Do categorical representations modulate early perceptual or later cognitive visual processing? An ERP study

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ARTICLE INFO

Keywords:
N-back
Categorization
Event-related potentials (ERP)
Reflection and Rotation sets
Visual Mismatch Negativity (vMMN)
P300

ABSTRACT

Encoding of perceptual categorical information has been observed in later cognitive processing like memory encoding and maintenance, starting around 300 ms after stimulus onset (P300). However, it remains open whether categorical information is also encoded in early perceptual processing steps (reflected in the mismatch negativity component; vMMN). The main goal of this study was to assess the influence of categorical information on both early perceptual (i.e., vMMN component) and later cognitive (i.e., P300 component) processing within one paradigm. Hence, we combined an oddball paradigm with a delayed memory task. We used five-dot patterns belonging to different categories even though categorical information is not mirrored in their physical characteristics. Distinct vMMNs were observed for patterns belonging to the same as compared to different categories, suggesting that abstract categorical information was encoded during early perceptual processing. However, inconsistent with prior studies, we observed no effect of categories on the P300, indicating no additional encoding of categorical information in later cognitive stages of processing. Our findings emphasize that the encoding of categorical information depends on specific task demands and hence is more flexible and dynamic than previously suggested.

1. Introduction

Categorization is a central mechanism of perception and hence the foundation for constructing our knowledge about the world (Cohen & Lefebvre, 2017). Categorization can be defined as the mental process of classifying instances, objects, or events into distinct subsets (i.e., categories); Beck, Berti, Czernochowski, & Lachmann, under revision). Most notably, categorization is fast and seemingly effortless (Mandler, 2003), suggesting it relies on early neuro-cognitive processing. However, research in cognitive science often evaluates comparatively late processing steps. The reason for this lies partly in the restriction of measuring response time data, which represents the end result of several cognitive processes, including the encoding, categorization, decision, and motor response phase of information processing (Massaro & Cowan, 1993). The method of event-related brain potentials (ERPs) allows the investigation of distinct processing steps, including comparatively early, perceptual processing (Rugg & Coles, 1995) and hence complements behavioral assessments. Here, we use ERPs to differentiate distinct stages of visual processing and categorization of a specific set of categorical patterns (i.e., five-dot patterns; see Garner & Clement, 1963). In more detail, we analyze the visual mismatch negativity (vMMN) and the P300 component of ERPs, associated with either early perceptual (i.e., vMMN component) or later cognitive (i.e., P300 component) processing, respectively. The goal of the present research is to assess at which stage effects of categorical information in these visual patterns can be observed, and specifically to evaluate the role of earlier perceptual processing stages for categorizing this specific stimulus material.

Perceptual categorization is based on perceptual similarities with a categorical representation of the category itself or other exemplars in the same category (Quinn, Elms, & Tarr, 2001). Perceptual similarities with a categorical representation refer to both similarities of an exemplar with category members and differences with category non-members (Cohen & Lefebvre, 2017). How categorical representations are encoded in the brain is an ongoing debate (for review see Hanson & Hanson,
one account suggests that encoding reflects both experience with this specific category and the current processing goal of categorization (Gauthier, 2000). This implies that categorical encoding is modulated by task context, and hence, encoding differences between, for instance, preattentive and task-relevant processing of categorical information. Perceptual similarities with other instances refer to shared perceptual properties that are deemed equivalent for a set of instances (Reznick, 2000). To investigate these perceptive properties, the physical energy delivered to the sensory system needs to be controlled. For instance, Garner and Clement (1963) used visual patterns, consisting of five dots in an invisible 3 × 3 square grid, by leaving no row or column empty. In total, there are 90 possible five-dot patterns, which can be sorted into 17 distinct subsets (i.e., categories) of different sizes (containing either 1, 4, or 8 categorically equivalent patterns). Similarities within instances of a subset are deemed equivalent (equivalence set; ES) by transformational rules. The transformational rule implies that each pattern within the same category can be transformed to any other by reflection and/or rotation. In several studies it was shown that all patterns in an ES share a common mental representation (Lachmann & Geisler, 2002; Lachmann & van Leeuwen, 2010; Lachmann & van Leeuwen, 2005a; see Van Leeuwen & Lachmann, 2004, for a review). One important feature of these patterns is that the physical energy of each pattern delivered to the sensory system is the same (i.e., each pattern consists of five dots). In the following, we summarize prior research using these stimuli with respect to comparably late stage of information processing (P300), and then move on to research regarding earlier perceptual processing (vMMN).

1.1. The modulation of memory encoding by categorical information

Employing the five-dot patterns in a cognitive task demonstrated that late stages of information processing like memory encoding and maintenance are influenced by perceptual categorization, for instance, in Berti, Geisler, Lachmann, & Mecklinger, 2000; Berti & Roeben, 2013; Carmo et al., 2017 and Takahashi, Yasunaga, & Gyoba, 2014, 2019. Berti and colleagues (2000) employed a delayed memory comparison task, in which two patterns were presented sequentially, separated by a 1500 ms interstimulus-interval. Participants performed the task under two conditions: In the identity-matching task, they were instructed to decide whether both stimuli were identical; in the categorical-matching task they were instructed to judge whether both stimuli belonged to the same category (i.e., ES). The results of this study suggested that categorical information is immediately encoded into working memory when this information is task relevant. In more detail, Berti and colleagues reported a difference between the two task instructions in the 300–500 ms time window at electrode Pz (P300). The P300 (also labeled P3b) is interpreted as a correlate of memory encoding in a broad sense (e.g., Donchin & Coles, 1988) and it was suggested that the amplitude varies with the amount of information transferred into working memory (Johnson, 1986). The study by Berti et al. (2000) reported a more positive P300 amplitude in the categorical-matching compared to the identity-matching condition; therefore, the authors concluded that perceptual features were encoded and maintained in working memory in the categorical-matching, but not the identity-matching task. These results were, in principal, replicated in a study by Berti and Roeben (2013) and by Takahashi et al. (2019). In addition, Berti and Roeben (2013) also reported an effect of ES-size (ESS), with a larger P300 amplitude for ESS-8 compared to ESS-4 patterns. All three studies support the assumption that categorical information is encoded into working memory, especially when this categorical information is task relevant.

