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Single-channel Electroencephalographic Recording in Children with Developmental Coordination Disorder: Validity and Influence of Eye Blink Artifacts

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Abstract

Background: The NeuroSky single-channel, dry-electrode, and wireless electroencephalographic (EEG) recording system is a fairly new measure of mental status, the validity of which had not yet been tested in children with developmental coordination disorder (DCD).

Purpose: To examine the validity of the NeuroSky single-channel EEG recording device (Mindwave Mobile EEG headset and NeuroView data acquisition software) and investigate the influence of eye blink artifacts on EEG attention-meditation measurements in children with DCD.

Methods: Thirty-seven children with DCD (with or without attention deficits) participated in the study. Validity was assessed primarily by correlating the EEG-derived attention and meditation indices with scores on other mental status measures (duration of gaze fixation and Movement Assessment Battery for Children bicycle/flower trial item score) in the DCD-attentive group and then comparing the EEG-derived attention and meditation indices of the DCD-attentive group (n = 20) with those of the DCD-inattentive group (n = 17) and among the frequent-blinking (7-8 eye blinks/trial), moderate-blinking (5-6 eye blinks/trial), and rare-blinking (3-4 eye blinks/trial) groups.

Results: The EEG-derived attention index was correlated with the duration of gaze fixation (r = 0.648, p = 0.002) and the Movement Assessment Battery for Children bicycle/flower trial item score (r = -0.688, p = 0.001). A significant difference in the attention index was found between the DCD-attentive group and DCD-inattentive group (p = 0.003), but no significant results were found for the EEG-derived meditation index. With regard to eye blinks, no significant differences in the EEG-derived attention or meditation indices were noted between the three blinking groups (p = 0.887).

Conclusion: The single-channel EEG device accurately measured the overall level of mental attention in children with DCD clinically and was not significant influenced by eye blinking. This portable device has potential utility in such children for whom ease of use is the first priority.

Keywords Clumsy children; Electroencephalography; Ocular artifacts; Validity

Introduction

Developmental coordination disorder (DCD) is a well-known movement disorder among children [1]. In addition to motor deficits, about 50% of children with DCD demonstrate mental attention deficits [2]. However, to the best of our knowledge, only two studies have quantified mental attention in this group of children using the Child Behavior Checklist [3] and eye movements [4]. Electroencephalography (EEG) is the gold standard to measure brain activity in children with attention deficit disorder (ADD) and attention deficit and hyperactivity disorder (ADHD) [5]. However, no study has used EEG to measure the brain activity (e.g., mental attention) in children with DCD who also demonstrate attention problems. Because this could be a future direction of research, validating the EEG recording system, particularly in children with DCD, is essential.

Traditional high-quality multiple-channel EEG recording is carried out in a laboratory, requires lengthy set-up procedures and may induce discomfort. This method is therefore not suitable or even feasible in some situations and populations, for example, recording brain engagement in the natural settings of young children [6]. Therefore, a new method of wireless, single-channel EEG measurement that is portable, easy to use and uses dry-sensor technology was recently introduced [7]. However, there are still doubts about the validity of the single-channel EEG device to detect and interpret EEG signals. The major criticism is that because a single active electrode is placed on the forehead above the eye, unavoidable eye blinking (an artifact) may contaminate the EEG signal [8,9]. Indeed, electrical potentials created during eye movements and blinks can be orders of magnitude larger than the brain-generated electrical potentials and can distort the EEG data. Therefore, methods such as principal component analysis and independent component analysis have been proposed to remove these ocular artifacts [10,11]. In the case of specific single-channel EEG recordings, the use of a prior set of information on the wave frequencies could minimize contamination of the EEG data by ocular artifacts [12], and the best-known single-channel Mindwave Mobile EEG headset (NeuroSky Inc., USA) uses this method for their detection and elimination [7]. However, the effectiveness of this method in eliminating ocular artifacts has not been thoroughly tested in pediatric populations.

