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Investigating neural dynamics in Autism Spectrum Conditions outside of the laboratory using mobile EEG

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Abstract:	There is currently a paucity of neuroscientific data recorded from more severely affected individuals with ASC. Enabling data collection to take place in a more familiar environment, e.g. at home, may increase access to research participation in this group. Here, we present a new accessible method of studying brain activity of autistic individuals outside the laboratory in their home environment, using mobile EEG technology. The primary aim of the present study was to test the feasibility of acquiring good quality EEG data from autistic children at home, assessed via a set of objective data quality metrics, and to develop a list of practical guidelines on how to successfully conduct an EEG experiment in such a naturalistic setting based directly upon participants' views. To demonstrate the utility of this method, we evaluated the EEG signal quality recorded from 69 children with ASC at home using a gel-based Eego Sports mobile EEG system. Five key indicators of data quality were assessed. Our results demonstrate that it is possible to record high quality EEG signal from children with ASC at home, generating data that could address a number of research questions. A user experience survey identified areas of good practice, which researchers should take into consideration when designing mobile EEG studies aiming to acquire data from children with ASC at a home environment.

Impact statement

This is the first study to demonstrate that high quality EEG data can be acquired from autistic children outside the laboratory in a home setting using mobile EEG technology and also the first to systematically gather data on user-experience regarding children's participation in EEG research. Given the shift in direction towards participatory autism research, this work provides an important approach by being the first to actively explore and document the experiences of autistic individuals participating in EEG experiments.

Investigating neural dynamics in Autism Spectrum Conditions outside of the laboratory using mobile EEG

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Abstract

There is currently a paucity of neuroscientific data recorded from more severely affected individuals with ASC. Enabling data collection to take place in a more familiar environment, e.g. at home, may increase access to research participation in this group. Here, we present a new accessible method of studying brain activity of autistic individuals outside the laboratory in their home environment, using mobile EEG technology. The primary aim of the present study was to test the feasibility of acquiring good quality EEG data from autistic children at home, assessed via a set of objective data quality metrics, and to develop a list of practical guidelines on how to successfully conduct an EEG experiment in such a naturalistic setting based directly upon participants' views. To demonstrate the utility of this method, we evaluated the EEG signal quality recorded from 69 children with ASC at home using a gel-based Eego Sports mobile EEG system. Five key indicators of data quality were assessed. Our results demonstrate that it is possible to record high quality EEG signal from children with ASC at home, generating data that could address a number of research questions. A user experience survey identified areas of good practice, which researchers should take into consideration when designing mobile EEG studies aiming to acquire data from children with ASC at a home environment.

1.1 Introduction

EEG is a commonly used neuroimaging method for those with neurodevelopmental conditions. Although despite being one of the more accessible neuroimaging methods, it is not without barriers to participation, including the requirement to visit a specific, usually unfamiliar location and the requirement to limit movement during the recording. For individuals with Autism Spectrum Conditions (ASC), entering a new environment to take part in unknown activities with an unfamiliar social partner- the experimenter- can be a daunting prospect. This can pose challenges for both the individual and the experimenter, as well as caregivers who accompany the participant to the appointment. Consequently, there is a tendency for research to be biased towards the inclusion of more able autistic individuals and a paucity of EEG data recorded from more severely affected individuals with ASC. This bias ultimately hinders the identification of behaviour-brain-gene pathways and limits opportunity to fully describe and understand variations in neural dynamics in ASC. Here we describe a new accessible method of studying the brain of autistic individuals at home, using mobile EEG technology.

An understanding of how mobile EEG hardware and software interact with specific features of the ASC phenotype is necessary to maximise the likelihood that individuals with ASC can participate in EEG research and allow for the acquisition of low-noise EEG signal (Webb et al., 2015). Certain elements of EEG hardware have previously been systematically assessed and solutions for capturing high-quality data proposed (Ratti et al., 2017; Kam et al., 2019). Aspects important for ASC research include the material of the cap, the speed with which the cap can be applied and engineering elements that allow for good signal-to-noise ratios (SNRs). For example, soft lightweight fabric EEG caps are likely to be more tolerable than caps made of hard plastic. Head caps with integrated “hidden” electrodes look less intimidating than caps with protruding wires and can also reduce the length of time required for preparation. Similarly, it’s important to balance the length of time it takes to prepare the participant for the recording, with the number of channels used to record data. Active electrodes show better SNRs and require fewer trials to detect significant effects compared to passive electrodes (Mathewson, Harrison & Kizuk, 2016).

Researchers should strive to maintain the fine balance between procedural adaptation and standardisation. Although processes should be adapted to meet the autistic individual's needs, which will ultimately allow for better quality of EEG data, this should not be to the expense of standardisation of procedures, which allows for comparability across non-clinical and clinical groups (Kylliainen et al., 2014; Webb et al., 2015). Shared understanding on how to achieve this is currently limited. In an effort to address the need for practical guidelines, Kylliainen et al. (2014) and Webb et al. (2015) have presented guidelines to consider when planning and implementing an EEG experiment with children with ASC. However, these are based on empirical data and the authors' personal recommendations and focus on data acquisition in the laboratory. To shed light on best practice when collecting data outside of the laboratory environment, it is important to define what consists of an optimal home-testing protocol for this group and develop practical guidelines that directly map onto the experiences of the children and adults with ASC that take part in such studies, rather the perspective of the researcher alone.

Considering the above, the primary aim of the present study was to test the feasibility of acquiring high quality EEG data from autistic children at home using mobile EEG technology and to explore children's views on the experimental process, which would in turn inform practical guidelines for EEG experimentation at home. To the best of our knowledge, this study is the first to directly record EEG signal from individuals with ASC in their own homes and also the first to systematically gather data on user-experience regarding children's participation in EEG research.

To demonstrate the utility of this method, a simple visual paradigm was administered, designed to elicit visual evoked potentials across multiple trials. This approach was selected as it is similar to many paradigms that are used to investigate neural dynamics in ASC and related conditions (Milne et al., 2009). EEG data were recorded from 69 children with ASC who had diverse neurocognitive profiles (see Methods section). There is currently no consensus on a single method of assessing EEG data quality (Clayson et al., 2020). We evaluated the EEG signal by computing five key indicators of data quality: a) the proportion of artefact-free channels, b) the proportion of artefact-free epochs, c) the number of components to which dipole models could be fitted with residual variance below 15% after ICA decomposition, d) the presence of P1 and N1 Event Related Potential (ERP) deflections- common ERP components that one would expect to be elicited by this paradigm, metrics

previously used in the literature to evaluate EEG data quality in ASC (Milne et al., 2009) and in validation of other mobile EEG devices (Badcock et al., 2015; Raduntz, 2018), and e) an indicator of reliability based on the comparison of the aggregated standard error of the mean of trials for each subject to the variance of mean ERP response across subjects (Luck et al., 2020). We also explored the user experience of the participants by asking each participant to rate specific aspects of the protocol and to comment on what they liked and disliked about the procedure. This information is essential to refine the ideas by Killiainen and colleagues (2014) and Webb et al. (2015) and promote experimental practices taking into account the experiences of the individuals with ASC participating in mobile EEG experiments.

