UNIVERSITY OF ICELAND

Bachelor's Thesis

in Psychology

Exploring Attentional Neural Differences During an Oddball Paradigm: An SSVEP Study

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February, 2023

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Abstract

Attention wields a significant influence on visual processing and its impact on neural activity seems to become progressively greater as information cascades through the visual stream. This study explores how attention modulates visual object processing. Recording neural activity with electroencephalography (EEG) using steady state visually evoked potentials (SSVEP) elicited by images of faces and objects we aim to investigate high-level visual processing.

Participants varying in self-reported symptoms of Attentional Deficit Hyperactivity Disorder (ADHD) took part in two SSVEP experiments, one for faces and the other for objects, where attention was modulated. The SSVEP response was elicited by fast periodic visual stimulation, with a rapid display at a rate of 6 cycles per second (6 Hz; base frequency) were 5 cycles consisted of the same face or object and every 5^{th}cycle a different face or object appeared. This oddball stimulus introduced during a stream of base level stimuli differs only on high-level dimensions and is therefore well suitable to high-level visual activity.

The measured effect of this oddball stimulus, or the oddball power, is used to estimate the influence of attention on high-level visual processes. Attention was modulated by having participants either attend to the high-level stimuli or a fixation point (a point with colour) superimposed on the stimuli so the effects of attention could be estimated. Participants were asked to pick the faces/colours or objects they saw during the trial.

Results indicate that the oddball power for complex stimuli, faces and objects, is positively correlated with ADHD scores.

Acknowledgments

While challenging, working on this thesis has been a rewarding and fulfilling learning experience. Grateful for the experience to learn from and be guided by our supervisors, Dr. Heiða María Sigurðardóttir and Dr. Hélène Devillez, we would like to thank them dearly for their time, effort and support. Constantly engaged in the task of helping us move forward with this project, they shared with us invaluable knowledge in the field of vision science and the pursuit of knowledge in general. Additionally, we would like to extend our gratitude to our peers that helped gather data for this study, including but not limited to, Ari Víkingsson, Elísabet Sesselja Harðardóttir, Ísak Örn Ívarsson, Karen Lísa Morthens, Katrín Guðnadóttir, Marelle Maekalle and Unnur Andrea Ásgeirsdóttir. Lastly, we would like to thank our friends and families. As with many of life's challenges, the pursuit and completion of this project was made possible by their love and support.

Contents

Exploring attentional neural differences during an oddball paradigm: An SSVEP study

Vision is humans' most dominant sense, and we rely upon it to complete a vast majority of our daily tasks. Visual attention is a key feature of vision that enables us to efficiently and effectively respond, learn and adapt to our environment. The goal of this study is twofold. First, we explore whether there is a difference in SSVEP oddball power to attended and unattended faces. Secondly, we ask whether attentional differences affect visual object processing.

We begin with an overview of the central themes of this study, attention and attentional modulation, where the focus is on feature- or object-based attention and attentional modulation of visual object processing. Since the aim is to explore these mechanisms by observing the neural responses of individuals varying in attentional abilities, a short discussion on the neural substrates of Attentional Deficit Hyperactivity Disorder (ADHD) and the method used to record the neural responses, electroencephalography (EEG), are included. High-level visual processing can be examined using the SSVEP method while using EEG. Here, the stimuli used to elicit these processes are faces and objects so an introduction on visual object processing is included. Additionally, neural adaptation is discussed given that it is influenced by attention.

Attention and Attention Modulation

The vast amount of information present in the visual field cannot be processed simultaneously, presenting the need for a mechanism enabling the selection of relevant and inhibition of irrelevant information. This mechanism is referred to as attention, and in the case of vision, visual attention. Although this process of selecting and disregarding information may sound simple, attention as a unitary construct is difficult to pinpoint. Several neural mechanisms seem to be at play giving rise to different varieties of attention, involving various brain regions (Hommel et al., 2019). Here, the focus will be on the forms of attention that play a role in modulating visual object recognition guided by the ventral visual stream, beginning in the primary visual cortex and running through the inferotemporal cortex (Goodale & Milner, 1992; Rajalingham & DiCarlo, 2019). Spatial attention plays a role, facilitating the ability to selectively focus on a specific location. An object needs to reside in this location for optimal processing. The type of attention facilitating object recognition is often referred to as feature-based or object-based attention, depending on the level of processing. Detection and processing of basic or low-level features, such as contrast and colour, is performed in the early stages of the ventral visual stream. As information flows to higher cortical areas up the visual stream, increasingly complex or higher-level features, such as faces and objects, are processed (Graham, 1989).

Top-down attention refers to the voluntary selection of features, locations, and objects, and bottom-up attention refers to selection driven by the stimulus (Pinto et al., 2013). Top-down and bottom-up control of visual attention seem to be related to activity in the prefrontal cortex and the visual stream, respectively (Buschman & Kastner, 2015; Buschman & Miller, 2007). Bottom-up attention, being stimulus-driven, is highly sensitive to changes in stimuli, such as changing images from one face to another. Top-down attention plays a role when an individual needs to voluntarily direct attention towards changes in stimuli when given a memory task.

Various studies have shown that directing attention to a stimulus enhances neural activity (Hillyard & Anllo-Vento, 1998; Mangun & Hillyard, 1988; McMains & Somers, 2004; Yamaguchi et al., 1994) and the impact of attention on neural activity seems to become progressively greater as information cascades through the visual stream (Hembrook-Short et al., 2017). A study conducted by Hopf (2006) demonstrated that the neural location of attention varies with the scale of the attended stimuli, with large-scale targets eliciting activity in higher-level cortical regions (the lateral occipital complex) and small-scale targets eliciting activity in lower-level regions. Furthermore, going from one area to the next in the ventral stream, receptive fields increase, and neural density decreases (Wilson & Wilkinson, 2015). Moreover, attentional modulation depends heavily on the relationship between neuronal feature selectivity and the relevant task features (Hembrook-Short et al., 2017). Chelazzi and colleagues have also shown that selective attention modulates neural responses to objects in the ventral stream. By presenting two or more objects on a visual display, they found that neurons in lower- and higher-level regions of the ventral visual stream, V4 and the inferior temporal cortex respectively, that were selective for a certain stimulus responded more when that stimulus was being attended to as opposed to not attended to but still present on the display (Chelazzi et al., 1993, 1998, 2001). This validates findings that visual attention seems to bias the responses of neurons selective for an object even though other objects are present in the visual field (Brooks et al., 2014; Desimone & Duncan, 1995; Reynolds et al., 1999).

These findings suggest that attention to specific features or objects should have an increasing modulatory effect on corresponding neuronal activity with increasing stimulus complexity. Additionally, it might be expected that the ability to direct attention to task-relevant features would have an effect on selective neural activity. There are individual differences in visual attentional abilities and in people with Attentional deficit hyperactivity disorder (ADHD) the ventral attentional stream seems to be impaired, impacting stimulus-driven attention (Helenius et al., 2011).

Attention Deficit Hyperactivity Disorder

Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder that involves inattention and/or hyperactivity/impulsivity that interferes with daily functioning (American Psychiatric Association, 2013). It is one of the most common neurodevelopmental disorders which affects people of all age groups (Mahone & Denckla, 2017).

People with ADHD can vary in their symptoms and how they display them (Wilens & Spencer, 2010), and accordingly, there is no single test to diagnose ADHD. However, self-report rating scales may be used to screen for the disorder. They typically consist of separate questions on childhood and adult behaviour (Mulraney et al., 2022; Stanton et al., 2018) that reflects inattention, hyperactivity, and impulsivity. Inattentive subscales measure difficulty in focusing, organization, and prospective memory. Impulsivity/hyperactivity subscales measure motor and verbal representations of the disorder such as fidgeting and difficulty staying still or excessively talking and interrupting others (Kessler et al., 2005).

The affected neuropsychological functions in ADHD include aspects such as selective attention, sustained attention, working memory and response inhibition as well perceptual functions (Lange et al., 2014; Thome et al., 2012). A systematic literature review conducted by Fuermaier et al. (2018) found that individuals with ADHD exhibit reduced perceptual functions for visual perception. Additionally, they found that perceptual problems in ADHD may aggravate problems of inattention and vice versa, that problems of inattention may modulate perception in ADHD. Another systematic review on ADHD and sensory processing indicated that individuals with ADHD have impairments in stimuli modulation, characterized by increased sensory gain and deficient sensory inhibition (Schulze et al., 2020).

