instructional video and time required for the completion of the calculations. Research assistants noted that some participants spent minimal time viewing the video and minimal time completing the calculation. Consequently it was determined that we would treat time viewing the instructional video and time spent completing the calculation as covariates to address this issue (participants were given extra course credit for participation and may not have devoted full time to completed the task successfully). To assess any discomfort, ratings of scalp sensations were used at two points in the administration, five minutes after the start and 15 minutes after the start. We used an eleven point scale to measure scalp sensations, 0 a significant sensation (not tolerable) and 10, no sensation.

Results

As noted in the procedures, the research assistants observed that some participants did not spend much time reviewing the instructional video nor spend much time on calculating the problem. We calculated a correlation between total time spent on the calculation (time spent on watching the video and time spent on the calculation) and the calculation scores. We found a Pearson correlation of .69 ($p < .00$) between total time spent on the calculation and the scores on the statistical problem, Kruskal-Wallis. Consequently, we concluded that both time spent on viewing the video and time spent calculating the problem should be a covariate, combined into one total time on the calculation. We calculated an ANOVA of overall calculation time, time spent on the calculation and time spent watching the video, by group and found no significant differences ($F(2,39)$ $p = .80$) and an effect size of .01 (η^2). The means (*SD*) were: control = 24.174 (2.26); 1 mA = 22.11 (2.18); and 2 mA = 22.73 (2.34).

Since there was a significant correlation between total time on the calculation, both time spent watching the video and time spent performing the calculation, with the calculation score we conducted an ANCOVA to compare the groups by success on calculating the Kruskal-Wallis. The ANCOVA with time spent on calculating the problem as a covariate, involved comparing success on the Kruskal-Wallis calculation by group (control, 1 mA, and 2 mA). The ANCOVA comparing the groups by success in completing the calculation with total time spent watching the instructional video and performing the problem calculation resulted in significant differences between the groups, $F(2, 38) = 3.87$, $p = .03$. The estimated marginal means (EMM) and standard deviations (*SD*) were: control = 1.97(.32); 1 mA = 2.59 (.31); and 2 mA = 1.34 (.33). A post-hoc analysis showed that the 1 mA group scored significantly higher than the 2 mA group, 1 mA compared to control ($p = .17$); and 1 mA compared to 2 mA group ($p = .01$). The observed power was .67 and η^2 was .04. The control group (EMM = 1.97) scored higher on the calculation than the 2 mA group (EMM = 1.34), but it was not significant ($p = .18$). The data presented in Table 1 shows frequency counts for scores on calculating the Kruskal-Wallis by group. Review of the data, Table 1, shows that 1 mA participants scored similarly to control group participants at the higher success rate, e.g. 5 points (out of 5 points). However, the 1 mA group participants had more scores in the midrange (3 points out of 5 points).

Participants were asked to rate scalp sensation at 5 minutes and 15 minutes into the administration. This was true for the control group and both brain stimulation groups. No significant differences were found between all three groups on reporting scalp sensation at 5 minutes and 15 minutes. An ANOVA was calculated and the three groups were compared at 5 minutes. We found, $F(2, 39) = 1.06$, $p = .98$ and an effect size of .00 (η^2). Mean (*SD*)

Table 1: *Participants Scoring Based on Group Assignments (scores ranged from 0 to 5 with 5 being a perfect score)*

	Control group	1 mA group	2 mA group
Scored 5/5	3	3	0
Scored 4/5	1	1	1
Scored 3/5	1	4	3
Scored 2/5	2	2	3
Scored 1/5	4	2	2
Scored 0/5	3	3	5

scores were: control = 9.71 (.28); 1 mA = 9.46 (.27); and 2 mA = 9.15 (.29). An ANOVA was calculated with comparison of scalp sensations ratings at 15 minutes. We found, $F(2, 39) = 1.81$, $p = .42$ and an effect size of .001 Mean(*SD*) scores were: control = 9.50 (.29); 1 mA = 9.20 (.37); and 2 mA = 8.77 (.40).

Discussion

The purpose of the study was to determine if low current brain stimulation combined with instruction using an instructional video, impacted success on completion of statistical calculations. Specifically we wanted to assess if those experiencing low and high current brain stimulation, tDCS, achieved better scores or outcomes than a control group or those not receiving stimulation. Second we wanted to assess whether there would be a difference in outcomes on statistical calculation with low versus high tDCS stimulation. We found that those who received low current, 1 mA, stimulation (anodal) over the left intraparietal sulcus (IPS) did not perform better than those not receiving any stimulation and that there was no difference between those receiving a larger tDCS stimulation, 2 mA, compared to those not receiving any stimulation, the null hypothesis was supported. Also, we found that those receiving a low dosage of stimulation, 1 mA, performed significantly better than those receiving a higher dose, 2 mA (with the anode placed over the left IPS or P3 and the cathode placed over or the left dorsal lateral prefrontal cortex, F3). Again the null hypothesis was not supported.