2.1 Methods

2.1.1 Participants

Seventy-three children with ASC were initially recruited for the study. From this cohort, four participants could not tolerate the EEG process. EEG data were therefore acquired from sixty-nine children with a diagnosis of ASC. Of these participants, thirteen were using limited or no language and could not complete the user experience survey. Fifty-six participants completed the evaluation questionnaire. Participants were recruited via online advertisement on social media, the local community and special schools. Participant demographics are presented in *Table 1*. Parents of all participants confirmed that their child had been given a diagnosis of ASC from a qualified clinical professional. A comprehensive overview of the formally diagnosed co-occurring conditions in the group is provided in *Table 2,* as reported by the carers. Thirteen participants were taking medication at the time of the testing session (see *Table 3*). All participants had normal or corrected to normal visual acuity. Consent from both the child and the carer was acquired in written form. The study was approved by the Department of Psychology Ethics Committee of the University of Sheffield.

Table 1

Participant demographics

	ASC (n=69)
Gender	
Female	17
Male	52
Age	
Mean	11.0
SD	2.3
Range	6-15
WASI Performance IQ score[a]	
Mean	109.0
SD	14.7
Range	78-147
SRS-2 T-score[b]	
Mean	84.0
SD	6.7
Range	68- >90

[a]*WASI Performance IQ score, Wechsler Abbreviated Scales of Intelligence (WASI, Wechsler, 1999)*
[b]*SRS- 2, Social Responsiveness Scale (SRS-2, Constantino & Gruber, 2012)*

Table 2

Number of participants with a diagnosed comorbid condition.

	Frequency	Percent (%)
Total	**42**	**62.68**
Sensory Processing Disorder	7	10.44
ADHD	7	10.44
Dyspraxia	4	5.97
Anxiety Disorder	6	8.95
Social Communication Disorder	2	2.98

Intellectual Disability	1	1.49
ADHD & Sensory Processing Disorder	2	2.98
ADHD & Intellectual Disability	1	1.49
ADHD & Dyspraxia	1	1.49
ADHD & Anxiety Disorder	1	1.49
Intellectual Disability & Sensory Processing Disorder	1	1.49
Intellectual Disability & Dyspraxia	1	1.49
Sensory Processing Disorder & Dyspraxia	1	1.49
Sensory Processing Disorder & Anxiety Disorder	1	1.49
Anxiety disorder & Depressive Disorder	1	1.49
Sensory Processing Disorder, Dyspraxia & Anxiety Disorder	2	2.98
Intellectual Disability, Social Communication Disorder & Anxiety Disorder	1	1.49
Tourette's Syndrome, Sensory Processing Disorder, Dyspraxia & Anxiety Disorder	1	1.49
Tourette's Syndrome, ADHD, PDA, Sensory Processing Disorder & Motor Disorder	1	1.49

Table 3

Drug intake of participants recorded up to 24 hours prior to the EEG experiment

	Frequency	Percent (%)
Total	**13**	**19.38**
ADHD medication		
Lisdexamfetamine	1	1.49
Atomoxetine	1	1.49
Methylphenidate	2	2.98
Depression medication		
SSRIs	2	2.98
Sleeping disorder medication		
Melatonin	6	8.95
Antipsychotic medication		
Risperidone	1	1.49

2.1.2 Psychometric measures

Participants completed the Matrix Reasoning and the Block Design subtests of the Wechsler Abbreviated Scales of Intelligence (WASI, Wechsler, 1999), a tool used to measure cognitive abilities of individuals aged 5-85 years old. The Matrix Reasoning and the Block Design scores combined form the Performance Scale and yield a Performance IQ (PIQ) score, summarised in *Table 1* for the present sample. All caregivers completed an online version of the Social Responsiveness Scale-Revised Child/Adolescent version (SRS-2, Constantino & Gruber, 2012). A T-score of 59 or below is not associated with clinically significant symptoms of ASC, whereas T-scores above 60 are indicative of clinically significant deficiencies in reciprocal social behaviour associated with ASC, symptoms ranging from moderate (n=9) to severe (n=60) for the present sample.

2.1.3 Procedure

2.1.3.1 Apparatus

A 32-channel Eego™ sports ANTneuro EEG system and ANTneuro Eego™ Software were used for EEG data acquisition. Stimuli were presented on a Dell Latitude 5490 with an Intel ® Core™ i5-8250U CPU at 1.60GHz processor, running on a Windows 10 and a 64-bit operating system. Visual stimuli were presented on an LCD display screen with a spatial resolution of 1920 × 1080 pixels, refresh rate of 60 Hz, bit depth of 6-bits and colour space of Standard Dynamic Range (SDR). The screen was connected to an Intel® UHD Graphics 620.

To solve the problem of sending triggers without a parallel port, the Lab Streaming Layer (LSL) was utilised for trigger transmission. The core transport library *liblsl* and its Matlab application programming interface (API), was used to transmit event marker data (*Figure 1*). A single hardware system, a Dell Latitude 5490, was used to send and receive data. LSL transmitted data through the Local Area Network (LAN) using a UDP protocol (Kothe, 2014). Matlab executables (.mex files) provided in the downloaded folders were recompiled using a 64-bit C/C++ compiler. All relevant *liblsl* folders and subfolders were added to the path of the Matlab script file of the experimental task. A new stream outlet was created by declaring a new lsl_streaminfo object, storing core information about the data stream (i.e

name, type, channel count, sampling rate, channel format, source ID). Event markers were pushed into the inlet chunk-by-chuck (using the function *outlet.push_sample*).

Figure 1

[Placeholder, Figure 1]

Figure 1: Schematic representation of the Lab Streaming Layer (LSL) protocol.

2.1.3.3 Visual task

A checkerboard stimulus was presented 100 times on the display screen (2 blocks of 50). Each sub-block consisted of a random number of checkerboard presentations each time ranging between 5-7, followed by an image of a red cross. The checkerboard appeared on the screen for an average of 1500ms, jittered between 1000 and 1500ms. The duration of the inter-stimulus interval (ISI) was a uniform distribution between 1000 and 1500ms. Similarly, the inter-trial interval (ITI) varied randomly between 1000 and 1500ms. At the end of each sub-block a black and white image of a spaceship was shown on the screen (deviant stimulus), in order to provide some interest for the participant and thus facilitate engagement. Participants were instructed to press the spacebar when the spaceship image appeared on the screen (*Figure 3*). Following 100 trials, participants were instructed to close their eyes while resting-state data were acquired for 120 secs.