Results from (Nazari et al., 2010) indicate that children with ADHD have deficits in visual sensory integration, early filtering and orientation processes, within the occipital cortex. Looking at neural activity they found that decreased activation in early stages of the visual stream as well as poor behavioural performance reflect inefficient stimulus detection, discrimination, and classification in individuals with ADHD.

Although ADHD is most often tied to deficits in the top-down allocation of attention (Rubia, 2018), earlier stimulus-driven bottom-up processing seems to be affected as well.

Visual Object Processing

Certain areas of the ventral visual stream play a crucial role in the visual recognition of objects and faces**.** Objects may be categorized at three levels depending on class inclusion and the degree of specificity, such as animal – superordinate level, dog – basic level, Saint Bernard – subordinate level. The superordinate level involves general concepts where items belonging to the same superordinate category may share few common perceptual features. The basic level contains the most perceptually and conceptually salient categories which share the greatest number of common features within a category and share the least number of features with concepts from other categories. Finally, the subordinate level contains the most specific categorization of concepts, which share many features with concepts from the same category and are therefore less perceptually distinctive (Zeifert, 2022).

Several studies have found that participants provide faster responses during an object verification task at the basic level (Morris & Murphy, 1990; Rosch et al., 1976). In the procedure, subjects heard the name of a category of objects (e.g., fruit) and then immediately saw a picture (e.g., chair). Participants were faster to decide if the picture was an object of the category just named if it was a basic level category than if it was a subordinate or superordinate category level. In addition, accuracy was higher at the basic level during object recognition performance in categories, such as animals and plants, as well as reaction time advantage (Taniguchi et al., 2020). Therefore, it seems that it is more difficult to discriminate between objects at the subordinate level than at the basic level.

Face recognition is a specific type of object recognition, with faces being an object type commonly discriminated at the subordinate level. It is a difficult task that requires detecting and extracting information sufficient for discrimination of a particular face from others. Individual face discrimination relies on a large set of brain areas, particularly those that respond preferentially to faces in the right ventral occipito-temporal cortex (Rossion, 2014). Results are supported by examining patients with prosopagnosia who have brain damage to the right occipitotemporal areas and fusiform cortex and have serious difficulty in recognizing faces (Albonico & Barton, 2019). Therefore, researchers keep finding the right hemisphere to be dominant in face recognition, especially the right middle fusiform gyrus (Lopatina et al., 2018). Raising the question whether attentional modulation of face processing is greater right or left hemisphere.

Neural Adaptation

Neural adaptation is a phenomenon of decreasing neural activity after prolonged or repeated stimulation (Benda, 2021). In many circumstances, neural responses decrease following the repetition of a stimulus but increase if there is a new stimulus or feature, a so-called release from adaptation as an altered feature or a new stimulus activates a non-adapted sub-population of neurons (Vakli et al., 2014). The traditional fatigue-based explanation of neural adaptation (Graham, 1989; Sekuler & Pantle, 1967) is that neurons show reduced responsiveness to repeated stimuli to which they are tuned as it takes time for them to recover after periods of high activity. Therefore, neurons should experience stronger fatigue if the adapter stimulus is presented for a longer duration, a phenomenon called the duration scaling law (Bao & Engel, 2012).

However, Solomon & Kohn (2014) proposed that a longer duration of adaptation does not necessarily cause a stronger adaptation effect. Repeated stimulation does not always reduce responsivity but can also increase it, which can be explained by sensory processing called normalization (Carandini & Heeger, 2012). The response of neurons depends on both the direct input they receive via the classical receptive field (CRF) and normalization signals which are drawn from a pool of neurons and have a divisive effect on the classical receptive field. Adaptation that targets this pool of neurons may reduce the normalization signals and consequently decrease the inhibitory effects of normalization and increase neural responsivity (Webster, 2015).

In conclusion, if a change in a stimulus leads to a release from adaptation in a neural population, then this implies that the neural population is selective for the stimulus change, and the stimuli are encoded by distinct neural populations. In this way, neural adaptation can be used to probe the sensitivity of neurons to different objects (Kim et al., 2009). For example, image transformation from a cup to a phone produces a large release from adaptation in the lateral occipital complex (LOC), an area that appears to play a central role in object recognition (Grill-Spector et al., 2001). Neural adaptation can also be used to probe the sensitivity of neurons to faces, and it will be discussed in further detail in the next chapter on electroencephalography (EEG) and the methods used to study neural responses to stimuli.

Electroencephalography and Steady State Visually Evoked Potential

The current study uses electroencephalography (EEG) to record neural responses to stimuli. It is a common and non-invasive method of studying neural activity that measures electrical activity at the scalp. Although spatial resolution is limited, temporal resolution is excellent which provides an opportunity to measure neural activity in response to a stimulus, or evoked potentials. Since around the middle of the twentieth century, evoked potentials have been used to study the relationship between sensory stimuli, neural activity, and cognition (Adrian, 1944; Adrian & Matthews, 1934; Dawson, 1954; Walter et al., 1946).

A certain type of visually evoked potential can be especially convenient to use when using EEG to study neural processes, the steady state visually evoked potential (SSVEP). The steady state response can be elicited using a method coined fast periodic visual stimulation (FPSV) (De Rosa et al., 2022) where a stimulus or some property of a stimulus is repeated periodically, at a fixed rate. This periodicity of the stimulus in turn generates a periodic change in voltage amplitude, or power, of the electrical signal, measured by EEG. This periodic neural signal has the same frequency as the stimulus frequency (Norcia et al., 2015). The convenience of the method is largely due to the high signal-to-noise ratio (SNR) of the response, or the SSVEP. Given the periodic quality of the SSVEP response, it is restricted to specific sets of frequencies and is therefore easily analysed in the frequency domain. The SNR can be computed by comparing the EEG power at the stimulation frequency to that of nearby frequency bins in the frequency spectrum. Using this method, a stimulus-related signal may be more easily detected compared to standard event related potential (ERP) responses to transient events. For example, after about 60 seconds of EEG recording while a visual stimulus is shown at a desired frequency, the EEG power at the stimulation frequency can be around four times larger than that of nearby frequency bins. Additionally, the harmonics of the stimulation frequency can be detected, although at lower amplitudes (Rossion, 2014).

Conventionally, SSVEP methods have primarily been used to study low-level visual processes, but more recently they have been used to study higher-level visual processes as well. Norcia et al. (2015) describe two approaches for this, indirect and direct approaches. Indirect approaches study higher-level processes by measuring an SSVEP generated by low-level processes over low-level areas that has been modulated by a higher-level process. This can be done by superimposing a uniform visual flicker on a static visual stimulus that engages participants in a memory task, and then comparing the SSVEP amplitude for the perceptual and memory components of the task (Silberstein et al., 1990). Direct approaches target the higher-level process in a direct manner by frequency tagging the process so that it can be distinguished from low-level processes, by analysis or design.

An effective way to target certain high-level processes with a direct approach is to use a fast oddball periodic paradigm where an oddball stimulus is introduced during a stream of base level stimuli, the oddball and the base stimuli differing on the high-level dimension of interest while low-level perceptual qualities are kept stable. For example, in the case of individual face discrimination a single face (image of individual A) differing in identity to a stream of faces (images of individual B) elicits a response over the right occipito-temporal cortex, an area associated with face recognition (Rossion, 2014). Using an indirect approach Silberstein et al. (2001) found that perceptual processes are related to a reduction in SSVEP amplitude while holding information in active working memory is associated with an increase in SSVEP amplitude. This indicates that neural adaptation is at play during the perceptual component of the task.

EEG recordings have shown that the amplitude of N170, which is a face-sensitive event-related potential (ERP), reduces during the repetition of the same face. This suggests adaptation of a neural population to the specific face. In addition, magnetoencephalography (MEG) scan found its counterpart M170 to be larger in response to a different face identity compared to when the same face was repeated (Fu et al., 2012). Therefore, EEG has been successful in recording transient neural responses to face stimulation. Rossion & Boremanse (2011) have found that the fast oddball paradigm can be used as a tool to investigate the sensitivity of the brain to individual faces, which is one of the most fine-grained processes to perform on faces (Rossion, 2014).

Current Study

In the current study, we will explore how attention modulates visual object processing by measuring the SSVEP response to faces and objects for participants varying in attentional abilities.

