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Does the semantic content of verbal categories influence categorical perception? An ERP study

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ABSTRACT

Accumulating evidence suggests that visual perception and, in particular, visual discrimination, can be influenced by verbal category boundaries. One issue that still awaits systematic investigation is the specific influence of semantic contents of verbal categories on categorical perception (CP). We tackled this issue with a learning paradigm in which initially unfamiliar, yet realistic objects were associated with either bare labels lacking explicit semantic content or labels that were accompanied by enriched semantic information about the specific meaning of the label. Two to three days after learning, the EEG was recorded while participants performed a lateralized oddball task. Newly acquired verbal category boundaries modulated low-level aspects of visual perception as early as 100–150 ms after stimulus onset, suggesting a genuine influence of language on perception. Importantly, this effect was not further influenced by enriched semantic category information, suggesting that bare labels and the associated minimal and predominantly perceptual information are sufficient for CP. Distinct effects of semantic knowledge independent of category boundaries were found subsequently, starting at about 200 ms, possibly reflecting selective attention to semantically meaningful visual features.

1. Introduction

Categorization is an important mechanism of human cognition or, as Lakoff put it, "…there is nothing more basic than categorization to our thought, perception, action, and speech" (Lakoff, 1987, p. 5). By means of neural mechanisms such as various forms of predictive coding, categorizing an object can be achieved intriguingly fast (Delorme, Rousselet, Macé, & Fabre-Thorpe, 2004), sometimes even as fast as merely detecting an object (Grill-Spector & Kanwisher, 2005). Taking into account the functional architecture of the brain, dynamic interactions of top-down and bottom-up processing set a plausible frame for cognitive factors such as expectations, previous knowledge, or language structures to serve as modulators of perception (Gilbert & Li, 2013; Lupyan, 2012). Concerning the relation between language and cognition it has been suggested that linguistic categories affect how we perceive our physical environment, a view that has typically been referred to as the Sapir–Whorf hypothesis (see Gentner & Goldin-Meadow, 2003; Levelt, 2013 for reviews). The language and thought debate has recently gained impetus following studies on the categorical perception (CP) of colors, demonstrating that colors from different verbal categories (e.g., green vs. blue) are discriminated faster than colors from the same category (e.g., different shades of blue; Gilbert, Regier, Kay, & Ivry, 2006; Regier & Kay, 2009; Winawer et al., 2007). Specifically, using a visual search task Gilbert et al. (2006) found a color CP effect in reaction times (RT) for stimuli presented in the right visual field (RVF), but not in the left visual field (LVF), an effect that extends to other stimulus domains such as animals (Gilbert, Regier, Kay, & Ivry, 2008). Given the special role of the left hemisphere in language processing (e.g., Caplan, 1994) these findings were discussed as evidence for stronger influences of linguistic representations on perceptual discrimination in the left hemisphere (e.g., Gilbert et al., 2006). However, Witzel and Gegenfurtner (2011) pointed out that the stimuli used in these previous studies may not have been psychophysically equidistant, which complicates the distinction between a bottom-up perceptual basis for CP and top-down factors such as language. In a series of experiments that sought to replicate lateralized CP with psychophysically well-controlled stimuli they found behavioral evidence for color CP, but no lateralization to the RVF (see also Liu, Chen, Wang, Zhou, & Sun, 2008). Moreover, whereas Witzel and Gegenfurtner (2011) questioned the lateralization of color CP to the RVF, recent results from Brown, Lindsey, and Guckes (2011) challenged the very existence of color CP under balanced

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perceptual conditions. Thus, one of the aims of the present study was to investigate CP while fully controlling physical stimulus features by using a learning design (see below).