Taken together, perceptual categories are relevant during information processing. Nevertheless, it remains open at which point in information processing this effect can be observed. The studies employing five-dot patterns – representing inherent perceptual categories – demonstrate the earliest effect of categorical information at the level of memory encoding (as reflected in the P300 component). However, another line of research suggests that categorical information processing occurs already at perceptual levels.

1.2. Perceptual processing of categorical information

In the auditory domain, perceptual categorization is well documented (see Näätänen, Paavilainen, Rinne, & Alho, 2007, for review). For instance, the auditory system can encode categorical information already within the first 200 ms of stimulus processing (see Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001). This line of research makes use of the so-called mismatch negativity (MMN) component of the ERP, which is associated with sensory classification processes (see Näätänen & Winkler, 1999). More importantly, the MMN allows to tap into processes at an early stage of stimulus processing (between 150 and 250 ms post-stimulus), hence preceding memory encoding. Although the visual system also generates a visual MMN (vMMN, see Pazó-Alvarez, Cadaveira, & Amenedo, 2003; Czigler, 2007), it remains an open question whether early visual processing comprises the same capacity for perceptual categorization as the auditory system.

With respect to artificial categories, a study by Kecskés-Kovács, Sulykos, and Czigler (2013) reported results supporting the idea of early perceptual categorization in vision. In this study, vertical symmetry was used as categorical information by applying patterns consisting of nine grey and seven black squares, in two 4 × 4 squared grids, separated by a vertical line. The patterns in both squared grids were either symmetrical or non-symmetrical (Kecskés-Kovács et al., 2013). Stimuli were presented in a classical oddball sequence (i.e., one stimulus type serving as the frequent standard stimulus and one stimulus type serving as the rare deviant). With this protocol, Kecskés-Kovács et al. (2013) were able to analyze the vMMN (i.e., the difference between standard and deviant ERPs) when symmetrical patterns were presented as standards and non-symmetrical patterns as deviant, or vice versa. They observed two posterior negative deflections (early: 112–120 ms; late: 284–292 ms) in the symmetrical condition, both identified as vMMNs (Kecskés-Kovács et al., 2013). In contrast, a recent study by Beck et al. (under revision) did not find an influence of category on the vMMN. In this study, the five-dot patterns were used as stimuli, which allowed for defining different categories (i.e., ES). Moreover, this study employed a three-stimulus oddball paradigm (see Courchesne, Hillyard, & Gaambos, 1975), presenting one frequent (i.e., standard), one rare target, and one rare task-irrelevant (i.e., deviant) pattern. Participants were asked to count the occurrence of the rare target pattern and ignore the standard and deviant pattern (Beck et al., under revision). By applying five-dot patterns from different ES, two variants of vMMNs were computed: When the deviant and standard stimulus were in the same ES, a congruence vMMN was derived, whereas an incongruence vMMN was derived when the deviant and standard stimulus were from different ES (Beck et al., under revision). Thus, the influence of categorical information on earlier perceptual processing would be associated by a difference between the congruence vMMN and the incongruence vMMN. The main result was that the congruence vMMN and the incongruence vMMN did not differ, indicating no influence of categorical information (Beck et al., under revision). While these two studies reported inconsistent results, there is a notable difference in the two protocols. In the first study (Kecskés-Kovács et al., 2013) a binary category was used, in which a pattern is vertical symmetrical or not. This study indicates that symmetry could serve as a deviant and was able to elicit a vMMN. However, with this stimulus material categorical modulations on the vMMN cannot be investigated. In comparison, in the second study (Beck et al., under revision) two abstract categories were used, in which a pattern belongs to one of two classes defined by abstract rules (i.e., transformation and rotation). Here, no categorical modulation on the vMMNs was observed.

1.3. The present study

In the present study, we assess the influence of categorization on
both early perceptual (vMMN) and later cognitive (P300) processing. For this purpose, we constructed a paradigm in which both processes - early perceptual processing associated with sensory classification of categorical information and later cognitive processing associated with memory encoding of categorical information - could be observed. Thus, we combined an oddball paradigm with a delayed memory task. To investigate early perceptual processing, the stimuli were embedded in an oddball paradigm. This means that rare patterns (i.e., deviants) were presented within a sequence of more frequently presented patterns (i.e., standards). Note that the relationship between the standard and the deviant pattern does not need to be encoded to solve the task. In the delayed memory comparison task, participants performed an identity-matching task between two sequentially presented five-dot patterns. Each five-dot pattern belonged to a different category (i.e., ESS-4 or ESS-8). In contrast to the studies summarized above, participants performed a continuous identity-matching (i.e., 1-back) task, resulting in a continuous comparison between the current and the previously presented target stimulus.

Based on the literature, we predicted to observe both a congruence and an incongruence vMMN (i.e., difference between the standard ERP and the deviant ERP; Beck et al., under revision). Second, we assessed whether categorical information has an influence on vMMN and/or P300. Lastly, we hypothesized no effect of categorical information on early perceptual (Beck et al., under revision), but rather on later cognitive processes (Berti et al., 2000). Specifically, no unique activation of the congruence vMMN and incongruence vMMN is predicted (Beck et al., under revision). However, we expected an influence of category (i.e., ES) on the P300 at central-parietal electrode sites, with the ESS-8 pattern eliciting a larger amplitude than the ESS-4 pattern (Berti & Roeber, 2013).