The SSVEP oddball paradigm was chosen here as it can be used to demonstrate an increase in neural activity as a result of a change in the category of the visual object (Stothart et al., 2017). First, we explore whether there is a difference in SSVEP oddball power to attended and unattended faces. We suggest that oddball power to changes in face identity will be higher while attending to rather than away from faces. Second, we will explore whether there is a correlation between oddball power and ADHD scores. We expect that participants with higher scores of ADHD will pay less attention to faces and will therefore be less sensitive to face identity changes and accordingly have lower oddball power while attending to faces. Participants with higher scores of ADHD are expected to recognize fewer faces and be slower during the memory test.

Methods

The current study is part of a larger research project aiming to look at individual differences, abilities, and disabilities, in mapping and tracking visual object representations by means of comparing typical and dyslexic readers. The project was run under a protocol approved by the Icelandic Bioethics Committee (no. 19-076). Participants attended two sessions. They answered questionnaires and completed one event-related potential (ERP) and one SSVEP experiment on the first day and one ERP experiment, two SSVEP experiments as well as a reading task on the second day (Devillez & Sigurdardottir, 2022). The SSVEP experiment from the first day on visual face processing and the SSVEP experiment from the second day on visual object processing will be considered here.

Participants

A total of twenty-two typical readers and thirty-six dyslexic readers took part in the experiment. In exchange, participants could get a gift card from a local shopping mall. If participants were students at the University of Iceland, they could choose to get partial course credits in exchange for participation. All participants were right-handed, reported normal hearing and normal or corrected to normal vision, non-colour-blind, above 18 years old, and native Icelandic speakers. There were two males and twenty females in the typical group and seven males and twenty-nine females in the dyslexic group. The mean age of typical readers was 29.3 years (age range 19 to 61 years old) and the mean age of dyslexic readers was 33.2

years old (age range 19 to 64 years old). In the typical group, one person had finished primary school, fifteen people had finished secondary school, three people had a bachelor's degree, and three people had a graduate degree. In the dyslexic group, one person had finished primary school, twenty-four individuals had finished secondary school, six people had a bachelor's degrees and five people had a graduate degree. Written informed consent was obtained from all participants prior to the experiment. The sample was collected through social media, news articles, radio, and word-of-mouth.

Stimuli

Faces: Sixty faces were generated using FaceGen Modeller 3.5 (Singular Inversions, https://facegen.com/). The following parameters were used to generate the faces: Camera: FOV Angle: 17; distance ratio: 3; yaw angle: -22, -16, -10, -4, 4, 10, 16, 22; pitch angle: 0; - View: background colour: R128 G128 B128; ambient brightness: 0.4; light source: 1; azimuth: 0; elevation: 0; brightness: 0.60 (Devillez & Sigurdardottir, 2022). The faces were set to European, but their shape was randomly determined by the application. The colour toolbox was used to control picture properties (Willenbockel et al., 2010). The rotational average of the Fourier amplitude spectra was matched with the histogram of the luminance of the faces.

Objects: Objects were selected from the "Massive Memory" Object Categories database (Konkle et al., 2010) and license-free objects were found online. There were sixteen object categories and twenty-four exemplars (e.g., 24 hats) within each category. Objects at 100% size were approximately 6.2° width and 9.8° height.

Scrambled background: MATLAB (MathWorks) was used to create scrambled background stimuli. A 2-D fast Fourier transform was performed, phase structure was randomized, and a 2-D inverse fast Fourier transform was applied to create a phase-scrambled version to keep low-level visual information, such as orientation and spatial frequency, constant. Scrambled backgrounds at 100% size were around 20° width and 20° height.

Adult and Childhood ADHD Measures

Two self-report questionnaires were presented to participants to identify symptoms of ADHD as defined by DSM-IV (Magnússon et al., 2006). The questionnaires are reliable and valid for the initial screening of ADHD (Magnússon et al., 2006). Participants were asked to recall their behaviour in the previous six months (ADHD-I) or from their childhood, specifically from 5 to 12 years old (ADHD-II) (Magnússon et al., 2006). The odd-numbered items were related to symptoms of inattention and even-numbered items were associated with hyperactivity/impulsivity. The maximum value for the ADHD questionnaires was 54 and the minimum score was 0. If the ADHD score was more than 25.8 on the childhood ADHD measure or ADHD score was more than 32.5 on the adult ADHD measure, it was considered an indicator of ADHD (Magnússon et al., 2006), however the cut-offs were not applied in the current study. The ADHD scores were used as a continuous scale and two scores were calculated separately for current and childhood symptoms of ADHD.

Procedure

Participants were welcomed and asked to sit down in a light- and sound-attenuated room. They were asked to read or listen to information about the study and sign an informed consent form. They were seated approximately 57 cm from a computer monitor. While researchers were placing the EEG cap on the head, participants answered demographic background questions on a Lenovo Desktop computer with a 27-inch monitor (resolution 2560 x 1440), using PsychoPy (Peirce et al., 2019). They also completed a visual acuity test (Landolt Cs), two ADHD questionnaires, and another set of questions as a part of the larger dyslexia study (Devillez & Sigurdardottir, 2022). The first ADHD form assessed their behaviour in the last six months, while the second ADHD questionnaire was about their childhood behaviour. The visual acuity test showed a black ring with a gap and participants had to decide on which side of the ring is the gap by pressing the up/down/right/left arrow keys on the keyboard. The stimulus decreased in size if the response was correct three times in a row and it increased if participants answered incorrectly. After that, the participants could start the experiment. First the ERP study and consequently the SSVEP experiment were completed. The SSVEP study with faces consisted of 30 trials each lasting 60s with 15 trials where participants had to attend to a face (attend-face condition) and 15 trials where they had to attend to the fixation point (attend-fix condition). The SSVEP study with objects had 32 trials, each lasting 60s with 16 trials consisting of objects from basic level of categorization and another 16 trials consisting of objects from subordinate-level. After each trial, the memory test was presented to participants in which they were asked to pick either faces/colours or objects that they have seen during the trial. The behavioural data was collected from the answers to the memory tests (accuracy and response time).

Behavioural analysis

The accuracy (percent correct) and response time (RT) (time between the onset of the memory test and the answer) were measured for the memory task. Before calculating final response times, a mean and standard deviation of RTs were calculated for each participant, and trials with RTs ± 3 standard deviations from each participant's mean RT were thrown out.

EEG recording

EEG was recorded from a 32-channel Easycap with 10-20 configurations through the amplifier to the BrainVision signal at a 1000-Hz sampling rate. The ground electrode was placed between FP1 and FP2, while Fz was used as a reference. Electrode impedances were kept at 15 **kΩ.** The data were preprocessed before the extraction of oddball power. Data pre-processing was performed with custom scripts in MATLAB (R2020a; The MathWorks, Inc., Natick, MA), using functions included in EEGLAB v2019.1 (Delorme & Makeig, 2004) and Fieldtrip (fieldtrip-20171026).

Preprocessing

A high-pass filter at 0.1 Hz, a low-pass filter at 100 Hz, and a notch filter from 45 to 55 Hz were applied to the analysis. Data were epoched on trials from -2s to 62s time-locked to trial onset. Particularly noisy epochs were rejected or interpolated after visual inspection. Data were re-referenced to the average signal. Data were epoched on trials from 0s to 57.9s time-locked to trial onset, corresponding exactly to 193 complete cycles within stimulation, where one cycle is the display of 6 images (Devillez & Sigurdardottir, 2022). Each condition (attend to face/attend to fix and objects) was averaged in the time domain, for each individual participant separately. A Fast Fourier Transform (FFT) was applied to these averaged segments. Amplitude spectra were extracted, where the square root of the sum of squares of the real and imaginary parts was divided by the number of data points. The power of the oddball frequency 1.2 Hz (F/5= 1.2 Hz) and its three first harmonics were found, and it was defined as SNR. SNR was calculated as the ratio of amplitude at each frequency to the average of 20 surrounding frequency bins (the size of the bin was 0.0175 Hz) (Lochy et al., 2015; Rossion et al., 2012). Electrodes montages over the left occipito-temporal (TP9, CP5, P7), right occipito-temporal (TP10, CP6, P8), frontal regions (FC1, FC2) and occipito-medial (O1, Oz, O2) were averaged (Tanaka et al., 2006).