Recently, a few studies validated the ability of the NeuroSky EEG headset to detect mental status (attention and meditation) in adult populations but the results were conflicting. For example, Rebolledo-Mendez et al. [13] and Johnstone et al. [6] reported that this headset had good concurrent validity with self-reported measures of mental attention and traditional EEG recording systems, respectively. However, Abo-Zahhad et al. [8,9] suggested that the single-channel NeuroSky EEG headset records both EEG and eye blink signals that may affect the validity of the measurements. Therefore, the objectives of this study were to (1) examine further the validity of the NeuroSky single-channel EEG recording device and (2) investigate the influence of eye blink artifacts on the EEG attention-meditation measurements in children with DCD.

Methods

Participants

Children with DCD were recruited from primary schools, child assessment centers, non-governmental organizations, parents' associations and physiotherapy clinics through poster advertising (i.e., convenience sampling).

The inclusion criteria were:

(1) a diagnosis of DCD according to the Diagnostic and Statistical Manual of Mental Disorders criteria [1];

(2) a percentile score of less than 5% on the Movement Assessment Battery for Children (MABC) [14];

(3) a total score of less than 46 (5 years to 7 years 11 months), less than 55 (8 years to 9 years 11 months) or less than 57 (10 years to 15 years) on the DCD questionnaire (2007 version) [15];

(4) between 6 and 10 years of age;

(5) normal vision (wearing glasses was acceptable); and

(6) receiving education at a mainstream primary school.

The exclusion criteria were:

(1) a formal diagnosis of emotional, cognitive, behavioral (co-morbid DCD and ADHD/ADD were allowed), neurological, or other movement disorders;

(2) significant visual, sensorimotor, or musculoskeletal disorders that might affect test performances;

(3) the demonstration of excessive disruptive behavior; or

(4) an inability to follow instructions. Children with DCD and ADHD/ADD who were on medication and those with an autism spectrum disorder were also excluded.

Screening was performed by physiotherapists to ensure that all participants were eligible to participate in the study. Children with DCD and without known attention problems were assigned to the DCD-attentive group while those with DCD and co-morbid ADHD/ADD were assigned to the DCD-inattentive group.

Ethical approval was obtained from the Human Research Ethics Committee of the administering University. The study was explained to all participants and parents and written informed consent was obtained. Data collection was performed by a physiotherapist and a trained research assistant. All procedures were conducted in accordance with the Declaration of Helsinki.

Measures

Demographic information, including age, sex, weight, height, exercise habits (i.e., the type of physical activity in which the child had been most actively engaged during a typical week within the previous year), co-morbid conditions, and medications, was first obtained from the participants and their parents. The level of physical activity (in metabolic equivalent hours per week) was estimated on the basis of the intensity, duration, frequency, and the assigned metabolic equivalent value of the exercise activity according to the Compendium of Energy Expenditures for Youth [16]. Parents were also invited to complete the DCD questionnaire (2007 version) and the total score was calculated. Higher scores indicated a better parental perception of the motor proficiency of the children [15].

The MABC was used to assess the motor performances of the participants because it is a standardized, well-validated, and reliable instrument for measuring motor proficiency in children and is commonly used to differentiate children with DCD from those with normal motor development [14,17]. It comprises eight gross and fine motor tasks for each of the four age bands (i.e., 4-6 years, 7-8 years, 9-10 years, and 11-12 years). The eight tasks are divided into three domains—manual dexterity, ball skills, and balance. The manual dexterity domain includes fine motor tasks, such as using a red pen to draw a continuous line following a bicycle or flower trail, that require considerable mental concentration. The detailed assessment procedures have been described in Henderson and Sugden [14]. The motor performance of each participant was evaluated with the appropriate age-band tests. The item score for each task were then summed to obtain a total impairment score (TIS). The TIS and the bicycle/flower trial item score were used for analysis in this study. A lower impairment/item score generally represented better motor performance [14].