2. Methods

2.1. Participants

All participants were students from the University of Kaiserslautern, and, according to self-reports, were right-handed, had normal or corrected-to-normal vision, had no diagnosis of psychological or neurological disorder, and did not consume medication affecting the central nervous system. Every participant provided written informed consent after being informed about the procedure and having the possibility to ask questions. The study was conducted according to the Declaration of Helsinki (World Medical Association, 2013) and approved by the ethical review board of the Faculty of Social Science of the University of Kaiserslautern. We recorded EEG data from 30 students, who were compensated with course credits. After initial data analysis, we excluded participants due to low performance (n = 2; i.e., four standard deviations below group average) and incomplete data (n = 1). Thus, EEG data from 27 students were analyzed (17 female; M_{age}: 24.96 years, SD = 1.85 years, range: 21–28 years).

2.2. Materials and procedure

We used a set of visual patterns, each consisting of five dots, constructed in a 3 × 3 squared grid, by leaving no row or column empty (first used by Garner & Clement, 1963). In this manner, 90 five-dot patterns can be constructed, which can be sorted into 17 distinct subsets (categories). Patterns within a subset can be transformed into each other by reflection and/or rotation (90°) operations and are therefore categorically equivalent (see Fig. 1). Notably, since each pattern only consists of five dots, categorical characteristics are not due to differences in physical properties. In addition, we controlled for complexity of the categories and meaningfulness of the patterns. Complexity was controlled for by choosing two categories which received similar ratings for perceived perceptual complexity (see ratings in Garner & Clement, 1963 and Lachmann & Geissler, 2002). From each category, we used two patterns with low ratings for meaningfulness (see ratings in Lachmann, 1998). We used a smaller subset of ESS = 4 with four equivalent patterns as categorical elements, and a larger subset of ESS = 8 with eight equivalent patterns as categorical elements (see Fig. 1). Additionally, the patterns were chosen based on a similar “direction” (upward). Between each stimulus, we presented either a black or red fixation cross at the center of the monitor.

Stimuli were presented on a 15.6” monitor with a resolution of 1920 × 1080 pixel and a refresh rate of 60 Hz. Dot patterns were presented in black (luminance = 0.417 cd/m²) on a white (luminance = 161.1 cd/m²) background. Instructions and stimuli were presented with the Software Presentation (Version 21.1, Neurobehavorial Systems, Inc., Berkeley, CA, www.neurobs.com). We used two categories (ESS-8 and ESS-4; see Fig. 1) and from each, two patterns (see Fig. 2). One of the two patterns was presented frequently (standard pattern) and the other rarely (deviant pattern, 15% of all trials). The standard pattern was presented in 85% of all trials and counterbalanced blockwise between both categories. Standards were repeated randomly for four (20%), five (30%), six (30%), or seven (20%) consecutive trials. Presentation of the deviant pattern was counterbalanced between both categories. In each block, 50 rare patterns were presented. We realized two conditions (condition A and condition B; see Fig. 2), since in each block we presented both deviant stimuli, but only one standard stimulus. In condition A the standard stimulus was from category ESS-8 and in condition B the

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Fig. 1. Stimulus Material. We use two equivalent set sizes (ESS), ESS-4 and ESS-8. Each prototype consisted of five dots in an imaginary 3x3 matrix by leaving no row and no column empty stimuli (first used by Garner & Cements 1963). The prototype can be transformed into equivalent patterns by rotation (90°) and/or reflection on any axis. A set of four equivalent patterns have an ESS of 4; a set of eight equivalent patterns have an ESS of 8.
standard stimulus was from category ESS-4. The six experimental blocks were presented randomly. In each trial, a stimulus was presented for 500 ms, followed by a fixation cross presented between 700 and 1100 ms (random variation).

Participants were seated 40 cm in front of the monitor, using no chin rest, and perceived stimuli foveally (visual angle = 0.72°). Participants rested their index fingers on the left and right key of a response box, corresponding to a “same” and “different” response (counterbalanced across participants). Participants performed a memory task, which was an adaptation of the so-called n-back task (for information see Kirchner, 1958): Participants were instructed to perform a same-different memory comparison with sequentially presented rare stimuli (see Fig. 2). In other words, rare stimuli served as targets; participants were asked to compare the current target with the previously presented target and to indicate whether they were the same or different. To complete this task, it is necessary to memorize the current rare stimulus until the next rare stimulus is presented and to continuously update the memory representation when the target changed. Responses could be given upon stimulus onset until the next stimulus was presented, resulting a response window between 1300 and 1600 ms due to the variable intertrial-interval (ITI). Frequent stimuli were task-irrelevant and could be ignored. However, we added catch trials to ensure the processing of frequent stimuli were task-irrelevant and could be ignored. In other words, rare stimuli served as targets; participants were asked to compare the current target with the previously presented target and to indicate whether they were the same or different. To complete this task, it is necessary to memorize the current rare stimulus until the next rare stimulus is presented and to continuously update the memory representation when the target changed. Responses could be given upon stimulus onset until the next stimulus was presented, resulting a response window between 1300 and 1600 ms due to the variable intertrial-interval (ITI). Frequent stimuli were task-irrelevant and could be ignored. However, we added catch trials to ensure the processing of the frequent, task-irrelevant stimulus. Thus, participants were also instructed to press a foot pedal whenever the fixation cross changed to red (1.5% of all trials). The red fixation cross only occurred after a standard stimulus. Overall, the trial duration did not depend on the responses. In the step-wise training blocks, participants had to respond with a 70% accuracy to start the experimental blocks. Between each block, there was a break in which participants got feedback about their performance (mean accuracy and mean reaction time).

### 2.3. EEG recording

During practice and experimental blocks, electroencephalography (EEG) was recorded with 27 Ag/AgCl cap-mounted electrodes (EasyCap GmbH; Gilching, Germany) positioned on an extended 10–20 system (Jasper, 1958), plus two electrodes placed at the mastoids and four electrodes around the eyes, with the BrainVision EEG-System (Brain-Products GmbH; Gilching, Germany). We used four electrodes around the eyes (above and below the right eye, and beside the right and left eye) to record eye-movements. The ground electrode was placed at the electrode site AFz. The electrode positioned at electrode site FCz was used as online reference. The signal was recorded with electrode impedances lower than 10 KΩ. The sampling frequency was 500 Hz.