Experiment 1: Faces

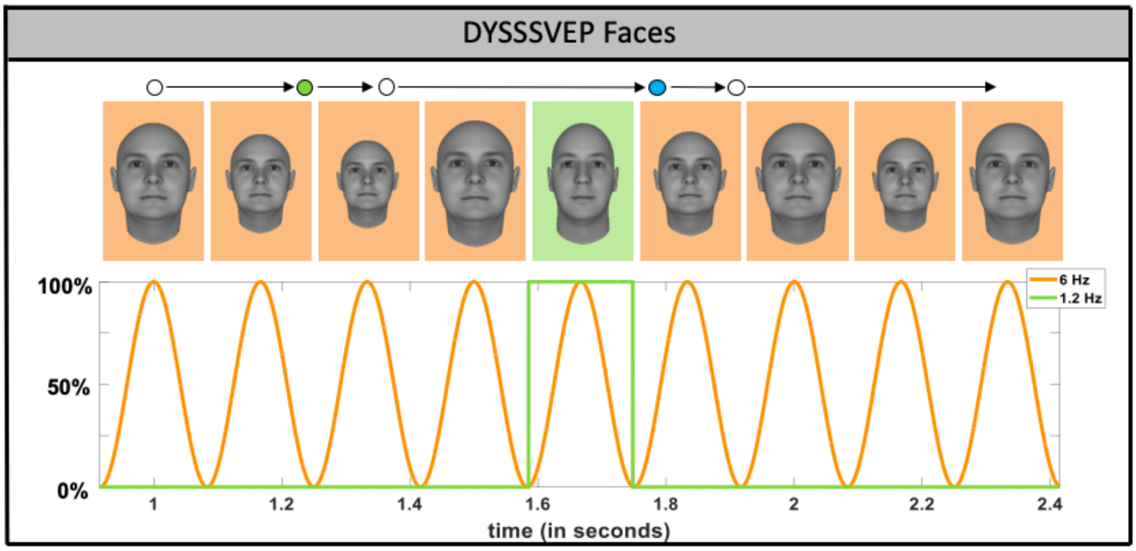
Methods

Procedure

There were two conditions, attend-fix and attend-face. They both included a colour-changing fixation point and an identity-changing face but differed in whether participants were asked to pay attention to (attend-face) or away (attend-fix) from the face. On attend-fix trials, people had to attend to the fixation point in the middle of the screen that changed from white to two different colours. On attend-face trials, they were asked to monitor changes in face identity (Figure 1).

Figure 1

Examples of faces and fixation stimuli



Note. By H. Devillez, 2021, https://doi.org/10.17605/OSF.IO/4DR3F.

Each trial was followed by two 3-alternative forced-choice memory tests where participants were asked to choose the two faces (attend-face) or the two colours (attend-fix) they saw during the trial.

A fixation point (about 0.88° width and height) was visible across a trial. The fixation point randomly changed twice per trial for 400 ms each time to one of two colours. The two colours were picked from basic colour categories (e.g., blue, green, red, pink). In the background, contrast of face images was ramped up and down in a sinusoidal cycle. A cycle began with a grey background from which a face image appeared as its contrast increased. Full contrast was reached after 83 ms and gradually decreased again until the face fully disappeared around 166 ms after the start of the cycle, at which a new cycle began. Face size varied randomly from cycle to cycle between 74%-120% to avoid confounding changes in face identity with changes in local pixel intensity.

Faces were displayed at a rate of 6 cycles per second (6 Hz; base frequency). Two face images were shown on each trial, one base face and one oddball face. The base face image was repeated throughout the trial except that it was replaced by the oddball face on every 5^{th}cycle. Therefore, a face identity change happened at a frequency of 6/5Hz (1.2 Hz; oddball frequency). We monitored EEG power at the base frequency, the oddball frequency, and the first three harmonics of the oddball frequency (2*6/5=2.4 Hz, 3*6/5=3.6, and 4*6/5=4.8 Hz). The oddball frequency was used as an indicator of the visual system's discrimination of individual faces.

Data analysis

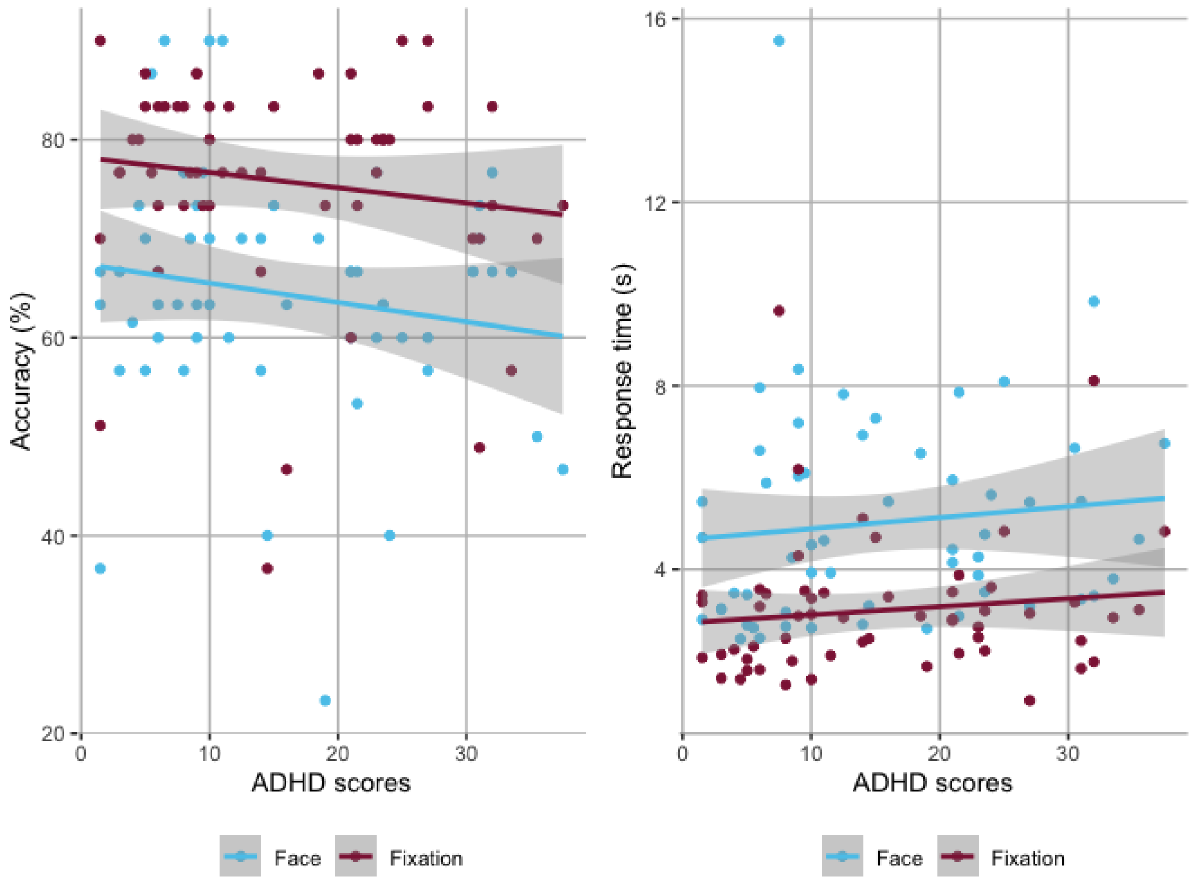
MATLAB (MathWorks), R and Microsoft Excel were used for data analysis. Custom MATLAB and R scripts were used to compute demographics, ADHD scores and behavioural data as well as arrange all frequency and subject data in separate Microsoft Excel files for each region of interest. The selected regions were: Right parietal superior or RPS (CP6, P8, TP10), left parietal superior or LPS (P7, CP5, TP9), occipital medium or OM (O1, Oz, O2) and frontal medium or FM (FC1, FC2). Using scores from ADHD-I and ADHD-II, a single ADHD z-score was calculated for each participant, as well as single attention (AD) and hyperactivity (HD) subscores for each participant. Signal-to-noise ratio (SNR) at the oddball frequency was calculated for attend-fix and attend-face conditions separately for each participant and region of interest. SNR was calculated by finding the ratio between the amplitude at each frequency and the average of the 20 surrounding frequency bins (10 on each side, except the immediately adjacent bin) (bin size is 0.0175 Hz) (Rossion et al., 2012, Lochy et al., 2015). To estimate the difference of SNR at the oddball frequency between the conditions, difference scores were calculated. In R, SNR difference scores for the conditions (attend-face SNR minus attend-fix SNR) were then calculated to estimate the effect of attention towards the faces. These were used to calculate a correlation matrix across regions of interest for the SNR difference scores. Subsequently correlation coefficients between ADHD scores and SNR difference scores were calculated, collapsing over all regions of interest, for typical and dyslexic readers separately.