2.1.3.4 User experience measures

Participants were asked to complete a brief user experience questionnaire at the end of the study when both parts of the experiment, the EEG task and the questionnaires were completed (*Figure 2*). A few participants had a shower to remove the gel and then completed the user experience questionnaire. Participants pointed at the right answer for Questions 1 to 3 and verbally provided an answer for Questions 4 and 5. In the first two questions children were asked to rate specific elements of the EEG equipment on a smiley face Likert 6-point scale, corresponding to "*Very poor*", "*Poor*", "*Okay*", "*Good*", "*Very good*", "*Excellent*". Question 3 asked children to rate how they felt about the experiment taking place at home.

The last two questions were open-ended, aiming to understand more about the child's overall experience of the EEG session, without biasing their responses. Children were asked to comment freely on aspects of the EEG session they liked (Question 4) and disliked (Question 5), questions that aimed to provide richer information about their individual experience.

Figure 2

[Placeholder, Figure 2]

Figure 2: User experience questionnaire

Figure 3

[Placeholder, Figure 3]

Figure 3: Schematic representation of the EEG experiment.

2.1.3.5 Standardisation of study parameters

Carers were instructed to turn off all electrical devices in close proximity of the location of testing to minimise power line noise interference. To avoid inter-site biases and minimise sources of variability, known to impact EEG outcomes (Farzan et al., 2017), the time of data acquisition and environmental conditions during data acquisition were kept as consistent as possible across sites. All children were tested in the evening after school (between 4pm and 7pm). To ensure consistency of environmental conditions across sites, the EEG experiment took place in a darkened room, where curtains were closed and lights were turned off. Caregivers were instructed to remain silent and outside the participant's visual reach but remained present during the testing session.

The visual task remained the same for all participants. However, the task was designed so that it could be either active or passive depending on the ability of the participant. Participants with greater developmental delay were encouraged to look at the red cross on the screen only (n=5), whereas more able participants were instructed to press spacebar when the spaceship image appeared on the screen (n=64).

2.1.3.6 Adaptation of procedures

The home visit involved a warming-up phase, aiming to familiarise participants with the communication style of the experimenter and allow for preparation of the testing environment. The length and content of the warm-up period differed from one child to the other, depending on their developmental level and need at the time of testing. The session was presented as a "science lesson" to more able participants, during which they could learn more about the human brain. For less able children, the experimenter engaged the child in

active play, using their favourite toys (e.g building Lego blocks). The experimenter introduced each element of the equipment and explained what the study would involve. During the warm-up period, the child chose their preferable seating arrangement. Cap preparation started as soon as the experimenter judged the participants to be engaged and relaxed to reduce the risk of the child getting bored. Communication style involved exaggerated body, facial and vocal expressions, imitation, short sentences, very simple words and/or communication cards.

Clear instructions about the experimental process were given to all participants. Language was adjusted to establish a stream of communication between the experimenter and the participant. Prior to the visit, carergivers were asked whether their child uses alternative and augmentative communication techniques prior to the visit. For those participants (n=9) as well as for younger children aged 6-7 years old (n=6), the experimenter utilised laminated Picture Exchange Communication System (PECS) flash cards to communicate the exact steps of the process. Both verbal instructions and visual aids were utilised to ensure that the child understood task requirements. Visual cues were used to make the process predictable and help with transitions. The user interface of the EEG acquisition system was used in most cases as a visual aid to show how movement affects the EEG signal in real time and the number of electrodes subjected to impedance check.

For children demonstrating sensitivity to tactile input, we gradually exposed the child to the gel and the cap until they felt comfortable with it. The experimenter first put gel on their own hand, then on the child's hand and encouraged them to touch it. Similarly, we asked the child to touch the material of the cap before wearing it. On some occasions, the cap was put on their favourite teddy bear or was placed on the carer's scalp. The EEG cap was presented as being similar to a "swimming hat", which helped some children relate previous experiences of wearing a tight hat to the new. A 3cc syringe with a blunt tip was utilised which ensured minimal noise during gel application. Rewards and positive reinforcement were the behavioural strategies used to increase motivation. Children could choose from a pool of rewards such as stickers, LEGO minifigures or time with their favourite toy at the end of the EEG experiment.

2.1.4 Data analysis

2.1.4.1 Temporal accuracy of LSL triggers

In order to validate the temporal precision of LSL event markers, the hardware clock of the data acquisition device was used to compute the temporal error, also known as jitter, between scheduled time and actual time of triggers being recorded in the hardware. LSL event markers were fired at different time points: when the checkerboard and spaceship stimulus appeared and disappeared from the screen, when the participant pressed space bar in response to the spaceship stimulus and when the resting state period started and ended. Every time one of the above markers was fired, the start stopwatch timer- in-built within Matlab- recorded the elapsed time between the two time points. Jitter time was computed for all triggers and all participants in the experiment.

2.1.4.2 Evaluation of EEG data quality

EEG data preprocessing

A number of preprocessing steps were followed to separate physiological signal of interest from sources of noise, non-neuronal in origin (Makeig & Onton, 2012). All EEG datasets were analysed using EEGLAB (Delorme & Makeig, 2004) running on Matlab 2014a (The Mathswork, Inc.). Electrode *Cz* was selected as the reference electrode. A high- pass filter of 1Hz was applied to the continuous data in order to remove large drifts or signal deviations. Channels exhibiting noise due to poor scalp connection were identified by visual inspection and were removed from the analysis. Channels visually identified as having unusual peaks following high-pass filtering were also excluded from the analysis. Continuous data were visually inspected and noisy time segments containing muscle or eye movement artefacts affecting multiple channels were manually rejected. This resulted in fewer epochs being retained and used for further analysis than the initial number of trials. Independent Component Analysis (ICA) was then applied using the *runica* function of EEGLAB. Data were interpolated and dipole source localisation of Independent Components (ICs) was performed using the *dipfit* plug-in of EEGLAB (Oostenveld & Oostendorp, 2002; Delorme et al., 2012). Data were segmented into epochs, from -1 to 1 secs around stimulus onset, and

corrected to baseline, using the average signal between 1 sec before stimulus onset to stimulus onset.

EEG data quality measures

The first indicator of data quality was the number of good channels retained for further analysis after the artefact rejection procedures described above. The greater the number of channels maintained for downstream analysis, the smaller the EEG signal loss. The second metric was the number of epochs retained after artefact rejection. This is a good indicator of how contaminated the raw EEG signal was with motion, or other, artefacts. As a third indicator of signal quality, we measured the number of Independent Components (ICs) to which dipole models could be fitted with residual variance below 15%. It is expected that a single equivalent dipole is projected onto ICs, representing neuronal activity within a cortical area. For this reason, the goodness of fit of the dipole model fitted for each IC is an indicator of signal quality as low residual variance of the model fit suggests that ICA has successfully resolved neural signals that can be localised to a single source (Makeig & Onton, 2012).