Co-registration of the EEG levels of mental attention and meditation and eye movements during a virtual MABC bicycle/flower trial was performed by two assessors after the MABC motor performance tests. Participants sat in front of a 13-inch Fujitsu computer screen monitor, with a resolution of 1366 × 768 pixels, about 50–60 cm away from the screen. The visual target was the MABC bicycle trail (for 4-6 year-old children) or the MABC flower trail (for 7-10-year-old children) picture [14], both of which are large static objects with a display size of 1240 × 1753 pixels. EEG (mental attention) and eye movements (visual attention) were recorded simultaneously while participants slowly moved their gaze along the MABC bicycle/flower trail displayed on the computer screen. They were instructed to fixate on one point within the two boundaries of the trail, then shift their gaze slowly to another point on the trail, and then imagine that they were slowly drawing a virtual line that was not allowed to move outside the boundaries. They had to pay attention to the shape of the trail and the direction of their eye movements should follow the trail from the starting point to the end point. One familiarization trial was performed before the actual recording (one trial).

Corneal reflection (i.e., remote video-based) eye-tracking technology has been commonly used to measure visual attention in children [18] because the metrics of eye gaze (e.g., the duration of fixation) represent the most outward demonstration of cognitive processes (e.g., mental attention) [19]. In this study, the eye movements of both eyes were recorded using a remote, video-based eye-tracking system (Gazepoint GP3 eye-tracker, Gazepoint Research Inc., Vancouver, Canada) sampling at 60 Hz, which allows natural head motion during the recording and has an accuracy of 0.5–1° of visual angle. With this remote eye-tracking set-up, concurrent eye tracking and EEG recording (participants wearing an EEG headset) was technically feasible [20]. A 5-point calibration procedure was performed on each participant using the Gazepoint Control software at the start of each measurement [21]. Participants were instructed to remain as still as possible when performing the eye-tracking task and not to look away from the target. When one of the eyes was not successfully captured by the eye tracker due to excessive head movements, the whole trial was repeated.

Data were captured and analyzed using the Gazepoint Analysis and Gazepoint Control software (Gazepoint Research Inc., Vancouver, Canada). The durations of fixation (in seconds) were detected and determined automatically by the Gazepoint Analysis software that is derived from a custom algorithm based on the gaze point displacement data, which are part of the proprietary information of the software [21]. The precision of fixation detection was improved using special filtering methods [22]. A relative duration of fixation score (i.e., percentage of time fixating on the bicycle/flower trail during the trial) was calculated by dividing the sum of the durations of fixation by the total duration of the test and then multiplying by 100, because the total time required to complete one trial varied among the participants. This percentage score reflected the total duration of fixation (visual attention) better and was used for the analysis. In addition, the locations and sequence (i.e., scan path) of visual fixation for each participant were analyzed manually using the Gazepoint Analysis software. If participants did not attempt to fixate on the bicycle/flower trail during the recording, the data were discarded. The frequency of eye blinks (i.e., the total number of eye blinks during the trial) was also determined by analyzing the gaze video of each participant manually using a video playback software (Window Media Player). Depending on the number of eye blinks during the test, participants were assigned to the frequent-blinking (7–8 eye blinks/trial), moderate-blinking (5–6 eye blinks/trial), or rare-blinking (3–4 eye blinks/trial) group for further analysis.

For the concurrent EEG measurement, each participant was asked to completely remove any hair from the forehead, clean it with an alcohol preparation pad and remove any earrings at the beginning of the test. The assessor then helped the participant to put on a Mindwave Mobile EEG headset (NeuroSky Inc., USA), which incorporates a single, dry, active electrode that is placed on the left side of the forehead (Fp1 position, according to the International 10–20 System of electrode placement) [23] and a reference electrode that is clipped to the left earlobe [7].