Results

The mean score on the ADHD questionnaires was 18.7 with standard deviation 10.28 in the dyslexic group. In the typical group, the mean was 11.05 with standard deviation 8.01. These results were expected since the comorbidity between ADHD and dyslexia is well-documented. The mean score on ADHD questionnaires combined across two groups was 15.82 with standard deviation 10.13. As shown in Figure 2, the accuracy of responses decreased with higher ADHD scores, while response time increased with higher scores of ADHD in the memory task for faces and colours. The correlation coefficient between accuracy (%) of responses and ADHD scores was negative for the attend-face condition with $r=-0.16$ with 95% CI [- 0.406, 0.107] as well as for the attend-fix (colour) condition with $r=-0.14$ with 95% CI [-0.392, 0.124]. The correlation coefficient between response time (s) and ADHD scores was positive for the attend-face condition with r=0.11 with 95% CI [-0.162, 0.358] as well as for the attend-fix condition with r=0.12 with 95% CI [-0.147, 0.371].

Figure 2

Correlation between accuracy/response time and ADHD scores in the memory task

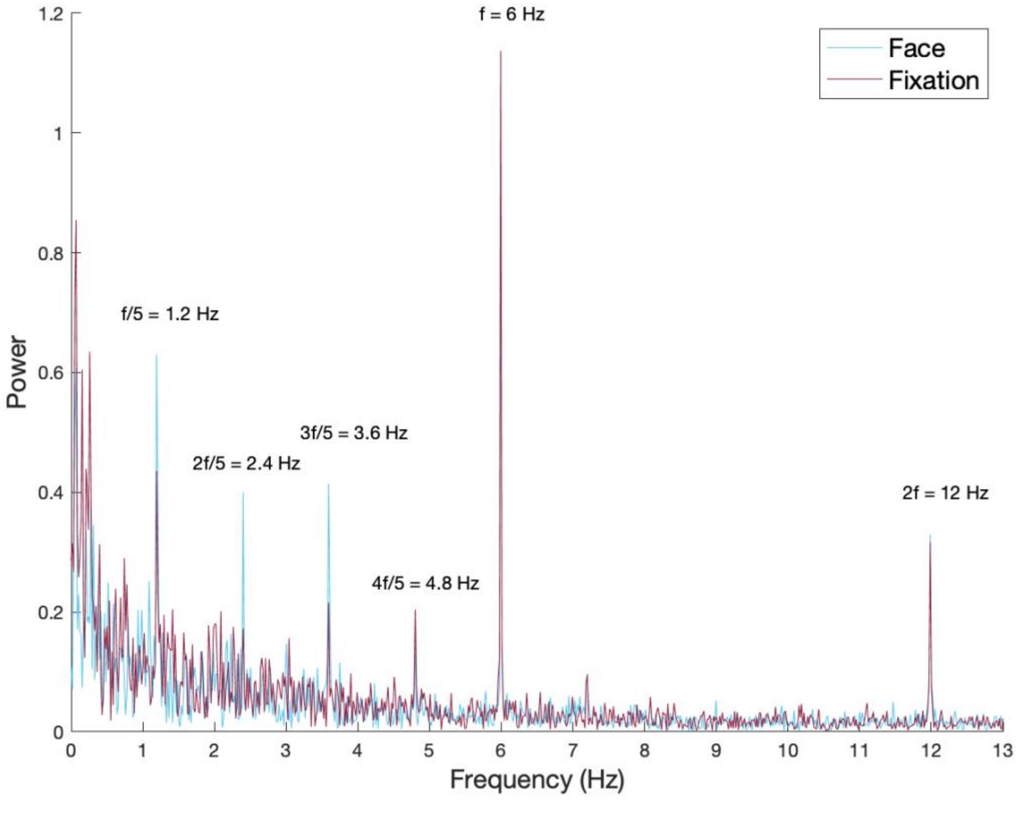


Note. The relationship between accuracy (%) and ADHD scores as well as response time (s) and ADHD scores for faces and colours in the memory task. Participants were asked to identify the oddball and base faces in the face condition and the oddball and base colour in the fixation condition. Each point on the left graph indicates the accuracy and ADHD score of one participant and each point on the right graph indicates the response time and ADHD score of one participant. The blue lines are the trend lines through the datapoints in the face condition and the shaded grey areas indicate the 95% confidence intervals for accuracy and response time. Similarly, the purple lines are the trend lines through the datapoints in the fixation condition.

As can be seen in Figure 3, the response at the oddball frequency as well as its harmonics are larger for faces than for the fixation point, or colour. A t-test looking at the responses from all regions of interest (ROI) showed increased power for the attend-face condition versus the attend-fix condition.

Figure 3

Power spectrum of the right parietal superior region

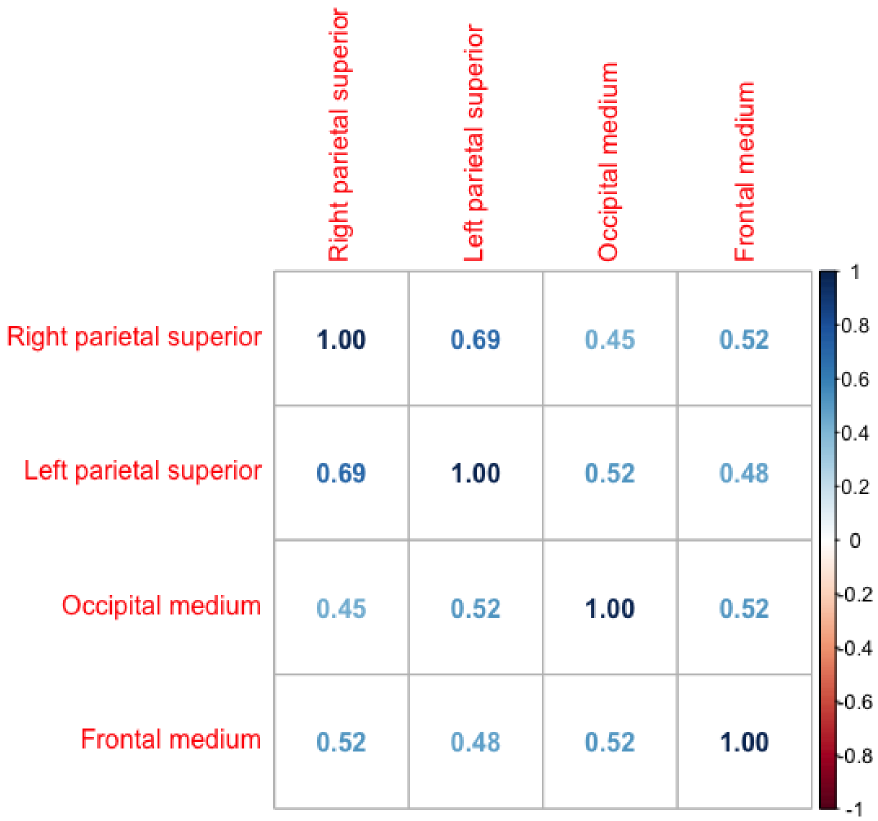


Note. The frequency spectrum of the right parietal superior ROI for one subject. The largest responses can be seen at the oddball frequency (f/5 = 1.2 Hz) and base frequency (f = 6 Hz). Responses at the harmonics of the oddball frequency (2f/5 = 2.4 Hz, 3f/5 = 3.6 Hz, 4f/5 = 4.8 Hz) and base frequency (2f = 12 Hz) can also be seen.

To be able to estimate whether there was a difference between responses at the oddball frequency (f/5 = 1.2 Hz) for the two conditions the difference scores were calculated for each ROI (RPS, LPS, OM and FM). These difference scores were calculated by subtracting the SNR at the oddball frequency for the fix condition from the SNR at the oddball frequency for the face condition for each participant. These difference scores were used to explore the correlations of the difference of the response in the two conditions between all regions of interest. This was done separately for dyslexic and typical readers. As shown in Figure 4, a moderate positive correlation was obtained. Given these results the remaining analysis will include SNR at oddball frequency from all regions of interest. The SNR at the oddball frequency was averaged across all regions for both conditions.