The fourth metric of signal quality was the reliable detection of the visual P1 and N1 event-related potential (ERP) components. First, we measured the amplitude and latency of the P1 and N1 deflections using an automated process. We measured peak P1 and N1 amplitude and latency of a cluster of channels (P3, P4, Pz, POz, O1, Oz, O2) covering the occipital and posterior regions. These deflections were given as the amplitude and latency of the maximum amplitude within a time-window occurring between 100 and 200 ms after stimulus onset (P1) and the amplitude and latency of the minimum amplitude within a time-window occurring between 220 and 280 ms after stimulus onset (N1). We then identified the number of participants who did not show P1 and N1 deflections in at least one of the occipital and posterior electrodes. Mean amplitude in time windows corresponding to the time at which the earliest and the latest P1 deflection was seen across all participants (130 ms – 200 ms) and the time at which the earliest and latest N1 deflection (220 ms – 280 ms) was seen was computed. If the mean value of the P1 window was greater than the mean +2 standard deviations of the baseline period, then P1 was considered as being present. Similarly, if the mean value of the N1 window was smaller than the mean -2 standard deviations of the baseline period, then N1 deflection was considered as being present.

The fifth metric was a 'reliability' measure which compares the aggregated standard error of the mean of trials for each subject to the variance of mean ERP response across subjects (Luck, Steward, Simmons & Rhemtulla, 2020). This gives an indication as to whether any differences in ERP magnitude or latency across subjects is due to genuine inter-subject variability or due to inter-trial variability within a subject. If the inter-trial variability is greater than that observed between subjects, data quality is poor. It results in a value between 0 and 1, with values closer to 1 indicating higher reliability.

2.1.4.3 Statistical analysis of user experience measures

We used a mixed method approach to analyse the questionnaire data. A percentage frequency distribution of responses is presented for Questions 1-3. We present the percentage of children who felt positive ("*Excellent*", "*Very good*"), neutral ("*Good*", "*Okay*") and negative ("*Poor*", "*Very poor*") about a) the material of the cap, b) the gel and c) taking part in an experiment at their home environment. Open-ended survey questions (Questions 4 and 5) were manually analysed using thematic analysis, a data-driven approach, which captures the richness of information provided by the participants (Braun, Clarke, Haufield & Terry, 2019). Key themes were assigned to the data using a coding frame that was not pre-defined but rather, it emerged from the participant text entries (inductive coding) (Thomas, 2006). Codes were first assigned to the raw data and text entries were re-coded to ensure test-retest reliability (Roberts, Dowell & Nie, 2019). Given the exploratory nature of this work, the experimenter encouraged children to elaborate on their experience and there was no limit in the number of given answers. Similar codes were put under the same thematic category, which allowed the emergence of main and overarching themes and subthemes.

3.1 Results

3.1.1 Temporal accuracy of LSL triggers

23.866 LSL event markers were fired in total. The latency distribution between scheduled time and actual time of triggers being recorded in the hardware, presented in *Figure 4*, demonstrates that temporal accuracy of LSL trigger markers is high, within millisecond precision or better (*M*=0.0003s, *SD*=0.0007, *Min*=0.00004s, *Max*=0.02s).

Figure 4

[Placeholder, Figure 4]

Figure 4: Histogram of jitter time (x axis), presented in seconds (s) for all triggers (y axis).

3.1.2 EEG data quality assessment

The number of channels and epochs retained after artefact rejection, extracted from the data recordings using the Eego Sports mobile system, is presented in *Table 4*.

Table 4

Mean (M), Standard Deviation (SD), Minimum (Min) and Maximum (Max) number of EEG channels and epochs retained, as computed from data acquired using the 32-channel Eego Sports mobile system

Metric	*M*	*SD*	*Min*	*Max*
1. EEG channels retained	26	2.93	16	30
2. Epochs retained	89	5.35	71	96

ICA applied on individual participant scalp data, returned as many components as the number of channels kept for further analysis after preprocessing.

The number of ICs with residual variance lower than 15% was also computed from the EEG recordings. We found that dipole scalp projections adequately fit the IC scalp maps for an average of 18 ICs per participant (*M*=18, *SD*=3, *Min*=10, *Max*=25). A previous laboratory-based study using similar methods to those reported here found a mean number of retained components of ~10, extracted from signal acquired from children with ASC using a static wet electrode EEG system that is frequently used in neurodevelopmental research (Milne et al., 2009). The number of ICs that likely reflect neural sources extracted from the mobile EEG signal is therefore comparable to laboratory-based alternatives. *Figure 5* shows a single IC from each participant to highlight the topographic projection of the IC to the EEG data in sensor space. For each participant, we selected an IC that projected at the occipital lobe, to demonstrate the consistency of these components across participants.

Figure 5

[Placeholder, Figure 5]

Figure 5: Example Independent Component (IC) scalp maps

Further to this analysis, we computed peak P1 and N1 ERP component amplitude and latency of electrodes P3, P4, Pz, POz, O1, Oz, O2 and their corresponding reliability values (see *Table 5*). For most participants, peak P1 amplitude occurred at electrode O2 around 175ms and peak N1 amplitude occurred at electrode O1 around 246ms. For 91% of the group, peak P1 amplitude was observed in one of the three channels O2, Oz and O1, whereas for peak N1 amplitude, the spread was greater, across all posterior channels.

Reliability values for the mean and peak amplitude of P1 and N1 ERP components at electrodes P3, P4, Pz, POz, O1, Oz, O2 are close to 1, ranging from 0.768 to 0.932 for P1 'mean', 0.863 to 0.966 for N1 'mean', 0.907 to 0.966 for P1 'peak' and 0.825 to 0.965 for N1 'peak'. Similarly, the latency where the peak amplitude for P1 and N1 occurs shows reliability ranging from 0.666 to 0.902 for P1 and 0.823 to 0.922 for N1 (*Table 5*). Therefore, is it established that both P1 and N1 ERP components show high reliability.

Table 5

Peak P1 and N1 Amplitude (uV) and Latency (ms) computed from electrodes P3, P4, Pz, POz, O1, Oz, O2 from all participants (Mean, Minimum, Maximum) and their corresponding reliability value (R).

