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Neuro-cognitive mechanisms of global Gestalt perception in visual quantification

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ABSTRACT

Recent neuroimaging studies identified posterior regions in the temporal and parietal lobes as neuro-functional correlates of subitizing and global Gestalt perception. Beyond notable overlap on a neuronal level both mechanisms are remarkably similar on a behavioral level representing both a specific form of visual top-down processing where single elements are integrated into a superordinate entity. In the present study, we investigated whether subitizing draws on principles of global Gestalt perception enabling rapid top-down processes of visual quantification. We designed two functional neuroimaging experiments: a task identifying voxels responding to global Gestalt stimuli in posterior temporo-parietal brain regions and a visual quantification task on dot patterns with magnitudes within and outside the subitizing range. We hypothesized that voxels activated in global Gestalt perception should respond stronger to dot patterns within than those outside the subitizing range. The results confirmed this prediction for left-hemispheric posterior temporo-parietal brain areas. Additionally, we trained a classifier with response patterns from global Gestalt perception to predict neural responses of visual quantification. With this approach we were able to classify from TPJ Gestalt ROIs of both hemispheres whether a trial requiring subitizing was processed. The present study demonstrates that mechanisms of subitizing seem to build on processes of high-level visual perception.

1. Introduction

Gestalt perception describes a holistic form of object processing where local parts are visually integrated into a global entity. Gestalt processing is responsible to gain a holistic percept of the visual world (Wertheimer, 1923) and is involved in visual processes, like scene perception (Dalrymple et al., 2013; Shakespeare et al., 2013) or perception of artificial stimuli, like Navon letters (Navon, 1977). It has been demonstrated that global Gestalt perception precedes processing of local parts (Navon, 1977) and can be particularly impaired in patients suffering from simultanagnosia (Bálint, 1909; Wolpert, 1924). Studies with simultanagnosia patients (Balslev et al., 2014; Friedman-Hill et al., 1995; Himmelbach et al., 2009; Huberle and Karnath, 2006; Luria, 1959) as well as functional neuroimaging work of global processing (Himmelbach et al., 2009; Huberle and Karnath, 2012; Rennig et al., 2015, 2013; Weissman and Woldorff, 2005; Zaretskaya et al., 2013) identified posterior temporo-parietal brain regions as neural correlates of Gestalt perception.

Global Gestalt perception – i.e. the integration of local elements into a superior global structure (Navon, 1977) – is comparable to a cognitive mechanism of visual quantification called 'subitizing'. In this process, a visual magnitude, usually a pattern of dots, can be estimated holistically without serial counting of local elements (Trick and Pylyshyn, 1994) and is considered to be pre-attentive (Kaufman et al., 1949; Trick and Pylyshyn, 1994; Wender and Rothkegel, 2000; but see Railo et al., 2008). However, this top-down mechanism is highly dependent on the presented quantity of elements and usually works up to a number of four elements (Wender and Rothkegel, 2000). Several behavioral studies already linked the mechanism of subitizing to automatic visual pattern recognition (Ashkenazi et al., 2013; Logan and Zbrodoff, 2003; Mandler

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and Shebo, 1982; Wolters et al., 1987) - a process highly similar to visual Gestalt perception. Mandler and Shebo (1982) claimed that the spatial arrangement of up to four elements creates recognizable visual patterns (e.g., two dots form a line; three dots a triangle, four dots a rectangle) that are processed by a specific pattern recognition system, thereby enabling fast and precise quantification.

Processes of visual quantification within and outside the subitizing range have also been distinguished on a neuro-functional level. While quantification outside the subitizing range was found to engage superior parietal (Demeyere et al., 2012; He et al., 2014; Vuokko et al., 2013) and frontal (Vuokko et al., 2013) brain regions, neural correlates of subitizing were associated with posterior temporo-parietal (Demeyere et al., 2014; He et al., 2014; Vetter et al., 2011; Vuokko et al., 2013) and occipito-parietal areas (Demeyere et al., 2012). Interestingly, the neural correlates of subitizing overlap considerably with activation patterns found in neuroimaging studies investigating Gestalt perception (Himmelbach et al., 2009; Huberle and Karnath, 2012; Rennig et al., 2015, 2013). A particular brain region associated with Gestalt perception (Huberle and Karnath, 2012; Rennig et al., 2015, 2013) as well as subitizing (Ansari et al., 2007; He et al., 2014; Vetter et al., 2011; Vuokko et al., 2013) is the temporo-parietal junction (TPJ).

Based on a body of work indicating a strong connection between global Gestalt perception and subitizing we hypothesized that visual mechanisms of global Gestalt perception should support visual quantification. The rationale for this assumption is the idea that subitizing takes advantage of superordinate processes of visual perception (e.g., Trick and Pylyshyn, 1994). To examine this hypothesis we designed two independent fMRI (functional magnetic resonance imaging) experiments: a functional localizer to identify brain regions involved in global Gestalt perception (Huberle and Karnath, 2012; Rennig et al., 2015, 2013) and our main experiment requiring visual quantification of dot patterns. In the Gestalt localizer, we used stimuli that required processes of global Gestalt perception (comparable to visual grouping) where single elements had to be integrated into a superior geometrical form (Navon, 1977). In the visual quantification experiment we presented dot patterns within and outside the subitizing range. In particular, we hypothesized that voxels identified as being activated in global Gestalt perception should contribute stronger to visual quantification for dot patterns within as compared to those outside the subitizing range.