We used Brain Vision Analyzer 2.1 (Brain Products GmbH, Gilching, Germany) to do a spline interpolation on electrodes with many artifacts (on average 0.5 electrodes per participant; ranging between 0 and 3 interpolated electrodes). The signal was re-referenced offline to the average of both mastoids. We used a Butterworth zero phase band-pass filter from 0.1 Hz to 30 Hz (with 24 dB/oct). We corrected for eye movement artifacts by using an independent component analysis (ICA) with the infomax restricted algorithm (Jung et al., 1998). For the ICA, we selected a 400 s interval from the fourth block of the experiment as a training data set for computing the unmixing matrix. ICA components were automatically identified by picking up blinks and saccades, as evidenced by their characteristic shape and location (at frontal electrode sites). After removing components manually (on average 2.7 per participant; ranging between 1 and 4 deleted components), the EEG signal was reconstructed. The EEG signal was segmented based on a time window 200 ms before and 1000 ms after the onset of the pattern presentation. Artifacts were removed automatically when (1) a voltage step of 50 μV/ms was detected, (2) a voltage difference of 100 μV occurred in any 200 ms interval, or (3) a low amplitude of 0.5 μV occurred in a 100 ms interval. Due to the artifact rejection on average 2.73% (SD = 3.02%) of all trials were removed. Segments were included in further analysis (1) when the response to a pattern was correct (i.e., no key press after frequent patterns and correct key press after rare patterns), (2) when the response to the rare patterns was slower than 200 ms, and (3) when the presentation of a frequent pattern was preceded by the presentation of a frequent pattern (number of average trials left per pattern can be found in Table 1).

| Condition | Mean trials | Range |
|-----------|-------------|-------|
| A         | Standard ESS-8 | 626.4 | 557–656 |
|           | Deviant ESS-8 – “same” | 34.0 | 27–38 |
|           | Deviant ESS-8 – “different” | 32.3 | 22–36 |
|           | Deviant ESS-4 – “same” | 31.6 | 22–36 |
|           | Deviant ESS-4 – “different” | 32.7 | 27–38 |
| B         | Standard ESS-4 | 621.4 | 510–647 |
|           | Deviant ESS-8 – “same” | 33.8 | 27–42 |
|           | Deviant ESS-8 – “different” | 31.1 | 23–36 |
|           | Deviant ESS-4 – “same” | 33.2 | 20–39 |
|           | Deviant ESS-4 – “different” | 32.3 | 25–37 |

Table 1: Trials per condition. Mean trials and range per condition used in the ERP analysis, calculated for adults. Note that standard stimulus of category ESS8 and ESS4 are only used for the vMMN analysis.
2.4. Analysis of behavioral data

Response accuracy in the memory task (ACC) and reaction times of correct responses to target stimuli (RTs) were analyzed. We analyzed only responses to rare, target patterns. In 1.2% of all trials, no response was given in the ITI (1300–1600 ms); no additional upper limit was used for RT analysis. Responses faster than 200 ms were excluded, corresponding to an average of 4.43% (SD = 3.1%) of all trials. For both, mean ACCs and mean RTs, we used a repeated measure Analysis of Variance (ANOVA) with the within-subject factors CONGRUENCY (congruent vs. incongruent), CATEGORY (category ESS-8 vs. category ESS-4), and RESPONSE (same vs. different). The interaction involving the category of the target and the irrelevant frequent pattern designated CONGRUENCY: a target from ESS-8 presented within the irrelevant pattern from ESS-8 and a target from ESS-4 presented within the irrelevant pattern from ESS-4 constitute congruence conditions; a target from ESS-8 presented within the irrelevant pattern from ESS-4 and a target from ESS-4 presented within the irrelevant pattern from ESS-8 constitute incongruence conditions. Behavioral data were aggregated in Python 3.6.5 (Van Rossum & Drake, 2009) and ACCs and RTs were analyzed with SPSS 26 (IBM Corporation, Armonk, NY). To clarify interaction effects, we compared congruence vs. incongruence for each response and each category using a planned comparison (repeated contrast). We report only effects and interactions with p-values below 0.05.

2.5. Analysis of event-related potentials

A baseline correction was applied to the segmented signal, using the time window of 200 ms before stimulus onset. All ERP components were analyzed with SPSS 26 (IBM Corporation, Armonk, NY). For the analysis of the vMMN, we computed difference waves by subtracting the ERPs of a frequent pattern from the ERPs of a rare pattern to obtain either a congruence vMMN or an incongruence vMMN. For the congruence vMMN, we subtracted the standard pattern from category ESS-8 from the deviant pattern from category ESS-8 in condition A and the standard pattern from category ESS-4 from the deviant pattern from category ESS-4 in condition B. For the incongruence vMMN, we subtracted the standard pattern from category ESS-8 from the deviant pattern from category ESS-4 in condition A and the standard pattern from category ESS-4 from the deviant pattern from category ESS-8 in condition B. For these two difference waves, we calculated the mean amplitude with the following rules: First, we identified the individual negative peak in an early (160–220 ms) and late (220–300 ms; based on visual inspection) time window and, second, we computed the mean amplitude within a 20 ms window, centered around individual peak latencies. The analysis was performed by averaging electrode sites P7 and P3 for the left region of interest (ROI) and P8 and P4 for the right ROI for each participant. For statistical analysis of the vMMN, we used (1) a one-sided t-test against 0 to verify that both vMMNs (congruence and incongruence) in each ROI (left and right) in each time window (160–220 ms and 220–300 ms) were elicited and (2) a repeated measures ANOVA with CONGRUENCE (congruence vs. incongruence) and LATERALITY (left vs. right) as within-subject factors, for both time windows separately. To clarify interaction effects, we compared the congruence vMMN with the incongruence vMMN for each ROI using a planned comparison (repeated contrast). As in the behavioral analysis, we report only those effects and interactions with p-values below the conventional significance value of 0.05; all remaining analyses are not listed in the result section.