Electrode	Amplitude (uV)				Latency (ms)			
	P1	*R*	N1	*R*	P1	*R*	N1	*R*
P3	6.99 [0.09 17.72]	0.907	-5.67 [-17.86 1.35]	0.825	172.20 [134 200]	0.733	243.74 [220 280]	0.824
P4	5.81 [0.10 16.72]	0.937	-4.16 [-13.98 3.82]	0.883	176.46 [108 200]	0.715	245.88 [220 278]	0.840
Pz	8.05 [1.92 24.05]	0.911	-6.39 [-18.38 5.90]	0.876	170.67 [132 200]	0.666	241.45 [220 274]	0.828
POz	13.11 [1.21 33.12]	0.945	-5.47 [-24.00 12.82]	0.925	177.01 [100 200]	0.836	248.67 [220 280]	0.892
O1	19.79 [0.99 47.40]	0.955	-7.17 [-40.59 7.02]	0.926	175.04 [130 200]	0.874	246.67 [220 280]	0.919
Oz	21.21 [1.06 47.87]	0.966	-4.96 [-40.50 14.20]	0.955	177.04 [130 200]	0.897	251.10 [220 280]	0.922
O2	22.14 [1.10 50.51]	0.964	-6.40 [-41.23 14.56]	0.956	175.42 [132 200]	0.902	249.48 [220 280]	0.920

As *Figure 6* demonstrates, P1 and N1 deflections are evident in grand-average ERP traces computed from occipital and posterior electrodes as well as the ERPs of individual channels- here we present ERP traces computed from electrode O2. This figure shows that visual ERPs were reliably detected in the signal. *Table 6* presents the number of participants showing P1 and N1 deflections at each electrode of the electrode cluster covering the occipital and posterior locations of the head. The majority of participants (99% and 97% respectively) showed clear P1 and N1 deflections in at least one electrode from the electrode cluster. Overall, P1 voltage deflections were completely absent in only one participant, whereas two participants did not show N1 ERP traces in any of the aforementioned channels.

Table 6

Number and percentage of participants in the group showing P1 and N1 deflections at each of the electrodes P3, P4, Pz, POz, O1, Oz, O2.

Electrode	ERP Component			
	P1		N1	
	Frequency (n=69)	Percent (%)	Frequency (n=69)	Percent (%)
P3	53	77	65	94
P4	53	77	58	84
Pz	61	88	66	96
POz	60	87	50	72
O1	63	91	46	67
Oz	60	87	23	33
O2	62	90	44	64

Figure 6

[Placeholder, Figure 6]

Figure 6: a) Grand-average ERPs computed from electrodes P3, P4, Pz, POz, O1, Oz, O2 for all participants and b) ERP traces plotted for the example electrode O2, as extracted for all participants.

3.1.3 User experience

The majority of children found the EEG cap pleasant and felt positive about the experiment taking place at home, but the responses to the electrolyte gel were more mixed. *Figure 7* summarises children's responses to Questions 1-3.

Figure 7

[Placeholder, Figure 7]

Figure 7: Proportion of children that responded positively ("*Excellent*", "*Very good*"), neutrally ("*Good*", "*Okay*") and negatively ("*Poor*", "*Very poor*") to Questions 1-3.

Five themes emerged from Question 4 ("*What did you like about the EEG session?*", see *Table 7* for a summary). The first theme relates to aspects of the equipment. A large number of children (*n*=25) pointed out that they were fascinated by software features of the EEG such as the interactive screen showing a) EEG data in real time and b) the impedance check view feature (e.g "*I liked seeing my brain waves*"). A smaller number of participants commented on the design of the cap (*n*=3) and the overall technology (*n*=2). A small number of children enjoyed the tightness of the cap and the cold feeling of the gel on the scalp (*n*=2).

The second theme that emerged relates to aspects of the experimental task. A large number of children found the task very engaging; incorporating play into the process made the experimental task very appealing (*n*=13). They explicitly commented on the alien/spaceship picture and pointed out that "*the game was fu*n". Others mentioned that the task was "*easy*" and "*not stressful*" (*n*=2) and that they liked the rewards offered by the experimenter (*n*=2). The third theme encompasses aspects of the environment. Children enjoyed taking part in a scientific experiment at home (*n*=2) and in a quiet environment (*n*=1).

The fourth theme relates to intrinsic motivation. Some children mentioned that they enjoyed improving their sense of social responsibility by taking part in the research study, "*knowing that they are helping others*" (*n*=2). This highlights the importance of communicating the aim and purpose of the study in an accessible way. Linked to this, the fifth theme relates to the experimenter. A subset of children (*n*=3) commented on the accessible and inclusive communication style of the researcher (e.g. "*[Name of the experimenter] communicated well the information*").

Five themes emerged from Question 5 ("*What did you not like about the EEG session?*"). The first theme relates to the equipment used during testing. Some children found the sensation of the gel touching their skin uncomfortable ("*I didn't like it when the gel wet my hair*") (*n*= 23). Oher children did not like the experience of wearing the tight cap (*n*=3), fastening the strap around their chin (*n*=1) or having the wire touching their neck (*n*=1). Other children commented negatively on the "*squirting noise*" of the liquid dispenser/syringe used to inject gel. The second theme relates to the subject preparation and equipment set-up. Some children found the time taken to prepare the wet electrodes very long (*n*=4). They report that "*it took so long*" and "*I didn't like waiting to get ready for the spaceship*". The third theme relates to the task itself. Two of the children found the task boring due to its repetitiveness ("*It was boring, I was drifting off*"). The fourth theme is about the environment. Even though all children chose freely their sitting arrangement, in one occasion, the child found the chair uncomfortable to sit for a long time. The fifth theme relates to the participant's physical state during the experiment. One child reported difficulty staying still during the EEG and another child found keeping their eyes closed in the resting-state condition challenging. To strengthen this point, five children could not complete the eyes-closed condition because they were unable to keep their eyes closed for two minutes.

Table 7

Key themes and subthemes, as emerged from children's responses to Question 4 and 5

Questions	Theme	Subtheme	Example answers
4. "What did you like about the EEG session?"	Equipment	Interactive screen-Software	"I liked seeing my brain waves", "I liked watching the dots changing colour"
		Design- Cap	"I liked the style of the hat"
		Sensory experience- Cap	"I liked the tight cap"
		Sensory experience- Gel	"I liked the gel going into the hair", "I liked the gel being cold"
		Overall technology	"It had brilliant technology"
	Task	Engaging task/use of play	"Spaceship was fun", "I liked the alien picture", "I liked the game"
		Easy task	"Task wasn't too hard", "The EEG wasn't stressful to do"
		Use of rewards	"I was offered stickers"
	Environment	Being tested at home	"I liked that it took place at home"
		Quiet	"I liked that it was quiet"
	Intrinsic motivation	Altruism	"I might be helping people"
		Fascination with science	"I liked the science of it"
	Experimenter	Accessible communication style	"[Name of the experimenter] communicated well the information", "[Name of the experimenter] was really nice to me"
5. "What did you not like about the EEG session?"	Equipment	Sensory experience- Cap	"The cap was too itchy", "I didn't like the colours of the cap"
		Sensory experience- Strap	"The strap around the chin was uncomfortable", "The bottom bit of the cap was too loose"
		Sensory experience- Wire	"I didn't like the wire at the back of the head"
		Sensory experience- Gel	"I didn't like it when the gel wet my hair"
		Sensory experience- Syringe	"I didn't like the needle squirting"
	Task	Boring task	"It was boring, I was drifting off"
	Environment	Uncomfortable sitting arrangement	"Back was hurting half way through, I had bad chair"
	Subject preparation/equipment set-up	Length of time	"It took so long", "I didn't like waiting to get ready for the spaceship"