The EEG activity of the prefrontal cortex was recorded continuously during the whole MABC bicycle/flower trial (i.e., eye-tracking period). During the EEG recording, the electrical potential from the prefrontal region was supplied to the chipset embedded in the headset for analog filtering with a band-pass filter (0.5–30 Hz) and notch filter to eliminate electrical noise at 50 Hz. Other known noise frequencies (e.g., those caused by eye blinks, and extraocular and muscular activities) were also eliminated automatically using proprietary algorithms. The sampling rate of the device was 512 Hz. The analog data were then converted to digital format in the headset circuit board and transmitted via Bluetooth to the NeuroView data acquisition software (NeuroSky Inc., USA), which was installed on a laptop [7].

The NeuroView data acquisition software converted raw prefrontal cortex EEG signals to an attention index and a meditation index using Fast Fourier Transform and a preconfigured proportion of EEG alpha (8–12 Hz), beta (12–30 Hz), theta (4–7 Hz), and delta (0.1–3 Hz) activities. These two indices, ranging from 0 to 100, were generated and recorded for every second of the EEG recording, and provided an indication of the degree of attention and meditation, from very low (0–20), low (21–40), and average (41–60) levels to moderate (61–80) and high (81–100) levels of mental concentration/relaxation [7,24].

The attention and meditation indices (recorded per second) during the virtual MABC bicycle/flower trial period were averaged to obtain an item attention index and an item meditation index, respectively. The item attention index (0–100) reflected the overall mental inattention-attention level during the MABC bicycle/flower trial while the item meditation index (0–100) indicated the overall level of tenseness-calmness during the same trial. Higher indices (close to 100) generally represent a higher level of mental attention or relaxation [7]. These two item attention and meditation indices were used for the analysis.

Moreover, participants were assessed for maximal handgrip strength using a Jamar dynamometer (Sammons Preston, Mississauga, ON, Canada) and standardized assessment procedures [25]. In brief, participants stood with the testing shoulder (i.e., the dominant side) adducted and neutrally rotated, the elbow flexed at 90°, the forearm in a mid-prone position, and the wrist in a neutral position and gripped the dynamometer by the hand. They were instructed to squeeze the dynamometer twice using maximal effort and the highest grip strength value was recorded [25]. The intra-rater reliability (ICC = 0.94–0.98) and inter-rater reliability (ICC = 0.98) of this test were reported to be good to excellent [25].

Statistical Analysis

All statistical analyses were performed using SPSS 20.0 software (IBM, Armonk, NY, USA) and the significance level was set at 0.05 (two-tailed). Descriptive statistics (mean ± standard deviations) were used to describe the demographic and outcome variables. The normality of the data was checked using histograms. Continuous demographic data of the DCD-attentive and DCD-inattentive groups were compared using independent t tests, and a categorical demographic variable (sex) was compared between the two groups using a chi-square test.

For the data from the DCD-attentive group, Pearson's correlation coefficient (r) was used to examine the degree of association of the EEG-derived item attention and meditation indices with (1) other established attention/inattention measures, such as duration of gaze fixation (i.e., concurrent validity); (2) instruments measuring attributes that are supposedly related to attention/inattention, such as

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the MABC bicycle/flower trial performance score (i.e., convergent validity); and (3) measures that assess unrelated characteristics, such as handgrip strength (i.e., discriminant validity). In addition, the known-groups validity was evaluated. A test with good known-groups validity should be able to distinguish individuals with a good attention level from those with a poor attention level. Therefore, comparisons of EEG-derived item attention and meditation indices were made between the DCD-attentive and DCD-inattentive groups, using the independent t test (objective 1).

To explore the influence of eye blink artifacts on the EEG-derived item attention and meditation indices in the DCD-attentive children (objective 2), the Kruskal-Wallis test was used to compare these outcome variables among the frequent-blinking (7–8 eye blinks/trial), moderate-blinking (5–6 eye blinks/trial), and rare-blinking (3–4 eye blinks/trial) groups. A non-parametric test was used because of the small sample size and because the data were not normally distributed. In addition, the Spearman rho was used to examine the bivariate relationship between the frequency of eye blinks and the EEG-derived item attention and meditation indices in the DCD-attentive group.