3. Results

3.1. Results of behavioral data

Overall, participants responded correctly to an average of 92.62% of all trials in the memory task (SE = 0.6%; for details see Table 2). Thus, the overall error rate was 7.38%. In the ANOVA of mean ACC, we observed a main effect of the factor CONGRUENCY, F(1, 26) = 9.98, p < .005, η² = 0.28. Participants responded more correctly to congruent (M = 93.57%, SE = 0.71%, 95% CI [92.11, 95.04]) than to incongruent targets (M = 91.67%, SE = 0.75%, 95% CI [90.12, 93.21]). We observed a triple interaction effect between CONGRUENCY, CATEGORY, and RESPONSE, F(1, 26) = 4.96, p < .05, η² = 0.16. Planned contrasts revealed that response accuracy was higher to congruent (M = 94.38%, SE = 1.46%, 95% CI [91.38, 97.38]) than to incongruent targets (M = 90.00%, SE = 1.90%, 95% CI [86.10, 93.92]; p < .005) when participants responded to an ESS-4 target with same as compared to different responses.

Overall, participants responded on average after 690 ms (SE = 17 ms) after target presentation (for details see Table 2). In the ANOVA of mean RTs, we observed a main effect in CONGRUENCY, F(1, 26) = 7.62, p < .05, η² = 0.23. Participants responded slower to congruent (M = 697 ms, SE = 17 ms, 95% CI [662, 733]) than to incongruent targets (M = 683 ms, SE = 17 ms, 95% CI [648, 719]). We observed a main effect in windows of 300–500 ms (early) and 500–650 ms (late) at the electrode sites CP1, CP2, P3, P4, and Pz. For statistical analyses, we used a repeated measures ANOVA with CATEGORY (category ESS-8 vs. category ESS-4), TIME (early vs. late) and ELECTRODES (CP1 vs. CP2 vs. P3 vs. P4 vs. Pz) as within subject factors. To clarify interaction effects, we compared ESS-4 vs. ESS-8 for each time window using a planned comparison (repeated contrast). In addition, to investigate interaction effects with ELECTRODES we averaged the electrode sites CP1 and P3 for the left ROI and CP2 and P4 for the right ROI. As in the analysis of the vMMN, we report only those effects and interactions with p-values below the conventional significance value of 0.05; all remaining analyses are not listed in the result section.

Table 2

Mean activity of accuracy (ACC) and reaction time (RT; standard error in brackets) was calculated for adults.

| Condition          | ACC [%]          | RT [ms] |
|--------------------|------------------|---------|
| Congruence – ESS-8 | 95.44 (0.81)     | 640 (17) |
| Congruence – ESS-4 | 91.94 (0.98)     | 723 (19) |
| Congruence – ESS-8 | 94.35 (1.46)     | 667 (24) |
| Congruence – ESS-4 | 92.52 (1.53)     | 759 (22) |
| Incongruence – ESS-8| 93.97 (0.97)    | 665 (23) |
| Incongruence – ESS-4| 89.98 (1.44)    | 721 (21) |
| Incongruence – ESS-8| 90.00 (1.90)    | 643 (16) |
| Incongruence – ESS-4| 92.71 (1.29)    | 703 (19) |

Table 3

Mean activity of vMMN and results of t-test against 0. Mean activity (standard error in brackets) of the vMMN was calculated for adults in µV. Note that the vMMN is the difference wave between the ERPs elicited by a standard and a deviant stimulus. * indicates p < .001.

| Time window          | Mean Activity [µV] | t-value (t(26)) |
|----------------------|--------------------|-----------------|
| Early time window    |                    |                 |
| ESS-8 – right ROI    | -2.51 (0.30)       | -8.44*          |
| ESS-8 – left ROI     | -1.80 (0.25)       | -7.19*          |
| ESS-4 – right ROI    | -3.22 (0.39)       | -8.30*          |
| ESS-4 – left ROI     | -1.97 (0.26)       | -7.51*          |
| Late time window     |                    |                 |
| ESS-8 – right ROI    | -2.55 (0.29)       | -8.78*          |
| ESS-8 – left ROI     | -1.60 (0.25)       | -6.38*          |
| ESS-4 – right ROI    | -3.50 (0.32)       | -10.84*         |
| ESS-4 – left ROI     | -2.06 (0.33)       | -6.33*          |
Fig. 3. Results vMMN. Grand average difference wave at the electrode sites P7, P3, P4, and P8 (A.) and at the left and right ROI (B.) for the congruence vMMN and incongruence vMMN. The congruence vMMN refers to the difference between ERPs of the frequent stimulus and the deviant of the same category (e.g., ESS-8 frequent and ESS-8 rare stimulus in condition A). The incongruence vMMN refers to the difference between ERPs of the frequent stimulus and the deviant of the different category (e.g., ESS-8 frequent and ESS-4 rare stimulus in condition A). The squares indicate the interval of 160–220 ms (early) and 220–300 ms (late) after stimulus onset, in which the peak detection was performed. (C.) The topographical maps of the difference between congruence vMMN and incongruence vMMN in the time window 160–220 ms and 220–300 ms.
Fig. 4. Results P300. Grand average ERPs for the ESS-8 target, ESS-4 target, ESS-8 irrelevant and ESS-4 irrelevant at the electrode sites CP1, CP2, P7, P3, Pz, P4, and P8 (A.) and at the left and right ROI (B.). The squares indicate the interval of 300–500 ms (early) and 500–650 ms (late) after stimulus onset, in which the mean amplitude was calculated. (C.) The topographical maps of the difference between the ESS-8 target and ESS-4 target in the time window 300–500 ms and 500–650 ms.
CATEGORY, F(1, 26) = 13.02, p < .005, η² = 0.33. Participants responded faster to the ESS-8 target pattern (M = 677 ms, SE = 15 ms, 95% CI [646, 709]) than to the ESS-4 target pattern (M = 703 ms, SE = 19 ms, 95% CI [663, 743]). We observed a main effect in RESPONSE, F(1, 26) = 58.92, p < .001, η² = 0.69. Same responses (M = 653 ms, SE = 17 ms, 95% CI [619, 688]) were faster than different responses (M = 726 ms, SE = 19 ms, 95% CI [688, 765]). Additionally, we observed an interaction between CONGRUENCY and RESPONSE, F(1, 26) = 14.21, p < .001, η² = 0.35. Planned contrasts revealed no difference between congruent and incongruent targets (p = .94) when the response was same, whereas responses were slower to congruent (M = 741 ms, SE = 19 ms, 95% CI [701, 780]) than to incongruent targets (M = 712 ms, SE = 19 ms, 95% CI [674, 750]; p < .001) when the response was different.