4.1 Discussion

The present study was the first to use mobile EEG technology to record data from children with ASC in their home environment. The primary aim of the present study was to test the feasibility of acquiring good quality EEG data from autistic children in such a setting. We evaluated the EEG signal quality recorded from 69 children with ASC at their home environment using a gel-based Eego Sports mobile EEG system. In order to evaluate the quality of data obtained via this method, we examined the number of channels and epochs retained, the number of returned components with residual variance <15%, detection of P1 and N1 ERP deflections and the reliability of these ERP deflections. The majority of participants showed clear P1 and N1 deflections in at least one electrode from the electrode cluster covering the posterior and occipital sites. N1 deflections were absent in 3% of the group, whereas only 1% did not show P1 deflections. In addition, both P1 and N1 ERP deflections demonstrated high reliability of close to 1. These values are comparable with reliability measures of EEG data collected in a lab-setting from neurotypical adults (Luck et al., 2020).We therefore established that visual ERP deflections can be reliably measured in the signal. Furthermore, the fact that many of the independent components derived from the continuous data could be fit with a dipole model with <15% residual variance, and no participants generated data from which less than 10 components where the dipole models were fit with residual variance of < 15%, suggests high quality of the EEG signal and its potential utility in studying a range of neural processes in this group.

Based on the above metrics, it was demonstrated that the EEG signal quality acquired using the Eego Sports mobile system and collecting data in the participants' homes was satisfactory to perform not only basic but also more fine-grained EEG analysis such as ICA decomposition and ERP examination. It was also demonstrated that the LSL protocol can be reliably used to send trigger markers through the network, enabling more complex task-based EEG designs to be implemented at home or other settings, where parallel port technology is not available.

Taking a more holistic approach to experimentation, the present study was also the first to explore the user experience of children with ASC in relation to the mobile EEG experiment;

this is crucial to understand how experimenters could acquire optimal signal quality from participants with ASC at home. Based directly upon the views and experiences of the children who participated in this experiment, we identified important aspects to consider when planning and implementing an EEG experiment with children with ASC at their homes.

In our sample, certain elements of the EEG cap interacted with individual differences in sensory sensitivity. A subsample of the children found the EEG cap, the chin strap and the wire connecting the cap with the amplifier to be uncomfortable, whereas a different subgroup enjoyed the tightness of the EEG cap. Therefore we suggest that EEG systems relying heavily on chin straps to ensure the electrodes are in place should be avoided. Wireless EEG systems may also be a good solution, solving the problem of the back wire touching the child's neck.

Due to heightened tactile sensitivity, the electrolyte gel was uncomfortable or just about tolerable for a third of the children tested in the present study. Considering the neurocognitive profile of participants with ASC, this is not surprising. In the present study, wet electrodes were chosen over dry electrodes to maintain low skin-electrode impedances and therefore achieve high signal quality. In addition, EEG signal recorded using dry electrodes is shown to be more prone to movement artefacts (Meziane et al., 2013), a parameter to be taken into consideration when testing young participants with neurodevelopmental conditions. As dry EEG technology is rapidly evolving, dry electrodes may be a good option to be used with children with ASC to minimise sensory reactions and maximise rates of participation in the future. Preliminary evidence has shown that dry electrodes can record EEG signal of similar quality to wet electrodes in a laboratory setting (Kam et al., 2019), although these results are necessary to be extended to a naturalistic setting such as the home environment and to clinical groups such as ASC.

In the present study, it is likely that the familiar environment together with the manipulation of experimental parameters helped children tolerate the EEG and cope with the experimental procedure. Although a hypothesis not directly tested in this research work, low levels of emotional arousal are likely to have played an important role in the successful acquisition of low-noise signal. In support of this proposition, a recent study by DiStefano et al. (2019) showed that elevated participant state, captured as vigilance or agitation displayed during testing, is linked to lower EEG data retention rates and greater reduction in alpha spectral

power in a sample of children with ASC of various cognitive abilities. We therefore suggest that conducting the EEG experiment in a familiar environment such as the home setting has the potential to be a very effective method of achieving low levels of emotional arousal, allowing for higher quality EEG data acquisition from subjects with ASC, particularly those with more challenging behaviour that would not otherwise comply with experimental processes.

Mobile EEG technology is a rapidly developing field and there are a number of different options available for experimentation, including wireless EEG systems and systems utilising dry electrode technology (see *Table 8* for a summary). Multiple research lines have compared dry-wet electrode EEG solutions (Marini et al., 2019). An important next step for future research is to compare the performance of dry and wet electrodes on similar metrics in a naturalistic environment such as the home setting, where access to a shielded room is not possible and the environmental conditions are more variable. Future work should also aim to test the functionality of using a wireless system instead of a wired EEG device, shown to exacerbate sensory sensitivities in our ASC sample and restrict participant's mobility in other studies.

A strength of this study is the sample size (n= 69), however potential sampling bias remains an important limitation of the work. Of the seventy-three participants who originally consented to take part, four children were not able to comply with the experimental process due to severe communication deficits, hindering effective communication between the experimenter and the participant. As our recruitment method was an opt-in method (i.e. we were contacted by parents who wanted their child to take part after seeing advertisement of the study) it is likely that the high success rate of successful recordings is due, in part, to the sample being this will have skewed towards children who were more able to engage with the protocol. Therefore, the limitation of increasing accessibility to research for children who are profoundly affected by ASC remains. Nevertheless, anecdotally, our impression of the data collection phase was that being able to complete the testing session in the participants' homes increased uptake to the study and allowed us to gain data from a larger sample than has been possible in previous studies where data collection is consigned to the lab. In conclusion, here we provided evidence and developed guidelines to support EEG data collection at home, potentially opening up possibilities for increased access to research for a range of participants.

