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Visual cortical networks align with behavioral measures of context-sensitivity in early childhood

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ABSTRACT

This study investigates how visual cortical networks align with context-sensitivity, namely the relative focus on the object versus the background of a visual scene, in early childhood. Context-sensitivity was assessed by a picture description and a recognition memory task. To segregate object and background processing in the visual cortex in 5- and 7-year-old children, object and background were presented at different frequencies (12 Hz or 15 Hz), evoking disparate neuronal responses (steady state visually evoked potentials, SSVEPs) in the electroencephalogram. In younger compared to older children the background elicited higher SSVEPs. Visual cortical processing of object versus background was associated with behavioral measures for older but not for younger children. This relation was strongest for verbal descriptions and generalized to the cortical processing of abstract stimuli and object and background presented alone. Thus, visual cortical networks restructure and align with behavioral measures of context-sensitivity in early childhood.

1. Introduction

Human basic visual cognition differs markedly between individuals, most compellingly demonstrated for the perception of the focal object and the background of a visual scene in cross-cultural studies (e.g., Chua et al., 2005; Nisbett and Masuda, 2003; Nisbett and Miyamoto, 2005). In their pioneer study, Masuda and Nisbett (2001) found that US-Americans tended to describe and memorize focal objects of a scene, such as a large fish swimming in an aquarium (analytic cognition), while Japanese participants described and memorized more details from the background, such as plants and smaller animals (holistic cognition). Investigating visual attention, Chua et al. (2005) recorded the gaze behavior of Chinese and US-American students and found a similar pattern, namely more visual attention directed to the context by Chinese, compared to US-American students.

Ontogenetically, context-sensitivity, as measured in behavioral tasks, undergoes a major developmental change during the late preschool years and the years thereafter (Duffy et al., 2009; Imada et al., 2013), diverging between cultures shortly after the fifth year of life (Imada et al., 2013; see Fig. 2). Based on the idea that context-sensitivity is socialized by the way mothers verbally guide the attention of their children (Fernald and Morikawa, 1993; Senzaki et al., 2016). Köster and Kärtner (2017) looked at the socialization of context-sensitivity in a scene description task. In addition, the authors tested the relation between verbal descriptions and the visual attention (gaze behavior) of mother and child. The authors found that the way mothers verbally described visual scenes to their 5-year-old children was related to their children's own verbal descriptions. Furthermore, verbal descriptions were related to visual attention measures (gaze behavior) in adult participants, but not yet in 5-year-olds. Based on these findings, the authors proposed that context-sensitivity is acquired via a verbal route and that earlier visual attention processes align with behavioral accounts of context-sensitivity only after the fifth year.

In the present study, we aimed to further scrutinize early visual processes associated with developmental changes in behavioral measures of context-sensitivity. Specifically, we tested the assumption that visual cortical processes related to object and background perception restructure after the fifth year and align with children's context-sensitivity, assessed in behavioral tasks. Developmental changes in basic visual processes can most directly be investigated by looking at the neuronal substrates of the object and background processing in visual cortical pathways (Felleman and Van Essen, 1991; Goodale and Milner, 1992).

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Steady state visually evoked potentials (SSVEPs) in the human electroencephalogram (EEG) have proven to be a useful tool to investigate visual cortical processes (e.g., Müller et al., 2003; Martens et al., 2011). An SSVEP is the oscillatory response of the visual cortex to a rapidly repeating (flickering) stimulus, in the specific frequency of the flickering stimulus. In particular, SSVEPs allow to segregate the brain responses for simultaneously presented stimuli (Müller et al., 2003), such as the object and the background of a visual scene (Martens et al., 2011): When presented at different driving frequencies (e.g., 12 Hz and 15 Hz) object and background evoke disparate oscillatory responses in the visual cortex that can be measured as separate frequency signals (SSVEPs) in the EEG.

Here we employed a SSVEP paradigm to compare the visual cortical processing of the object and the background of a visual scene between 5- and 7-year-olds. Furthermore, we tested children context-sensitivity in a picture description and a memory task, to investigate the relation between their visual cortical processes and behavioral measures of context-sensitivity at both ages. In the EEG task, we used conventional, natural scenes as well as abstract, non-semantic scenes (i.e., abstract objects in front of abstract backgrounds). Abstract, non-semantic stimuli may provide a more objective measure for cortical processes, since they avoid interference with subjective experience and semantic content (e.g., as suggested by highly reduced SSVEP responses for the object in consistent versus inconsistent object and background combinations; *tree in the woods phenomenon*, Martens et al., 2013). Second, other than behavioral measures, SSVEPs allow to quantify object and background processing independently and to test whether context-sensitivity is an emergent phenomenon of the combined perception of object and background or whether it can also be found in the cortical processing of both elements when presented on their own. Thus, we also presented the object and the background of natural and abstract pictures in a single condition. Based on the idea that basic cognitive functions, such as context sensitivity, are shaped by cultural learning (e.g., Nisbett and Masuda, 2003) and language (e.g., Majid et al., 2004), we hypothesized that visual cortical processes reorganize and align with context-sensitivity, measured in behavioral tasks, after the fifth year of age. We expected that the results may be clearer for abstract, non-semantic stimuli and we tested whether object and background processing in the visual cortex are similar, when both elements are presented alone.