Results

A total of 37 children with DCD were eligible to participate in the study, 20 of whom were assigned to the DCD-attentive group and 17 were assigned to the DCD-inattentive group. All of them completed the assessments successfully. Detailed participant characteristics are presented in Table 1. The basic demographic characteristics were comparable between the two groups (all $p > 0.05$) (Table 1).

	DCD-attentive group (n = 20)	DCD-inattentive group (n = 17)	p
Age (years)	7.7 ± 1.0	7.2 ± 1.4	0.242
Sex (male/female) (n)	18/2	14/3	0.498
Weight (kg)	25.9 ± 4.2	26.1 ± 8.2	0.932
Height (cm)	125.3 ± 6.6	121.9 ± 7.1	0.152
Body mass index (kg/m2)	16.5 ± 1.5	17.2 ± 3.6	0.417
Physical activity level (MET hours per week)	17.6 ± 29.3	11.3 ± 16.9	0.437
DCD questionnaire 2007 total score	36.5 ± 8.7	39.9 ± 7.9	0.213
Movement Assessment Battery for Children total impairment score	16.2 ± 8.6	14.9±10.5	0.682

Table 1: Participant characteristics.

Values are mean ± standard deviations unless noted otherwise, MET = metabolic equivalent, DCD = developmental coordination disorder, Body mass index was calculated by dividing weight (kg) by height (m)2.

Concurrent validity

In the DCD-attentive group, a significant relationship was found between the EEG-derived item attention index and the duration of gaze fixation ($r = 0.648$, $p = 0.002$), indicating good concurrent validity. However, no significant correlation was detected between the item meditation index and the duration of gaze fixation ($r = 0.364$, $p = 0.114$) (Table 2).

Convergent and discriminant validity

In the DCD-attentive group, the EEG-derived item attention index was significantly correlated with the MABC bicycle/flower trial item score ($r = -0.688$, $p = 0.001$), but not with handgrip strength ($r = 0.157$, $p = 0.508$), demonstrating good convergent validity and discriminant validity. However, no significant correlations were found between the item meditation index and the MABC bicycle/flower trial item score ($r = -0.081$, $p = 0.734$) or handgrip strength ($r = 0.024$, $p = 0.918$) (Table 2).

	Attention Index	Meditation Index
Gaze fixation duration (%)	0.648*	0.364
Movement Assessment Battery for Children bicycle/flower trial item score	-0.688*	-0.081
Handgrip strength (kg)	0.157	0.024
Number of eye blinks	-0.138	-0.036

Table 2: Correlation analyses in the DCD-attentive group (n = 20).

*$p < 0.05$ (two-tailed).

Known-groups validity

A significant difference in the EEG-derived item attention index ($p=0.003$), but not in the item meditation index ($p = 0.278$), was found between the DCD-attentive group and the DCD-inattentive group (Table 3).

	DCD-attentive group (n = 20)	DCD-inattentive group (n = 17)	p
Item attention index	63.52 ± 10.25	50.14 ± 15.27	0.003*
Item meditation index	57.76 ± 10.12	52.87 ± 16.59	0.278

Table 3: Known-groups validity of the single-channel EEG device.Values are mean ± standard deviations, *$p < 0.05$ (two-tailed).

Influence of eye blink artifacts on EEG-derived attention and meditation indices

In the DCD-attentive children, no significant differences were noted in the EEG-derived item attention ($p = 0.887$) or meditation indices ($p = 0.057$) among the frequent-blinking, moderate-blinking, and rare-blinking groups (Table 4). In addition, no significant relationships were found between the item attention ($\rho = -0.138$, $p = 0.561$) and meditation indices ($\rho = -0.036$, $p = 0.880$) and the total number of eye blinks (Table 2). These results collectively suggested that eye blink artifacts did not affect the EEG-derived indices in children with DCD.