3.2. Results of event-related potential data

First, we focus on the results of the vMMN. Table 3 summarizes mean activity of all vMMNs (each condition, ROI, and time window) and their deviation from zero. The more positive activation of the congruence vMMN than the incongruence vMMN is shown for individual electrodes sites (P7, P3, P4, and P8) in Fig. 3A and for the ROIs (left and right) in Fig. 3B. As illustrated in Fig. 3C, differences between both vMMNs were observed only in the right hemisphere in both time windows.

For the vMMNs in the early time window (160–220 ms), we observed a main effect in CONGRUENCY, F(1, 26) = 8.37, p < .01, η² = 0.24. Mean amplitudes at both ROIs were more negative for the incongruence vMMN (M = 2.59 μV, SE = 0.28 μV, 95% CI [−3.16, −2.03]) than for the congruence vMMN (M = −2.15 μV, SE = 0.24 μV, 95% CI [−3.16, −2.03]). We observed a main effect in LATERALITY, F(1, 26) = 9.72, p < .005, η² = 0.27. Mean amplitudes of both vMMNs were more negative at the right ROI (M = −2.87 μV, SE = 0.33 μV, 95% CI [−3.55, −2.18]) compared to the left ROI (M = −1.88 μV, SE = 0.24 μV, 95% CI [−2.38, −1.38]). Additionally, we observed an interaction effect between CONGRUENCY and LATERALITY, F(1, 26) = 8.32, p < .01, η² = 0.24. In the right ROI, we observed a more negative amplitude for the incongruence vMMN than the congruence vMMN (p < .001), whereas in the left ROI there was no difference between the congruence vMMN and the incongruence vMMN (p = .28).

For the vMMNs in the late time window (220–300 ms), we observed the same pattern of results. We observed a main effect in CONGRUENCY, F(1, 26) = 15.28, p < .001, η² = 0.37. The mean amplitudes at both ROIs was more negative for the incongruence vMMN (M = −2.78 μV, SE = 0.26 μV, 95% CI [−3.32, −2.25]) than for the congruence vMMN (M = −2.08 μV, SE = 0.22 μV, 95% CI [−2.53, −1.62]). We observed a main effect in LATERALITY, F(1, 26) = 12.56, p < .005, η² = 0.33. The mean amplitudes of both vMMNs was more negative at the right ROI (M = −3.03 μV, SE = 0.30 μV, 95% CI [−3.63, −2.42]) compared to the left ROI (M = −1.83 μV, SE = 0.27 μV, 95% CI [−2.38, −1.28]). Additionally, we observed an interaction effect between CONGRUENCY and LATERALITY, F(1, 26) = 5.93, p < .05, η² = 0.19. In the right ROI, we observed a more negative amplitude for the incongruence vMMN than the congruence vMMN (p < .001), whereas in the left ROI we observed a marginal difference between the congruence vMMN and the incongruence vMMN (p = .06).

Second, we focus on the results of the P300. The activation of P300 for the ESS-4 and ESS-8 target is shown for the electrodes (CP1, CP2, P7, P3, Pz, P4, and P8) in Fig. 4A and for the ROIs (left and right) in Fig. 4B. A reversed polarity of activation between left and right ROIs regarding ESS-4 and ESS-8 targets was observed only in the early time window, as shown in Fig. 4C. For mean activity of the specific P300s for each target category, electrode, and time window, see Table 4.

For the P300, we observed a main effect in TIME, F(1, 26) = 5.71, p < .05, η² = 0.28, with a smaller P300 amplitude in the early (M = 5.91 μV, SE = 0.57 μV, 95% CI [4.74, 7.01]) than in the late (M = 6.95 μV, SE = 0.64 μV, 95% CI [5.62, 8.27]) time window. We observed an interaction effect between CATEGORY and ELECTRODES, F(1,26) = 15.41, p < .001, η² = 0.37. Planned contrasts revealed no difference between categories at Pz (p = .90) and in the right ROI (p = .13), whereas a tendency for a larger amplitude in ESS-8 (M = 6.21 μV, SE = 0.58 μV, 95% CI [5.01, 7.41]) than ESS-4 (p = .061; M = 5.78 μV, SE = 0.56 μV, 95% CI [4.64, 6.92]) was observed in the left ROI. Additionally, we observed an interaction between TIME, CATEGORY, and ELECTRODES, F(1,26) = 16.05, p < .001, η² = 0.38. Planned contrasts revealed no effect of CATEGORY or TIME on the P300 at Pz (p = .99). However, we observed an interaction between CATEGORY and ELECTRODES in the early, but not the late time window. More specifically, we observed a larger amplitude in the ESS-4 than in the ESS-8 (p < .05) in the right ROI. Reversely, in the left ROI we observed a larger amplitude in the ESS-8 than in the ESS-4 (p < .01).