Figure 4

Correlation matrix for the SNR at the oddball frequency across brain regions

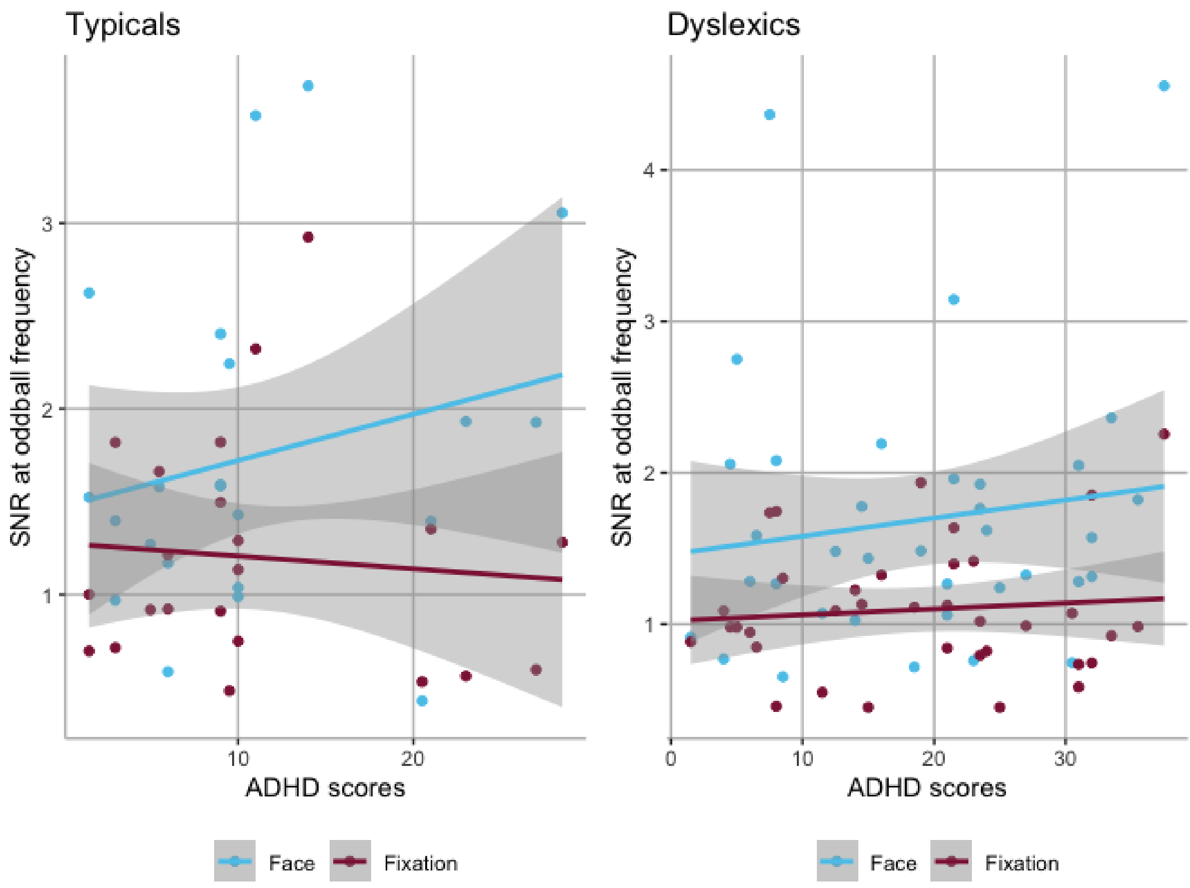


Note. Signal to ratio (SNR) at the oddball frequency (f/5 = 1.2 Hz) correlated between all regions of interest for typical readers (picture above), and for dyslexics (picture at the bottom).

Figure 5 shows the relationship between ADHD scores and the SNR at the oddball frequency for both face and fix conditions, separately for typical and dyslexic readers. Note that for clarity Figure 5 shows the results from the conditions separately but for analysis the difference between the two is used (see discussion about difference scores above). The difference score between the two conditions were used to calculate the correlation between the SNR at the oddball frequency (SNR at attend-face minus attend-fix averaged across all regions) and ADHD scores for the typical and dyslexic group. A positive correlation coefficient for typical readers was found, r=0.338 with 95% CI [-0.097, 0.665]; p-values were not included in the current results, given the study's exploratory nature (Cumming, 2014). A weak positive correlation was found for dyslexics, r=0,107 with 95% CI [-0.229, 0.421]. Both confidence intervals include 0, therefore the results are not significant.

Figure 5

Relationship between the SNR at oddball frequency (f/5 = 1.2 Hz) and ADHD scores for the face/fix conditions



Note. Correlations between the SNR at the oddball frequency and ADHD scores, averaged across all regions of interest for both attend-face and attend-fix conditions, shown for typical readers (left) and dyslexic readers (right). Lines are trendlines through datapoints and the grey areas are 95% confidence intervals.

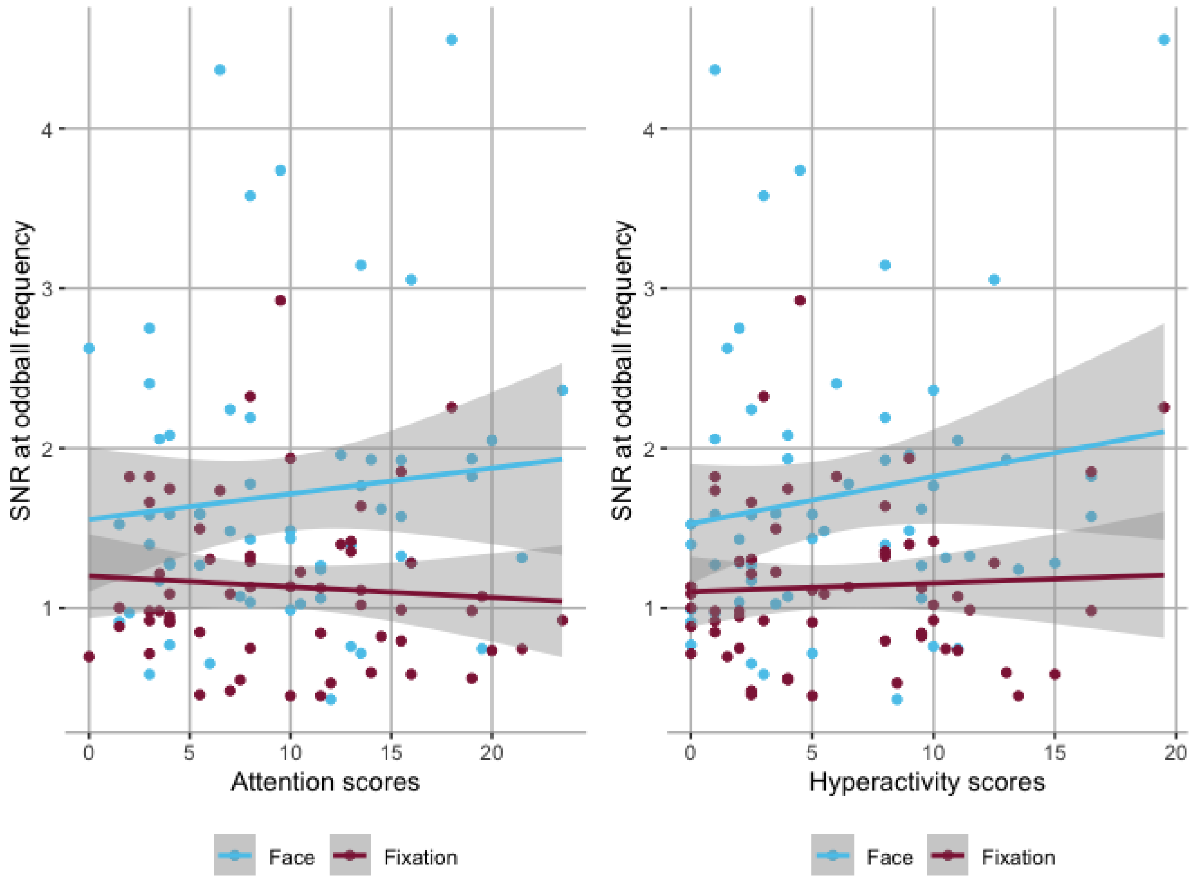
Despite results being insignificant, both groups showed a positive trend, and their confidence intervals overlapped considerably. We decided to collapse the data across typical and dyslexic readers to further investigate a possible correlation between the SNR at the oddball frequency and ADHD subscale scores for inattention and hyperactivity/impulsivity.

