Neuropsychologia 102 (2017) 11–18

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

A fast and implicit measure of semantic categorisation using steady state visual evoked potentials

George Stothart[a,*], Susanne Quadflieg[b], Alexander Milton[c]

[a] Department of Psychology, University of Bath, Claverton Down, Bath BA2 7AY, UK
[b] School of Experimental Psychology, University of Bristol, Bristol, UK
[c] Psychology, University of Southampton, UK

ARTICLE INFO

Keywords:
Semantic categorisation
Oddball
Steady-state
EEG
Implicit
Visual evoked potentials
Fast periodic visual stimulation
Fastball toolbox

ABSTRACT

There is a great need for objective measures of perception and cognition that are reliable at the level of the individual subject. Although traditional electroencephalography (EEG) techniques can act as valid bio-markers of cognition, they typically involve long recording times and the computation of group averages. To overcome these well-known limitations of EEG, vision scientists have recently introduced a steady state method known as fast periodic visual stimulation (FPVS). This method allows them to study visual discrimination at the individual level. Inspired by their work, we examined whether FPVS could be used equally effectively to capture abstract conceptual processes. Twenty subjects (20.9 (± 2.1) yrs, 6 male) were asked to complete a FPVS-oddball paradigm that assessed their spontaneous ability to differentiate between rapidly presented images on the basis of semantic, rather than perceptual, properties. At the group level, this approach returned a reliable oddball detection response after only 50 s of stimulus presentation time. Moreover, a stable oddball response was found for each participating individual within 100 s. As such, the FPVS-oddball paradigm returned an objective, non-verbal marker of semantic categorisation in single subjects in under two minutes. This finding establishes the FPVS-oddball paradigm as a powerful new tool in cognitive neuroscience.

1. Introduction

Physicians and psychologists have a long history of measuring people's ability to notice variation. Their interest in doing so frequently arises from the fact that deficits in this ability can signal severe neural impairments. To diagnose colour blindness, for example, physicians typically ask patients to distinguish red from green figures (e.g., using the Ishihara Plate Test, Birch, 1997). Similarly, to detect face blindness, psychologists often require their clients to recognize faces of different individuals (e.g., via the Cambridge Face Memory Test, Bowles et al., 2009). In both cases (as in many other behavioural tests), however, assessing people's ability to distinguish between certain entities requires that they provide active and truthful replies. Yet, some individuals may simply not be able (e.g., children, stroke patients) or willing (e.g., eye witness) to give such replies. Hence, physicians and psychologists are frequently interested in developing tests that can be reliably administered without requiring test-takers' overt replies.

These alternative measures include standard brain imaging techniques, such as electroencephalography (EEG; Chennu et al., 2013) and functional magnetic resonance imaging (fMRI; cf Monti et al., 2010). One popular EEG marker of people's ability to detect variation is known as Mismatch Negativity (MMN). This marker is typically derived by subtracting a person's neural response to a frequently presented standard stimulus from that of a rare oddball stimulus in a so-called oddball paradigm, and can be elicited both with and without the subject's explicit attention (Czigler, 2014; Kimura, 2012; Näätänen et al., 1978; Näätänen and Michie, 1979). In recent years, there has been growing interest in using the MMN as an early marker of attentional deficits in the pre-symptomatic stages of clinical disorders, such as schizophrenia (see Näätänen et al., 2011 for a review). Meta-analyses have repeatedly demonstrated clear MMN deficits in schizophrenia (Bodatsch et al., 2015; Erickson et al., 2016; Umbricht and Krljes, 2005) however despite decades of converging findings, viable clinical tools for assessing these deficits in a reliable manner are still lacking. The great challenge in the translation of experimental EEG findings into viable clinical tools lies in finding measures that are reliable not only at the group level, but at the level of the individual.

This is not just a challenge with MMN, but with EEG measures more broadly (Duncan et al., 2009). To obtain sufficient Signal to Noise Ratio (SNR) using traditional Event Related Potential (ERP) techniques, for

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* Corresponding author.
E-mail address: G.Stothart@bath.ac.uk (G. Stothart).

http://dx.doi.org/10.1016/j.neuropsychologia.2017.05.025
Received 9 December 2016; Received in revised form 12 May 2017; Accepted 24 May 2017

example, subjects must typically complete hundreds or thousands of experimental trials, resulting in long recording times. This problem is compounded in oddball paradigms in which a minimum number of standard stimuli are required between oddball stimuli in order to ensure their "rareness". An alternative to ERPs is the Steady State Visual Evoked Potential (SSVEP), in which periodic visual stimulation elicits a periodic neural response at an equivalent frequency (see Norcia et al., 2015 for a review). Recently a new technique combining oddball paradigms with SSVEPs has shown considerable potential for solving the issues of SNR that have hampered traditional ERP approaches.

First demonstrated by Heinrich et al. (2009a) and developed extensively by Rossion et al. (e.g. Alp et al., 2016; Liu-Shuang et al., 2016; Rossion et al., 2015) the Fast Periodic Visual Stimulation (FPVS) technique involves frequency tagging standard and oddball stimuli. Standard stimuli are presented at a fast rate typically about 6 Hz with oddball stimuli embedded in the train of standard stimuli at fixed intervals, resulting in a slower equivalent presentation rate for oddball stimuli, typically around 1 Hz (e.g., S S S S S **O** S S S S S **O** S S S S S **O** S S S S S **O)**. The advantage of this approach in signal processing terms is that the noise in EEG signals is distributed across all frequencies. Traditional ERP techniques will inevitably include both the signal and the noise from all frequencies. The FPVS-oddball paradigm examines only the exact frequency of the visual stimulation, that is, 6 and 1 Hz. Noise in neighbouring frequencies does not affect the signal of interest, consequently providing very high SNRs.