2. Materials and methods

2.1. Participants

Participants were 29 5-year-old (14 females; age in years: $M = 5; 6$, $SD = 0; 3$, $Range = 5; 0–5; 11$) and 28 7-year-old children (11 females; in years: $M = 7; 4$, $SD = 0; 4$, $Range = 6; 11–7; 11$) from a German city. The study was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki and the EEG procedure was approved by a neurologist. Informed written consent was obtained from the parent and children gave informed consent. Three additional children were excluded from the analysis, because they refused to participate in the behavioral tasks after completing the EEG assessment (two 5-year-olds) or because they were extreme outliers (one 7-year-old child).

2.2. Stimuli and procedure

Children visited the EEG laboratory with their parents for one experimental session. The EEG paradigm was conducted first, before the recognition memory task and the picture description task. Natural pictures were taken by the first author or from pixabay.com and displayed animals or everyday objects in their natural environment (e.g. a rabbit in the grass or a car on the road). Abstract pictures in the EEG paradigm were artificial objects (greebles, fribbles, geons and multipart geons; e.g., Gauthier and Tarr, 1997, http://wiki.cnbc.cmu.edu/Novel_Objects) in front of fractal pictures (cf. Kaspar and König, 2011; created with quadrium 2.0), used as backgrounds. The psychophysics toolbox (Version 3.0.12, on MATLAB Version R2008b) was used for stimulus presentation.

2.2.1. EEG paradigm

Participants saw 40 natural pictures and 40 abstract pictures with a focal object, in front of a background (see Fig. 1A), in three versions each: combined (object and background presented together) and single (object and background presented alone). The single presentation was to test whether the visual cortical processing of object and background would be similar for the presentation of object and background alone. This design resulted in 240 stimuli, presented to each child. We used steady state visually evoked potentials (SSVEPs; e.g., Müller et al., 2003) to separate the neuronal responses for object and background (cf. Martens et al., 2011). In particular, to elicit disparate SSVEPs for object and background, the object was presented at 12 Hz and the background was presented at 15 Hz, or vice versa. This was achieved by controlling the presentation at every single refresh cycle of a 60 Hz of a CRT monitor (one refresh cycle = 16,67 ms). For example, to establish a flicker rate of 12 Hz for the object, the object was presented at a duty cycle of 3:2, i.e. three screen refresh cycles with the object presented and two refresh cycles without the object (black shape of the object). A non-flickering gray circle was included between the object and the background to avoid a shadow of the object in the single presentation of the background. Each picture was presented for 3 s, after a black screen (1 s) and a white fixation dot with the size of the gray circle separating object and background (variable duration of 0.5–1.0 s). The pictures were presented at a visual angle of about 7.4 × 7.4°. Noteworthy, this visual angle is covered by the fovea, such that the whole picture is perceived sharply,

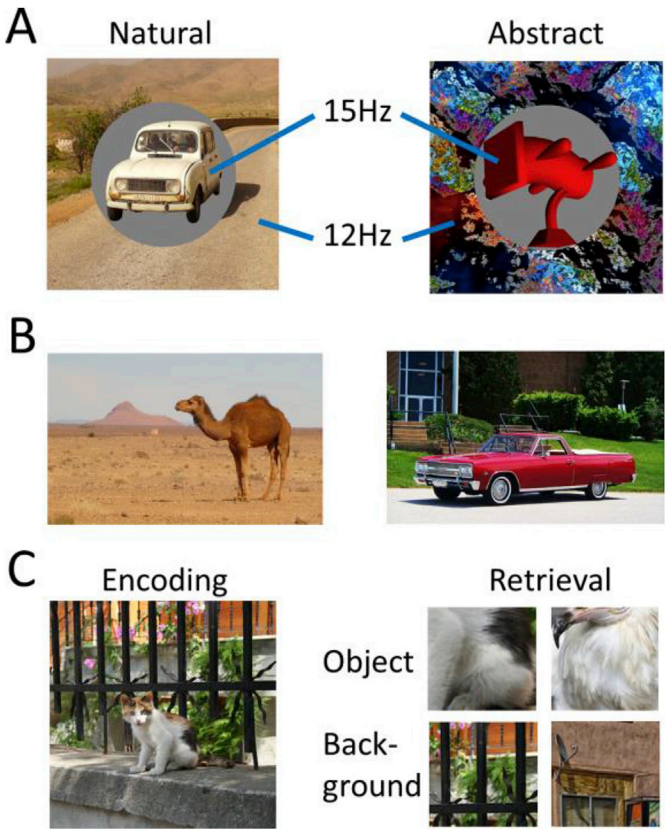

Fig. 1. Example stimuli used in the experimental tasks. (A) Pictures presented in the EEG paradigm. Natural and Abstract scenes were shown for 3 s and the object and the background were presented in different frequencies (12 and 15 Hz, or vice versa), to elicit specific brain responses. Object and background were presented in combination (combined) and on their own (single). (B) Pictures displayed here were used for the picture description task. (C) In the recognition memory task participant saw a series of pictures in the encoding phase. During retrieval, they had to decide, which of two snippets (a target or a distractor) was presented in a picture before (two alternative forced choice).