The relationship between attention scores and the SNR at the oddball frequency as well as the relationship between hyperactivity scores and the SNR at the oddball frequency can be seen in Figure 6. Note again, that for clarity it shows the results from the conditions separately but for analysis the difference between the two is used. The difference scores between the two conditions were used to calculate the correlation between the SNR at the oddball frequency (SNR at attend-face minus attend-fix averaged across all regions) and attention/hyperactivity scores for both groups (dyslexic and typical readers) combined.

The attention and hyperactivity subscales were z-scored and combined from the adult and childhood questionnaires to get a single score for each participant for each of the subscales. The average score and standard deviations were calculated for both subscales. The mean for attention scores was 9.66 with standard deviation 5.84. The mean for hyperactivity scores was 6.16 with standard deviation 4.87. As figure 6 depicts, a weak positive correlation was found between the attention score and the oddball power, r=0.176 with 95% CI [-0.087, 0.415]. A positive trend was found for the hyperactivity scale as well, r=0.156, 95% CI [-0.107, 0.398].

Figure 6

Correlation between attention/hyperactivity scores and the SNR at the oddball frequency



Note. Correlations between the SNR at the oddball frequency and attention/hyperactivity scores, averaged across all regions of interest for both attend-face and attend-fix conditions. Lines are trendlines through datapoints and the grey areas are 95% confidence intervals.

Discussion

First, we wanted to see whether there was a difference in the SNR at the oddball frequency to attended and unattended faces. A difference in the SNR at the oddball frequency (f/5 = 1.2 Hz) was found between the two conditions, attending to the face and colour. Second, our hypothesis was that the SNR at the oddball frequency would decrease with higher scores of ADHD. The results did not support this hypothesis which prompted further investigation into the matter. We now propose that a positive trend will be found between ADHD scores and the SNR at the oddball frequency for the objects experiment similar to what was found for faces. We expect people with higher ADHD scores will have a lower oddball power, i.e., a lower correlation at the subordinate rather than at the basic level. Furthermore, we postulate that there will be a stronger positive correlation between the subordinate categories and ADHD scores compared to the correlation between the basic categories and the ADHD scores. The reasoning being that attentional abilities are thought to be of more importance for distinguishing between objects within categories (subordinate) than between categories (basic).

Experiment 2: Objects

Methods

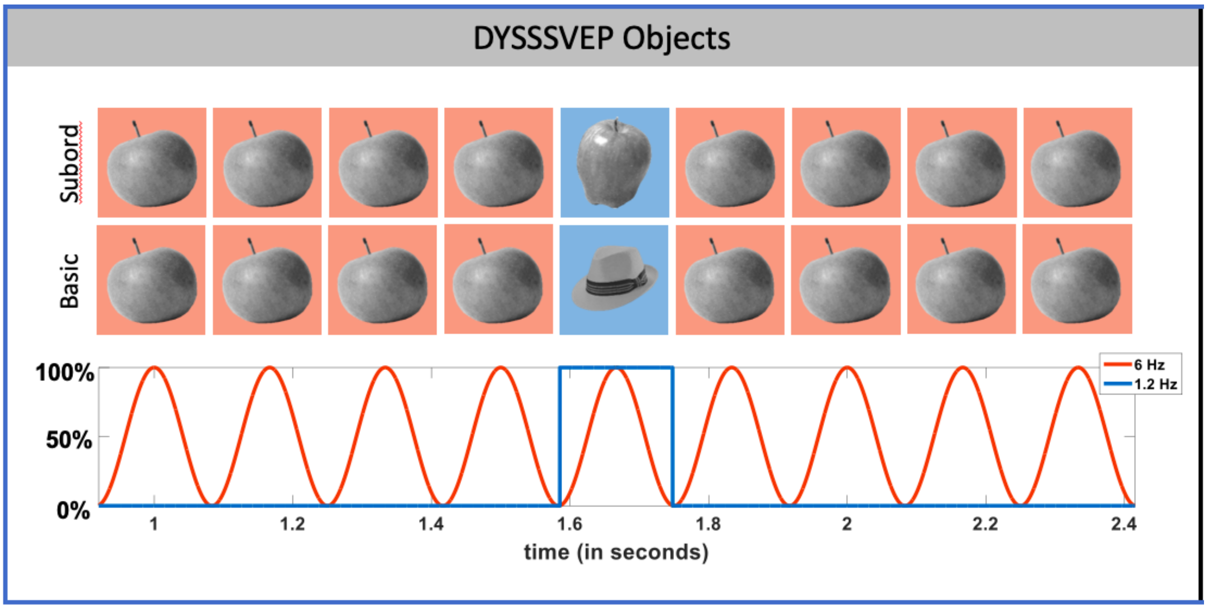
Procedure

There were two conditions: basic-level trials and subordinate-level trials. In the basic-level trials, the standard stimulus and oddball image were of two different categories, for example, a hat and an apple. In the subordinate-level trials, the oddball and standard (base) images were different exemplars of the same category, for example, two different apples (Figure 7). A fixation point ensured minimum eye movements. Each trial was followed by two

6-alternative forced-choice memory tests where participants were asked to choose the two objects that they saw during the trial among distractor objects of the same category.

Figure 7

Example of object stimuli at the basic/subordinate levels



Note. By H. Devillez, 2021, https://doi.org/10.17605/OSF.IO/4DR3F.

Data analysis

The same procedures were applied to the data as was done in Experiment 1 with the exception that when calculating the correlation coefficient and confidence interval for the SNR at the oddball frequency and ADHD scores, SNR was averaged over basic and subordinate conditions instead of the difference scores being calculated. This is because both conditions are expected to give similar results since they both require high-level visual processing as opposed to only the face condition in the Experiment 1.

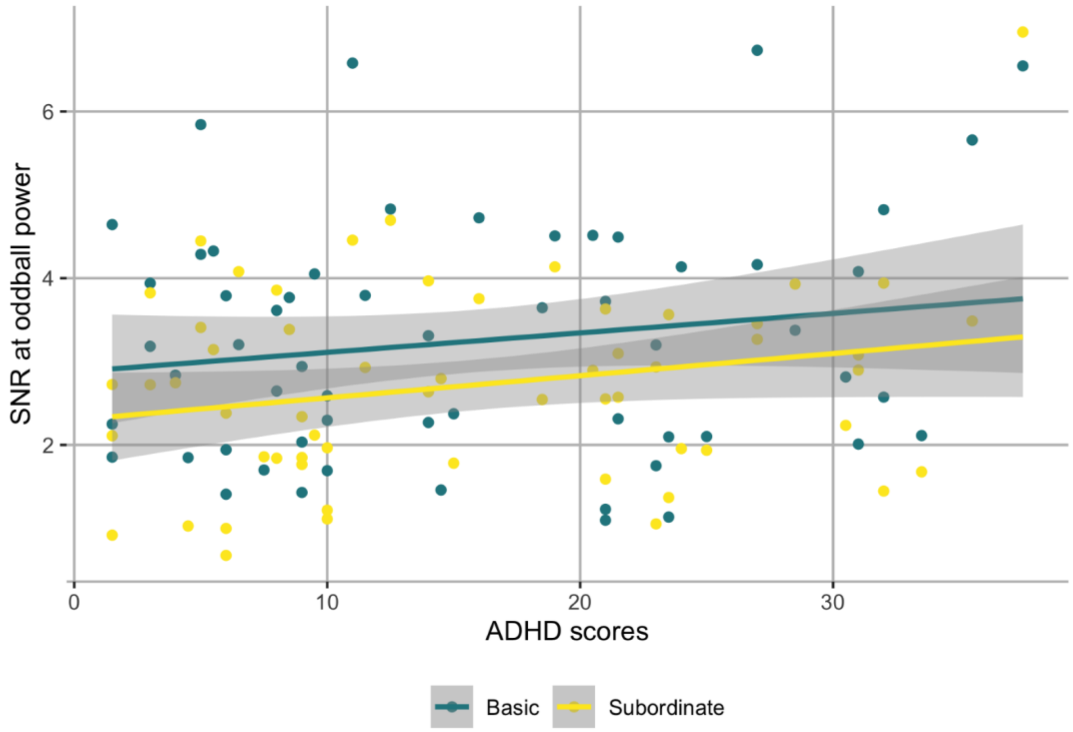
Results

Figure 8 demonstrates the relationship between ADHD scores and the SNR at the oddball frequency in the object experiment (basic and subordinate levels of categories of objects).