To date the approach has been used most commonly in studies of face processing and recognition (Dzhelyova and Rossion, 2014; Liu-Shuang et al., 2014, 2016; Rossion, 2014; Rossion et al., 2015). But it has also proven successful in probing low-level visual processing (e.g., orientation encoding; Heinrich et al., 2009a) and basic lexical representations (e.g., word/non-word discrimination; Lochy et al., 2015). To further advance our understanding of the method's potential, our objective was to extend this approach to other domains of mental processing, specifically to an example of higher level cognition, such as abstract semantic categorisation. Semantic categorisation refers to people's ability to group information in a manner that highlights conceptual commonalities or differences between different entities (Rosch, 1975). As it can occur at different levels of specificity, the same entities can be classified in many different ways (Mervis and Rosch, 1981).

Common objects such as furniture, for instance, can be categorised into so-called subordinate categories (e.g., as chairs, tables, beds etc., Mack et al., 2008) which, in turn, can prompt even more fine-grained subordinate classifications (e.g., chairs may be considered dining chairs or office chairs; Tversky and Hemenway, 1984). At the same time, however, furniture can also be categorised according to so-called superordinate categories (e.g., just like vehicles, but unlike tools, as non-graspable objects; Rice et al., 2007) which, in turn, can prompt even coarser superordinate classifications (e.g., furniture, vehicles and tools together can count as man-made rather than natural entities; (Caramazza and Shelton, 1998; Rogers and Patterson, 2007). In short, based on a perceiver's domain-specific knowledge (Tanaka and Taylor, 1991) and/or momentary processing goal (Barsalou, 1991), multi-level conceptual hierarchies can provide numerous levels of specificity according to which objects can be categorised.

To gain an even better hold on the mechanisms of semantic categorisation in the human brain, it seems warranted to develop tasks that can objectively quantify an individual's ability to categorise objects upon perception along various levels of semantic specificity. Such a task would not only be of particular experimental value, but could ultimately also inform the assessment of neural disorders characterized by difficulties with semantic categorisation, such as fronto-temporal dementia. We believe that the newly developed FPVS-oddball paradigm lends itself well for such a purpose. The paradigm has already been used to assess the integrity of face processing in prosopagnosia (Liu-Shuang et al., 2016). Inspired by this prospect, the aim of this study was to extend the FPVS-oddball paradigm to semantic processing. We predicted that increases in power at the oddball stimulation frequencies would be observed when standard and oddball stimuli differed in their semantic categories. We also predicted that when stimuli were scrambled, therefore removing any semantic category level information, oddball responses would not be observed.

2. Method

2.1. Participants

Twenty adults (aged 18–28, mean age 20.9 (± 2.1), 6 males) gave consent to participate in the study. They were recruited from the University of Bristol student population and declared themselves to be in normal health and had normal or corrected-to-normal vision. Ethical approval for our procedures were obtained from the University of Bristol Science Faculty ethics board. Participants provided written informed consent before participating and were free to withdraw from the study at any time.

2.2. Stimuli

Images were selected from a previously validated set of 360 high quality colour images belonging to 23 semantic categories (Moreno-Martínez and Montoro, 2012). Images were selected to form three separate sets expected to prompt semantic categorisation at different levels of specificity. Based on prior work on semantic categorisation (e.g. Chan et al., 2011; Moss and Tyler, 2000), one image set (set A) probed the coarse categorisation of everyday items as natural versus non-natural objects. This set comprised 60 images of natural objects (e.g, birds, mammals, and trees, mean pixel intensity 0.91 (0.06), mean contrast 0.22 (0.08)) and 15 images of non-natural objects (e.g. buildings, clothing, and furniture, mean pixel intensity 0.88 (0.06), mean contrast 0.25 (0.06)). A second set of images (set B) included only natural items and probed the more fine-grained classification of these items as animals versus non-animals (c.f Blundo et al., 2006; Hart and Gordon, 1992). Hence, it comprised 60 images of animals (e.g. mammals, birds, and marine animals, mean pixel intensity 0.91 (0.05), mean contrast 0.22 (0.06)) and 15 images of non-animals (e.g. fruit, vegetables, and nuts, mean pixel intensity 0.92 (0.05), mean contrast 0.19 (0.08)). The third set (set C), finally, contrasted different types of animals (c.f. Naselaris et al., 2012). Specifically, it contained images of 60 birds (e.g., blackbirds, budgies, and owls, mean pixel intensity 0.94 (0.06), mean contrast 0.18 (0.04)) with images of 15 non-birds (i.e., small mammals such as mice, rabbits, and squirrels mean pixel intensity 0.93 (0.02), mean contrast 0.19 (0.04)). As there were not enough bird images in the original Moreno-Martínez and Montoro image set, an additional 30 images were sourced using a Google image search and adapted to match the Moreno-Martínez and Montoro images in relevant physical characteristics. All images were 250 × 250 pixels, 72dpi, subtending 9° visual angle, with the central image cropped to a white background. In order to reduce systematic low-level colour confounds between the standard and oddball categories all images were converted to greyscale. In addition, control images were created by box scrambling the original images using the Matlab Randblock function (https://uk.mathworks.com/matlabcentral/fileexchange/17981-randblock). Box scrambling has been shown to remove semantic category information content, whilst preserving low-level visual content (e.g. Grill-Spector et al., 1998). An example of the images is provided in Fig. 1 and the full image set is available in Supplementary information A.

2.3. Procedure

Participants were seated 55 cm from the monitor and instructed to maintain their gaze within a blue fixation square in which images were presented. They were instructed to press a hand held button every time the blue fixation square turned green. Images were presented onscreen