Discussion

This study confirms that the commercially available single-channel, dry-electrode, and wireless EEG device (Mindwave Mobile EEG headset and the NeuroView data acquisition software) provides a valid measure of the level of mental attention in children with DCD, with no significant influence of eye blinking. However, the validity of this device in measuring the meditation level is questionable. Our results were concordant with the findings of Rebolledo-Mendez et al. [13], who found a significant correlation between self-reported attention levels and the EEG-derived attention indices ($r = -0.391$, $p = 0.022$) and thus concluded that the NeuroSky EEG headset provides accurate readings for measures of attention in young people (i.e., concurrent validity). In fact, the raw EEG waveforms recorded by the NeuroSky headset were very similar to a traditional EEG recording system (Nuamps, Neuroscan, USA) in terms of the underlying frequency characteristics and the Fast Fourier Transform processing of raw EEG data, thus demonstrating good concurrent validity [6]. The comparative validity of the NeuroSky EEG recording system was also good – the headset-processed EEG band power data showed expected patterns of variation corresponding to the psychological/emotional states (e.g., attention and relaxation) of the pediatric participants [6].

	Frequent-blinking group (n = 5)	Moderate-blinking group (n = 8)	Rare-blinking group (n = 7)	p
Item attention index	59.22 ± 13.98	64.57 ± 8.28	65.40 ± 10.08	0.887
Item meditation index	60.80 ± 11.44	51.62 ± 7.54	62.62 ± 9.24	0.057

Table 4: Influence of eye blink artifacts on the EEG-derived item attention and meditation indices in the DCD-attentive group (n = 20). Values are mean ± standard deviations.

Recently, NeuroSky Inc. also conducted validation tests comparing brainwave signals acquired using a traditional wet-electrode EEG machine (Biopac System) and the NeuroSky ThinkGear, which is the technology inside the Mindwave Mobile EEG headset. The results showed that the EEG signals of both systems were comparable and the NeuroSky system was even more noise-resistant in low frequency bands due to the shorter wires between the electrodes and the preamplifiers [26]. All of these findings collectively suggest that the portable NeuroSky single-channel EEG recording device is valid and has a potential utility for measuring mental attention, especially in pediatric populations in which ease of use is a priority.

Although the NeuroSky headset can effectively show the trend of the participant's emotional (attention) changes, it may not be able to register the precise and mixed emotional status of the participant instantaneously [27]. In addition, the accuracy of the NeuroSky meditation eSense algorithm is not known [27], which may explain the invalid measurement of meditation using the meditation index. Further studies could analyze the raw EEG signals and EEG power spectrum directly [7] to confirm these results.

Our results also revealed that eye blinking during EEG recording did not significantly affect the attention and meditation indices. Although the active electrode of the NeuroSky headset rested on the forehead above the eye, eye blink artifacts were removed automatically using a prior set of information on the wave frequencies [7]. This method is feasible and effective because ocular artifacts have a higher frequency than EEG signals and can be filtered using a low pass filter to a 30 Hz or 40 Hz cut-off frequency [12]. Thus, eye blinking had a minimal effect on the attention and meditation indices overall.

This study had some limitations. First, the eye blink artifact rejection method used (mentioned above) may not be perfect and residual artifacts could be present in the data. Further studies could identify and extract the blink artifact from the raw EEG signal using MATLAB processing. Electro-oculographic signals can easily be identified by abrupt changes/peaks in the EEG wave [8,9]. Second, because the Mindwave Mobile EEG device used in this study only produces one-dimensional measures [7,13], its measurements are not sufficiently precise for some psychological-related experiments, such as those investigating attention disorders in children with special needs. Rather, a measure of the absolute and/or relative EEG power across the four frequency bands at various sites on the scalp may be more appropriate [5]. Finally, we only validated the NeuroSky EEG device in children with DCD. Thus, the results cannot be generalized to other populations.

Conclusion

To conclude, although the single-channel, dry-electrode EEG device has limited scalp recording locations, it could accurately measure the overall level of mental attention in children with DCD clinically with no significant influence of eye blinking. This portable device has a potential utility in special pediatric populations, in which ease of use is the first priority.

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