4. Discussion

The pattern of behavioral results confirms that categorical information was processed even though it was not necessary for successful task performance. The present study observed faster responses to same compared to different targets (fast-same effect; see Farell, 1985, for review) and to ESS-4 compared to ESS-8 targets (see Lachmann & van Leeuwen, 2004, for review). The ESS effect is in line with a number of earlier studies reporting RTs in successive same-different tasks increasing with the ESS of the pattern to be compared. The finding that processing time for a pattern depends on the number of equivalent patterns belonging to same set (of rotational and reflexional transformations) suggests categorical representation for each (Lachmann & Geisler, 2002). This explains also why we found, as in earlier studies (Lachmann and van Leeuwen, 2005b, 2008), a strong effect of ESS even though it was not task-relevant; the categorical representation in terms of ES makes it hard to ignore the equivalence of patterns (e.g., response conflict for patterns from the same set that require a different response in earlier studies, Lachmann & van Leeuwen, 2004). Furthermore, we found that targets incongruent to non-targets received faster, but less accurate responses compared to congruent targets. This also indicates that a categorical representation affects processing, even though it is task-irrelevant.

Prior EEG studies using these five-dot patterns focused on the influence of categorical information on later cognitive processing. The literature indicates no influence of categorization in early perceptual (Beck et al., under revision), but later cognitive processing (Berti & Roeber, 2013; Berti et al., 2000). The goal of this study was to assess effects of categorical information on both the early perceptual and later cognitive processing within one paradigm. For this purpose, we combined an oddball paradigm with a delayed memory task. In turn the results of the early perceptual (i.e., vMMN component) and later cognitive (i.e., P300 component) processing will be discussed.

### Table 4

| Mean Activity [μV] | ESS-8 target | ESS-4 target |
|-------------------|--------------|--------------|
| Early time window (300–500 ms) | | |
| CP1               | 5.21 (0.60)  | 4.83 (0.58)  |
| CP2               | 5.69 (0.58)  | 6.01 (0.57)  |
| P3                | 6.23 (0.61)  | 5.39 (0.62)  |
| P4                | 5.59 (0.67)  | 6.28 (0.63)  |
| Pz                | 6.94 (0.68)  | 6.88 (0.67)  |
| Late time window (500–650 ms) | | |
| CP1               | 6.16 (0.75)  | 5.95 (0.71)  |
| CP2               | 6.70 (0.75)  | 6.80 (0.67)  |
| P3                | 7.22 (0.65)  | 6.95 (0.64)  |
| P4                | 6.50 (0.69)  | 6.90 (0.62)  |
| Pz                | 8.13 (0.77)  | 8.14 (0.70)  |
4.1. Perceptual processing of categorical information

The vMMN component is defined as the difference between ERPs elicited by deviant and ERPs elicited by standard patterns and mirrors perceptual processing of visual input. Here were compare the congruence vMMN with the incongruence vMMN, connotating the categorical relation between deviant and standard patterns. As in the study by Beck and colleagues (under revision), we observed both vMMNs, indicating that early perceptual processing encodes abstract information. However, in contrast to our previous study, we observed a unique activation for both vMMNs, which suggests encoding of categorical information in early perceptual processing. This inconsistent result might be explained by a notable difference in both paradigms: In the study by Beck and colleagues (under revision), the deviant pattern was task-irrelevant in a three-stimulus oddball paradigm, whereas in the present study, the deviant pattern was task-relevant. Hence, categorical encoding in early perceptual processes might depend on the processing goal (i.e., task; Gauthier, 2000).

In more detail, we observed a more negative amplitude for the incongruence vMMN than for the congruence vMMN in the right ROI (i.e., P8 and P4), in both early (160–220 ms) and late (220–300 ms) time window. First, observing unique vMMNs only in the right ROI is in line with a source location analysis, demonstrating that the main sources to elicit a vMMN are located in the right occipital sensory extrastriate areas (Kimura, Ohira, & Schröger, 2010). Second, since unique vMMNs are observed in both time windows, one might conclude the same underlying evoked potential (i.e., the vMMN). However, it is important to note that ERPs indicate dissimilar underlying evoked potentials (i.e., the vMMN or the visual N1; see Kimura, Schröger, & Czigler, 2011). To distinguish the evoked potentials of the vMMN and the visual N1, an equiprobable control sequence could be introduced in a future study. Thus, the standard would be presented to several equiprobable stimuli rather than a single stimulus. Presenting several equiprobable stimuli would eliminate a neuronal refractoriness effect. The refractoriness effect describes the observation that the neurons processing a frequent stimulus (i.e., standard) are firing more frequently, resulting in a “exhausted” neuronal response (see Schröger & Wolff, 1996). Hence, subtracting an “exhausted” neuronal response from a “fresh” neuronal response, elicited by the rare stimulus (i.e., deviant), would result in a confounded difference. This effect influences in particular the visual N1, which would be clearly distinguishable from the vMMN. Third, the more negative amplitude for the incongruence vMMN than the congruence vMMN can be associated with studies investigating the influence of color categories on early perceptual processing. Clifford, Holmes, Davies, and Franklin (2010) investigated a congruence vMMN and an incongruence vMMN, considering the color of the standard in contrast to the color of the deviant stimuli (i.e., in the congruence vMMN the standard and the deviant stimulus had the same color). They used a three-stimulus oddball paradigm in which the target differed from the standard and deviant by shape (i.e., standard and deviant were circles, the target was a square). By using color as a category, a more negative deflection was observed for the incongruence vMMN than congruence vMMN, like in the present study. While such a congruency effect is surprising with regard to color as relevant category, with regard to our stimulus material the congruency effect supports the perceptual processing of categorical information at this early stage of processing: Here, rare stimuli, which are congruent to the standard, deviate with regard to one feature from the standard presentation (i.e., sensory information) while incongruent rare stimuli deviate with regard to two features (i.e., sensory and categorical information). In other words, the vMMN seems to mirror the degree of deviation, as proposed by the predictive coding model of the vMMN (for instance, see Czigler, 2007; Kimura et al., 2011). In contrast, this hardly fits to color as categorical information. Therefore, more research is required to solve this puzzle.