An explanation of the lower success rate of those receiving the 2 mA stimulation may be a consequence of the cathode placement, left DLPFC, dorsal lateral prefrontal cortex, which has been found to be associated with selective attention (Gladwin et al., 2012). Gladwin et al. (2012) used tDCS at the left dorsal lateral prefrontal cortex and found that anodal stimulation increased selective attention. Also, the left dorsolateral prefrontal cortex is associated with working memory and can contribute to performance on math/statistics calculations (Zaehle, Sandmann, Thorne, Jancke, & Herrmann, 2011). Our findings suggest that with cathode placement over the left dorsal lateral prefrontal cortex the result was decreased cortex excitability (Nitsche & Paulus, 2000). Consequently cathode stimulation potentially impaired the participants successfully performing the statistical calculation. It may be that the 1 mA was not intense enough to dominate the anodal effects and consequently those participants were more successful in completing the calculation, e.g. the anode or positive electrode was strong enough to still have an impact on the IPS and increasing cortical excitability so participants could do well. Additionally, the finding that the cathode placement over the DLPFC affected statistical calculation in a negative way at 2 mA suggests that this region of the brain is important in math performance along with IPS. These findings support connectivity in math/statistical performance, e.g. between the left IPS and the left DLPFC.

Additionally, we noted a differential pattern of mid-range computational scores in the 1 mA group. One explanation for this observation is that tDCS administration (1 mA or lower brain current stimulation) influences those who have average knowledge and ability in math/statistics. By contrast, stimulation may not impact those who have higher levels of math/statistics knowledge and abilities, e.g. results of control and 1 mA that received perfect scores (3 participants in each group) whereas the cathodal, negative electrode, stimulation appears to have hindered higher scores (1 participant achieved a perfect score of 5).

A limitation of the research concerns the complexity of math/statistical calculation contributing to math/statistical calculation, and our results which were specific to the region stimulated. As was noted earlier, some researchers have found that math/statistical calculations also are associated with the right IPS (Kadosh et al., 2010). A second potential limitation is based on the use of a posttest only research design. We did not know the beginning academic abilities/knowledge of the participants with respect to math/statistics. However, our design did include random assignment which theoretically should distribute the abilities/knowledge across the groups.

There are several implications and practical applications obtained from these findings for those teaching statistics or other disciplines in higher education. One is the potential to use tDCS to improve success in learning statistics/math and other tasks. Many college students use prescription medications (not necessarily prescribed for them) such as Adderall to improve their academic performance. There have been a few studies showing negative consequences in the use of stimulants (Swanson et al., 2007). For example, Swanson et al. found that stimulates impacted growth rates. tDCS to-date has not shown any long term negative effects. A second implication is an opportunity to identify specific interventions that can be combined with tDCS. For example, combining music with tDCS may result in an additive effect and increase the effectiveness of what is learned. We are not suggesting that everyone buy a tDCS unit, but a better understanding of the effects may result in other ways of improving neuronal potentiation and improve learning, in this case learning statistics. Alternatively, research may show that the use of low current brain stimulation can be an effective method of improving statistical calculations and that there are minimal side effects.

There are several avenues for future research. One possible research idea is to change the cathode placement site, negative electrode, and attempt to control/reduce impact on the areas of the brain that potentially have an effect on math/statistical performance. A second possible research focus could be altering the stimulation level from 2 mA to 1.5 mA and using the same montage. This action may provide information about the intensity necessary to understand depressing cortical excitability. A third possible focus of future research may involve investigation into the effect of treatment over time, e.g. once or twice weekly stimulation for four to six weeks. The question is whether there is a cumulative effect on math/statistical calculation associated with stimulation of the left IPS. A fourth possible future study may involve comparison of stimulation, anodal, for both left and right IPS since both have been associated with math/statistical calculation (Dormal et al., 2007; Dehaene et al., 2010). Finally, there could be research into the whether the left DLPFC plays a bigger role in performance on math/statistical calculation compared to the left IPS. This research would involve placing the anode over the left DLPFC and the cathode over the left IPS.

In summary, we found that 1 mA stimulation to the left IPS resulted in no differences on statistical calculation scores than a control group. We did find that the 1 mA scored significantly better than 2 mA on statistical calculation when stimulating the left IPS. It appears that one explanation for lower scores for the 2 mA group may be the use of cathodal, negative electrode, stimulation over the left DLPFC. Stimulating the left DLPFC potentially reduced cortical excitability through impacting selective attention and higher executive function, potentially an important function in math/statistical calculations. These results which supported the null hypothesis are significant because they demonstrate that multiple brain regions may be responsible for successful completion of statistical calculations.

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