Table 8

Available mobile EEG systems and their technical specifications

	Hardware												Overall device				
	Electrodes				Amplifier						Head cap		General characteristics				
Model/Company	Number	Type	Sensor shielding	Material	Max sampling rate (Hz)	Bandwidth (Hz)	Resolution (bit)	CMRR (dB)	Input impedance (MΩ)	Input noise (mV)	Material	Cable shielding	Weight (gr)	Battery life (h)	CE mark	Price*	Prep time (mins)
MindWave (NeuroSky)	1	dry	passive	stainless steel	512	1-100	12	N/A	20	Not stated	plastic, rubber	yes	90	6-8	no	low	0
4S JellyFish (Mindo)	4	dry	passive	spring-loaded pins	256	0.23-1300	24	110	3	<1.25	plastic	no	95	10	no	low	Not stated
BR8 (BRI)	8	dry	passive	spring-loaded pins, polymer foam	500	0.12-125	24	Not stated	Not stated	Not stated	plastic	no	269	10	no	low	Not stated
EPOC [X] (EMOTIV)	14	wet (saline)	passive	gold-plated, felt	256	0.16-43	14-16	85	1	N/A passive amplifier	plastic	no	1000	6-12	no	low	10-15
B-Alert X24 (ABM)	20	wet (gel)	passive	polymer foam	256	0.1-100	16	105	$>10^2$	1.5	plastic	no	110	8-15	yes	high	Not stated
Smarting (mBrainTrain)	24	wet (gel)	passive	sintered Ag/AgCI	550	0-250	24	>140	$>10^3$	<1	soft fabric	no	60	5	no	low	5-10
EPOC [Flex] (EMOTIV)	32	wet (saline or gel)	passive	sintered or electroplated Ag/AgCl	1024	0.16-43	14	85	30	N/A passive amplifier	soft fabric	no	500 (saline) 1500 (gel)	9	no	low	20
32 Trilobite (Mindo)	32	dry	passive	spring-loaded pins, polymer foam	512	0.23-1300	24	110	3	<1.25	plastic	no	578	10	no	low	Not stated

actiCAP Xpress, V-amp (BrainProducts)	32	dry	active	gold-plated	20.000	0-320	24	100	$>10^2$	<1	soft fabric	no	430	Not stated	no	medium	Not stated
ENOBIO (Neuroelectrics)	8, 20, 32	dry or wet (gel)	passive	Ag/AgCl (dry, wet)	500	0-125	24	115	$>10^3$	<1	thick elastic fabric	no	<97	5.5-24	yes	low, medium	1-3 (dry), 10-30 (wet)
SAGA (TMSI, BIOPAC)	32, 64	wet (gel or water)	passive	Ag/AgCI	4096	0-800	24	100	$>10^2$	<0.8	soft fabric	yes	700	8-10	yes	medium	10-20
Eego Sports (Ant-neuro)	32, 64	wet (gel)	passive	Ag/AgCI	2048	0-532	24	>100	$>10^3$	<1	soft fabric	yes	<500	5	yes	medium	10-15
g.NAUTILUS RESEARCH (g.tec)	8,16,32, 64	dry or wet (gel)	active	spring-loaded graphene pins (dry) or sintered Ag/AgCI (wet)	500	$0\text{-}10^4$	24	>90	$>10^2$	<0.6	hard fabric	no	<140	>10	no	medium	5-10
g.NAUTILUS PRO (g.tec)	8, 16, 32	dry or wet (gel)	active	spring-loaded graphene pins (dry) or sintered Ag/AgCI (wet)	500	$0\text{-}10^4$	24	>90	$>10^2$	<0.6	hard fabric	no	<110	>10	yes	high	5-10
Mobile (Cognionics)	64, 128	wet	active	Ag/AgCI	1000	0-131/262	24	Not stated	Not stated	<1	hard fabric	no	460	6-8	yes	high	10-40

*low <6000 GBP, medium 6000-15000 GBP, high >15.000 GBP

5.1 Conclusions

The present study demonstrated that it was possible to record high quality EEG signal from children with ASC at a home environment. Here, we used a gel-based Eego Sports mobile system to record EEG signal and the LSL protocol was successfully used to send trigger markers through the network, paving the way for more complex EEG experiments to be implemented at home by ASC researchers. In addition, we developed a protocol for home visits in ASC. The user experience survey flagged up a few areas experimenters should take into consideration when designing an EEG experiment aiming to acquire EEG data from children with ASC at a home setting.

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Author contributions

Aikaterini Giannadou: Conceptualisation; Formal analysis; Investigation; Methodology; Visualisation; Writing- original draft; Writing- review & editing. **Elizabeth Milne**: Supervision; Conceptualisation; Formal analysis; Methodology; Writing- original draft; Writing- review & editing. **Myles Jones**: Supervision; Formal analysis; Methodology; Visualisation. **Megan Freeth**: Supervision; Writing- review & editing. **Andrea Samson**: Writing- review & editing.

Declarations of Interest

None.

Name[a] and email address[b] for preprints

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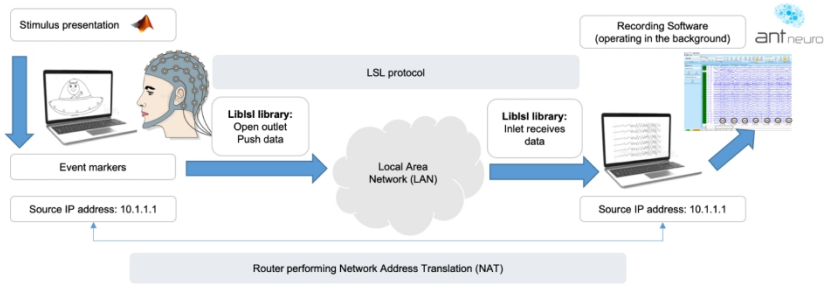

Figure 1: Schematic representation of the Lab Streaming Layer (LSL) protocol.

Participant number_____

EVALUATION

How did the **material of the cap** feel?

How did the **gel** feel?

How did you feel about the experiment taking place at **home**?

What did you **like** about the EEG?

_____
_____
_____

What did you **NOT like** about the EEG?

_____
_____
_____

THANK YOU!

Figure 2: User experience questionnaire

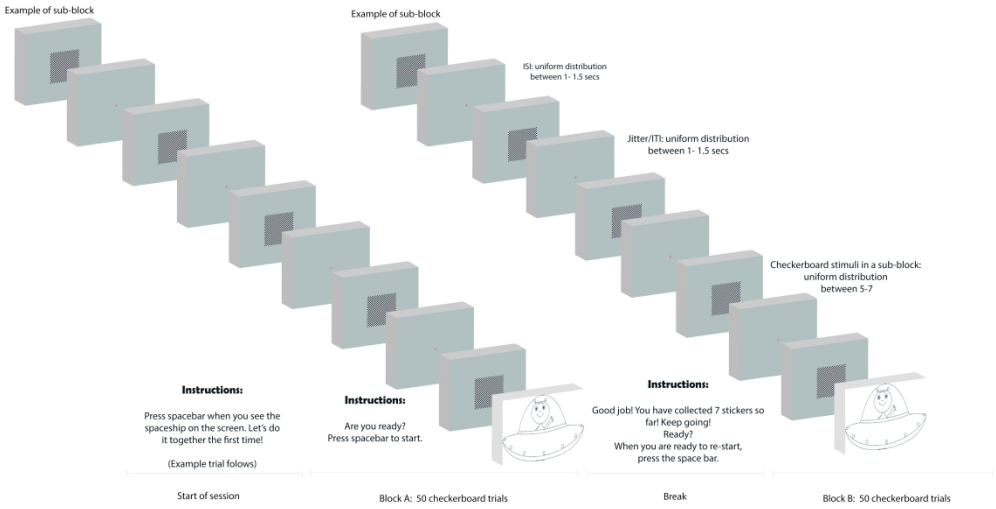

Figure 3: Schematic representation of the EEG experiment.