4.2. The modulation of memory encoding by categorical information

In the present study we applied the P300 component as a measure of memory encoding. We compared ERPs for ESS-8 and ESS-4 targets, because in order to perform the memory comparison task the current target need to be encoded into working memory. Therefore, as suggested by earlier studies (Berti & Roeber, 2013; Berti et al., 2000), categorical information should modulate the P300 component. In contrast to the literature (Berti & Roeber, 2013; Berti et al., 2000), we observed no effect of categorical information at Pz in either time window (300–500 ms and 500–650 ms). This lack of effect indicates no encoding of categorical information at this stage of cognitive processing. Form this perspective, our results suggest that categorical information might be encoded already at an early stage of processing, in line with the behavioral results demonstrating that this information was also processed. We can only speculate at this point that categorical information might be processed at the stage of perceptual processing as indicated by the vMMN results. In this case an additional encoding into working memory would not be necessary.

However, when investigating laterality effects, we observed the predicted larger amplitude for ESS-8 compared to ESS-4 (Berti & Roeber, 2013) in the early time window and right ROI, whereas we observed a reversed effect in the left ROI. To consider the inconsistency between the prior and the current results in more detail, we want to point out the three main modifications in the methods: inter-target interval, task, and the EEG analysis. First, in the study by Berti and colleagues (2000) the interval between each target stimulus was 1.5 s, whereas in the present study the interval varied between 5.2 and 11.2 s. A longer inter-target interval might result in an interference of the encoded information in working memory with the information of the stimuli presented in between. Another explanation could be that categorical information is encoded during a shorter interval, whereas categorical information about the target is not encoded during a longer interval. Second, in the present study we used a continuous matching task, which results in a less differentiated observation of retrieval and encoding processing of information. In prior studies (Berti & Roeber, 2013; Berti et al., 2000) the matching task was not continuous, making it possible to investigate only the encoding of information. Thus, our results might either only represent or be confounded by the retrieval process. Note that no categorical information needs to be retrieved in the identity-matching task. Third, during the processing of the EEG data, both prior studies (Berti & Roeber, 2013; Berti et al., 2000) used the left mastoid as reference. In the present study we used the linked averaged (right and left) mastoids as offline reference. Using a one-sided reference might create an imbalance between the electrodes in the left and right hemisphere. This modification might explain the laterality effect obtained in the present study and maybe even the null-finding at the electrode site Pz. Irrespective of these modifications, we would like to emphasize that encoding of categorical information into working memory is especially prominent when categorical information is task relevant (Berti & Roeber, 2013). In the present study, to solve the task, pattern categorization was not relevant for the task.

4.3. Implications

Overall, we obtained behavioral results consistent and ERP results inconsistent with prior literature. Behaviorally, we observed the fast-same and the ESS effect as reviewed by Farell (1985) and Lachmann and van Leeuwen (2004), respectively. Both effects seem persistent irrespective of the differences in the participants’ task in the current and the prior studies. Note that RT analysis represent the end result of multiple cognitive processes (Massaro & Cowan, 1993). Hence, changes in the paradigm did not influence the end result of cognitive processing. To investigate distinct processing steps, we used the method of ERPs. In additional to prior ERP studies (Beck et al., under revision; Berti et al., 2000; Berti & Roeber, 2013) that focused on early perceptual
processing, we also assessed later stages of cognitive processing. The main modification in the current study is participants’ task, which was a more demanding task than those employed previously: In prior studies, participants performed either a counting task (Beck et al., under revision) or a delayed memory comparison task (Berti & Roeber, 2013; Berti et al., 2000; Carmo et al., 2017; Takahashi et al., 2014; Takahashi et al., 2019), whereas in the present study a continuous delayed memory comparison task was performed. Hence, the encoding of categorical information might be more variable and dynamic with respect to the participants’ task than expected based on earlier paradigms.

4.4. Limitation and future directions

Two major aspects could be considered in the future to examine the potentially variable, dynamic encoding of categorical information. The first aspect to be considered is the generalization of stimuli to other instances, objects, or events. In the current study we used a specific stimulus set (five-dot patterns by Garner & Clement, 1963) to control the physical energy delivered to the sensory system. This was done since early perceptual ERP components might be influenced by this factor. However, by using this specific set of stimuli, our results are difficult to be generalized across other visual categories, for instance, more namable categories such as facial emotions (e.g., Stefanics, Csukly, Komlósi, Czobor, & Czigler, 2012), lexical categories (e.g., Tu, Mo, Zeng, Zhao, & Mo, 2017), or colors (Clifford et al., 2010). Additionally, our results are difficult to be generalized across other sensory domains, such as auditory, olfactory, or tactile categories. Therefore, further studies could investigate the potentially variable and dynamic encoding of categorical information with stimuli across different sensory modalities. The second aspects to be considered is the influence of task demands and strategies to solve the task. Since task demand was not varied in the current study, we can infer its potential role only implicitly. In future studies, it would be interesting to investigate whether encoding of categorical information is influenced by task demands or the participants’ strategy to solve the task.

4.5. Conclusion

Categorical information is encoded even when it is not task relevant. While behavioral correlates of visual categorization generalize across paradigms, closer inspection of brain activity suggests that the encoding of categorical information can occur in different processing stages. Together, our results suggest that task demands play a major role to fine-tune the order in which perceptual categories contribute to visual categorization.

Funding

A.B. was supported by the Rhineland-Palatinate Research Initiative (Potentialbereich Cognitive Science) of the Federal Ministry of Science, Further Education and Culture (MWWK).

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee (Ethical Committee of the Faculty of Social Sciences, SOWI/16) and with the 1964 Helsinki declaration and its later amendment or comparable ethical standards.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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