2. Materials and methods

2.1. Participants

24 right-handed volunteers (16 women, mean age = 24 years; SD = 6) participated in the study. Written informed consent was obtained from all participants. The study was approved by the Ethics Committee of the Medical Faculty of the University of Tuebingen. All participants had normal or corrected to normal vision and reported no previous history of neurological or psychiatric disorders.

2.2. Stimuli and procedure

Gestalt Localizer Task. We used Gestalt stimuli from a previous study by Huberle and Karnath (2012). The stimuli were global circles and squares that were constructed from local images of circles or squares. Analog to previous studies (Huberle and Karnath, 2012; Rennig et al., 2015), both congruent (e.g., global circle constructed from local circles) and incongruent (e.g., global circle constructed from local squares) Gestalt stimuli were used. Stimuli were scrambled by randomly exchanging a certain percentage of local elements. As the global Gestalt of the stimuli was easily perceived in the 20% scrambling condition (97% correctly identified) and global Gestalt perception was notably disturbed in the 80% scrambling condition (52% correctly identified, Huberle and Karnath, 2012) we used a set of stimuli with these scrambling levels (see Fig. 1 A). Participants saw 64 stimuli of each condition. Intact and scrambled global Gestalt stimuli were presented for 300 ms followed by a blank screen with a central fixation cross for 2700 ms. During the blank period, participants were required to indicate by button press whether the local elements formed a global circle or a global square. Responses with an MR-compatible button in the left and right hand were balanced for the expected responses. Additionally, 20% blank periods were randomly presented over the experiment. The blank periods ranged from 750 to 1250 ms. During these additional blank periods a central fixation cross was presented. All Gestalt stimuli had a horizontal and vertical extension of 10° visual angle.

Visual Quantification Task. Dot arrangements were adapted from Wender and Rothkegel (2000) with random and canonical dot patterns and numerosity ranging from two to eight. For each numerosity, three canonical and three random patterns were generated. Each of the two runs comprised 168 quantification trials, resulting in 336 critical trials in total. Dot patterns were presented in black against white background with an overall diameter of 2.5°. The diameter of the local dots was identical over all stimuli with a size of about 0.2°. Examples of all dot patterns used in the present study are depicted in Fig. 1B.

Trials started with a central fixation cross. Subsequently, the dot pattern was presented for 200 ms followed by 2000 ms of visual noise preventing afterimages. Participants had to respond by pressing an MRI compatible response button, as soon as they had recognized the numerosity of the presented dot pattern in order to record reaction times (RT). After the noise mask a number pad appeared on the screen for 3000 ms and participants had to navigate to the respective number by button presses to record error rates (ER) for the trial. From a pre-selected number, they navigated to the right with a right hand button press and to the left with a left hand button press until the respective number on the number pad was selected. The described procedure allowed to record RT and ER in the scanner for each trial. Finally, each trial was followed by a jittered inter-trial-interval of 1 s on average (ranging from 750 ms to 1250 ms). Due to the rapid stimulus presentation it was not possible to enumerate dot patterns outside the subitizing range by serial counting and participants had to rely on an approximation strategy in these trials. Therefore, the term ‘estimation’ will be used throughout the course of the present report for these trials.

Stimuli of both experiments were projected onto a screen at the end of the scanner bore. Participants viewed the stimuli through a mirror mounted on the head coil.

2.3. Eye tracking

To ensure that eye movement patterns did not differ between the two stimulus conditions in the Gestalt localizer (20 and 80% scrambled) as well as the subitizing and estimation ranges we recorded eye movements during all fMRI sessions with an MR compatible tracking device (EyeLink 1000 Plus, SR Research Ltd., Ottawa, Ontario, Canada). Prior to each run of functional imaging the eye tracker was calibrated. Preprocessing of eye tracking data included selection of stimulus presentation periods and saccade/fixation detection. Afterwards, the distance of gaze from the fixation cross was calculated for every sample. For the Gestalt localizer, we sorted the distance values per subject for trials with 20 and 80% scrambling. For the visual quantification experiment, we first sorted the data for each subject by dot quantity (subitizing and estimation). Only gaze data recorded during the entire time of stimulus presentation were considered for analyses later on; fixation periods, cue events and response periods were discarded from the analysis. Five subjects had to be excluded from the eye tracking analysis due to poor data quality.

2.4. MRI acquisition

MRI data were acquired using a 3T Siemens Magnetom Prisma MRI system (Siemens AG, Erlangen, Germany) equipped with a 64-channel head coil. A high resolution T1-weighted anatomical scan (TR = 2300 ms, matrix = 256 × 256 mm^2, 176 slices, voxel