The correlation coefficient for the SNR at the oddball frequency and ADHD scores in the subordinate condition was r= 0.230 with 95% CI [-0.030, 0.461] and the correlation coefficient for the basic condition was r= 0.165 with 95% CI [-0.097, 0.406]. Given that these correlations are similarly the SNRs from both conditions will be combined for further analysis. The SNR at the oddball frequency (f/5 = 1.2 Hz) from both conditions was averaged for each participant. The correlation coefficient for the averaged SNR at the oddball frequency and ADHD scores was r= 0.211 with 95% CI [- 0.050, 0.445].

Figure 8

Correlation between oddball power and ADHD scores in the object experiment



Note. Correlations between the SNR at the oddball frequency and attention/hyperactivity scores, averaged across all regions of interest for both attend-face and attend-fix conditions. Lines are trendlines through datapoints and the grey areas are 95% confidence intervals.

Discussion

Now, the main hypothesis of the second experiment was confirmed and a positive correlation between the SNR at the oddball frequency and ADHD scores was found. However, another suggestion was not confirmed, where it was expected to find higher SNR at the oddball frequency for the subordinate condition than the basic condition.

General Discussion

It is a complex task to understand how the brain makes sense of complex environment and the objects within it. Visual attention has been found to play an important role in object processing. Selective attention modulates neural responses in the visual ventral stream and neurons that are selective for a certain stimulus seem to respond more when that stimulus being attended to compared to not attended to (Chelazzi et al., 1993, 1998, 2001). The processing of simple features, such as contrast and colours is happening in the early stages of ventral stream, while increasingly complex objects, such as faces are processed in higher cortical areas. The following study has attempted to explore the attention modulation of different objects, such as faces in individuals with different self-reported attentional abilities. Neural adaptation can be used to probe the sensitivity of neurons to faces and it likely underlies the SSVEP oddball response, which is why the paradigm was chosen in the current study.

The aim of the study was to explore how attention modulates the visual object processing by measuring the SSVEP neural response and behaviour of participants varying in attentional abilities. We wanted to see if there is a difference in the oddball power when attending or not attending to faces while face changes are happening on the monitor. Then the correlation between the ADHD scores and oddball power was calculated. In addition, we wanted to see if participants with lower ADHD scores would recognize fewer faces and would be slower in the memory test.

First, it was postulated that in the face condition neurons that carry information about face identity would respond more to face changes via attentional selection than in the fixation to the point condition when faces were unattended. Second, it was proposed that people with higher scores on the ADHD continuum would have a lower oddball power and therefore be less sensitive to face identity changes while attending to the face. Finally, it was proposed that people with more attention difficulties would be less accurate and slower in answering the questions from memory test after the trial.

Behavioural data confirmed our proposal that people with higher ADHD would be slower and would make more mistakes in the memory test. Another hypothesis was supported and it was found that oddball power was higher for the attended to the face condition compared to the attended to the fixation point condition for both dyslexic and typical readers. However, the main hypothesis did not stand, and a positive non-significant trend was found between ADHD scores and oddball power. We decided to explore the subscales of the ADHD questionnaire (inattention vs hyperactivity/impulsivity). We wanted to see if inattention subscale is more related to changes in oddball power rather than hyperactivity/impulsivity subscale. We expected that neurons will not respond much differently to faces unless faces are processed via attentional selection. An almost identical correlation was discovered between both subscales and the oddball power. Therefore, either the questionnaire is not measuring the symptoms well or both inattention and hyperactivity/impulsivity subscales are similarly related to oddball power. However, further analysis is needed to be clear on this issue.

The results of experiment 1 were surprising. Therefore, a new hypothesis was conducted to further explore the matter in experiment 2. We wanted to see if there would be a similar positive trend between the oddball power and ADHD scores in the experiment with “odd” objects. The same positive but non-significant correlation was found for the second experiment, where participants were looking at “surprising” objects in different categories (basic vs subordinate). The higher scores on the ADHD questionnaire, the higher the oddball power was found for both subordinate and basic categories. These results mean that people with higher scores on the ADHD questionnaire did not demonstrate the decreased sensitivity to changes in objects, as well as to face identity changes in our study.

It is possible that we got different results from what we expected because of few reasons. During a stop-signal task (Khaleghi et al., 2019), participants with ADHD had lower SSVEP amplitude than controls in temporal and occipital regions, but their amplitude was higher than that for controls in prefrontal and frontal areas. However, in the current study we decided to collapse the oddball power across the brain regions, since there was a moderate positive correlation between them. It is possible that we got a positive correlation between higher ADHD scores and oddball power because of that. However, it is always difficult to know where the signal comes from since the EEG signal is diffused. Furthermore, Silberstein et al. (2001) suggested that holding information in active working memory is associated with an increase in SSVEP amplitude, but perceptual processes are related to a reduction in SSVEP amplitude. Although the above-mentioned studies use different types of tasks and are not looking at SNR at the oddball frequency, our experiment where participants had to attend to the face identity change included an active working memory. Therefore, as Silberstein et al. (2001) stated the active working memory is related to an increase in SSVEP amplitude and possibly people in our experiment who had higher scores on the ADHD questionnaire had to use their working memory more, consequently they had a higher oddball power/SSVEP amplitude.

Another possible reason could be that people with ADHD have impaired top-down and bottom-up processing and they are less able to predict future activity in the brain and therefore are less able to minimize “surprise” coming from an oddball stimulus (Luczak et al., 2022). Therefore, the higher oddball power that comes with higher scores on ADHD questionnaire can be related to an inability to minimise the surprise from the new stimulus, the neurons do not get used to the repeating stimulus during the trial.

There were several limitations to the study. First and most importantly, the experiment was not conducted to investigate attention modulation as a main goal. It was created to research dyslexia and a new hypothesis related to it. Therefore, it was hard to compare this study to any previous literature, and it is more common to research attention modulation through other tasks, such as visual search tasks (Treviño et al., 2021). The current experiment involved a memory component, which was not controlled for, and it would be better to separate the effects of attention from memory in future research.

Another limitation of this study was the duration. The experiment took three hours to complete. It is hard enough to sustain attention for only twenty minutes, especially for individuals with higher scores on the ADHD questionnaire, therefore such a lengthy study is not ideal for measuring attention modulation to objects. For further research, it would be better to use a shorter experiment to keep participants interested in the task and not distracted. In addition, the ADHD questionnaire that was used in the current study has been found valid and reliable for at least at-risk populations. Both dyslexic readers and typical readers took part in the current experiment and although there is a comorbidity between dyslexia and ADHD, the questionnaire might be better suited for a clinical sample. Finally, data collection is still ongoing for a larger study that a current study is a part of. Therefore, we had fewer typical readers than dyslexic readers, which might have affected the results. Despite this, the purpose of the research was not to investigate attention-deficit/hyperactivity disorder but to look closer into attention modulation by examining people with different scores on the ADHD questionnaire, therefore possibly with different attentional abilities.

The main advantage of the current study was that it explored attention modulation with thought-provoking approaches such as SSVEP and the oddball paradigm. It is an exploratory analysis that has attempted to open new ideas for further investigations of attention modulation of objects. In addition, a current study had a high control over the basic visual properties to which even the earliest stages of visual processing are sensitive by creating a scrambled background.

There are several additional proposals and implications of the study. First, it is intriguing to compare how the power at the oddball frequency changes from the beginning to the end of the experiment. It is possible that oddball power will be different closer to the end of the experiment after the considerate learning and adaptation of the brain. Second, previous studies found a strong relationship between the prefrontal cortex and attention. In a current study it was decided to collapse across brain regions to explore oddball power, however, in a future exploratory analysis, researchers may want to focus more closely on the frontal lobe. However, it will always be difficult to pinpoint the location of the signal when measuring with EEG scans, since the signal is diffused. It would also be interesting to investigate the relationship between different harmonics and attention modulation of objects in further research. Furthermore, it is a promising idea to use brain-imaging techniques, such as EEG-scans, for therapeutic intervention and cognitive enhancement (Enriquez-Geppert et al., 2017). For example, EEG-biofeedback has been already used to regulate symptoms of ADHD (Monastra et al., 2002) and it would be interesting to use brain-imaging for the investigation biomarkers of ADHD.

In conclusion, this thesis explored the attention modulation of objects by measuring the SSVEP oddball power. Researchers aim to understand how the brain processes complex environment rich in multiple objects, and looking at the neural correlates of visual attention could be a big leap forward.

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