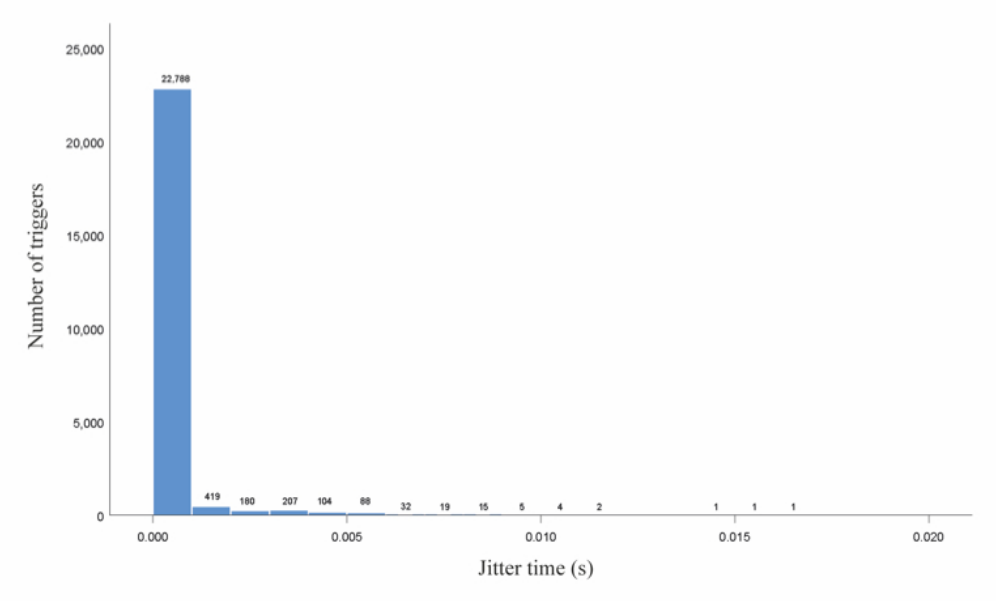

Figure 4: Histogram of jitter time (x axis), presented in seconds (s) for all triggers (y axis).

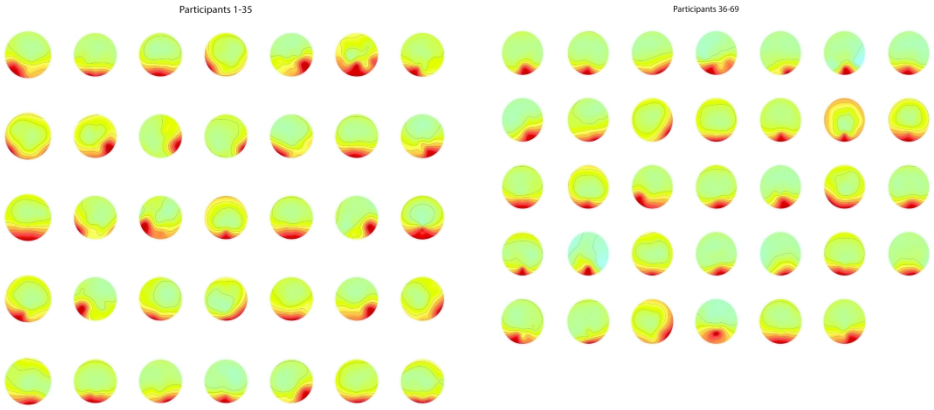

Figure 5: Example Independent Component (IC) scalp maps

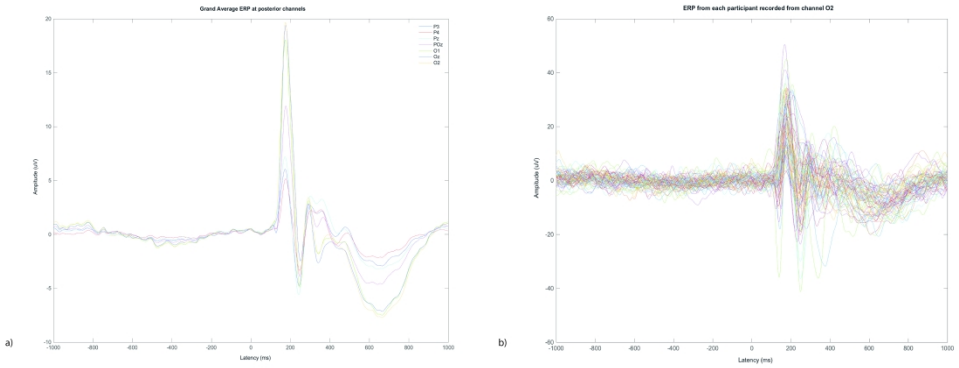

Figure 6: a) Grand-average ERPs computed from electrodes P3, P4, Pz, POz, O1, Oz, O2 for all participants and b) ERP traces plotted for the example electrode O2, as extracted for all participants.

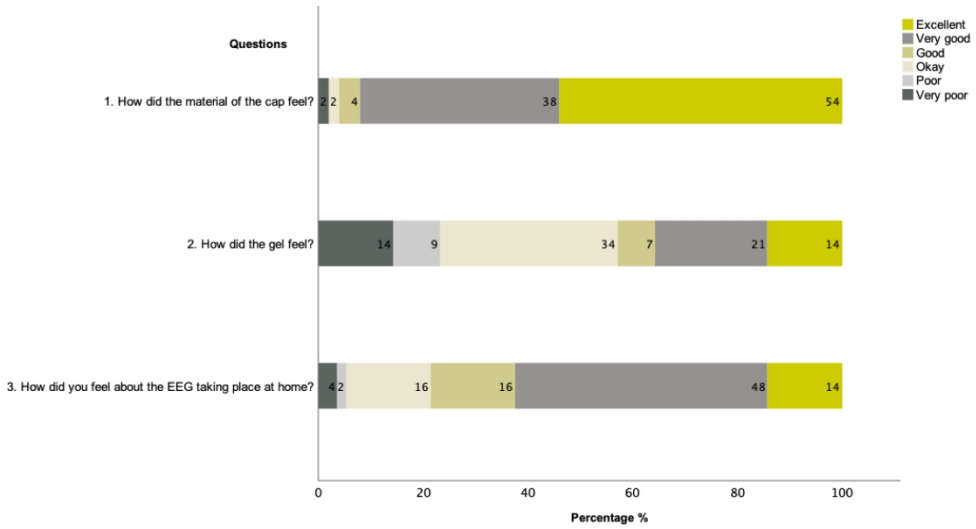

Figure 7: Proportion of children that responded positively ("Excellent", "Very good"), neutrally ("Good", "Okay") and negatively ("Poor", "Very poor") to Questions 1-3.