Evidence on the time course of color CP has been provided by recent studies using event-related potentials (ERPs). Unlike most behavioral studies, several electrophysiological studies employed oddball paradigms to investigate CP, bearing the advantage of a well-known succession of visual ERP-components in these tasks (Boutonnet, Dering, Vinas-Guasch, & Thierry, 2013; Clifford et al., 2012; Holmes, Franklin, Clifford, & Davies, 2009; Mo, Xu, Kay, & Tan, 2011; Thierry, Athanasopoulos, Wiggett, Dering, & Kuipers, 2009). For instance, Holmes et al. (2009) reported earlier onset latencies of the P1 and N1 components, associated with low and high level visual perception in extrastriate cortex (Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2002) and spatial attention (Hillyard & Anllo-Vento, 1998), for deviants that crossed linguistic boundaries compared to deviants from the same category in a non-lateralized visual oddball task. Using a lateralized oddball paradigm and similar color stimuli as Gilbert et al. (2006), Mo et al. (2011), reported an effect of color term boundaries for stimuli presented in the right visual field on the visual mismatch negativity, a component taken to reflect preattentive change detection (cf. Thierry et al., 2009). These findings suggest that CP effects for colors are located at early stages before or during attentive visual perception, rather than later post-perceptual stages (but see Clifford et al., 2012).

Theoretically, CP can be explained in terms of feedback connections from areas associated with language processing and perceptual areas (e.g., Bar, 2004; Kveraga, Ghuman, & Bar, 2007). The effects of linguistic categories on perception described above can be accounted for by assuming feedback from (predominantly left-hemispheric) areas associated with language processing to perceptual regions in the brain (Gilbert et al., 2006). In line with this account, Lupyan (2012) pointed out that in CP, language exerts an on-line top-down influence on perceptual processes. For instance, mental representations could become transiently more categorical when a verbal label is activated. Lupyan (2012) argued that, if CP merely consisted of a perceptual long-term warping of the underlying mental representations, it would seem paradoxical that color CP can be disrupted by verbal interference, but not by comparable nonverbal interference (Drivonikou et al., 2007; Gilbert et al., 2006; Winawer et al., 2007; Witthoft et al., 2003). Accordingly, the fact that CP appears to be both deep, i.e. affecting basic perceptual processes, and shallow (i.e. disruptable) is best explained by assuming linguistic top-down influences on perceptual processes in a highly dynamic neurocognitive system. Specifically, if mental representations may become transiently more categorical in the sense that objects that belong to the same category are perceived as more similar because shared features relevant for categorization are highlighted or "warped" (Goldstone, Lippa, & Shiffrin, 2001; Lupyan, 2012), feature-based visual processing might play a major role in CP. We will test this idea with components of the event-related brain potential that are associated with low and high level aspects of visual feature processing and their integration (see below).

1.1. Learning studies on CP

Several studies have shown that CP can be induced by perceptual training (e.g., Clifford et al., 2012; Goldstone, 1994; Notman, Sowden, & Özgen, 2005; Özgen & Davies, 2002; see Goldstone & Hendrickson, 2010 for a review). For instance, in a study by Özgen and Davies (2002), participants acquired a new category-boundary in the green color space by sorting different shades of green into two categories. This led to a CP-effect comparable to the effect observed in the "natural" green–blue distinction (see also Clifford et al., 2012). Other findings on trained CP include the discrimination of geometric shapes (Goldstone, 1994), similarity ratings of faces (e.g., Stevenage, 1998) and discrimination of grating patterns, in the latter case with effects located in area V1 of the visual cortex (Notman et al., 2005).

These perceptual training studies show that CP can be acquired relatively fast and appears to rely at least partly on genuine perceptual mechanisms. However as new category boundaries were introduced via perceptual training, the specific role of language—independent of training—remains unclear. Thus, demonstrations of CP could be stronger evidence for a role of language if perceptual conditions were balanced, with category boundaries being introduced by an arbitrary assignment of verbal labels (Livingston, Andrews, & Harnad, 1998). Zhou et al. (2010) and Holmes and Wolff (2012) presented learning studies designed to test for CP based on new verbal categories with an equal amount of perceptual training in all conditions. In the study by Zhou et al. (2010), participants in the experimental group learned to label four color stimuli from the blue and green color spaces with pseudowords. Participants in the control group were exposed to the same color stimuli for the same amount of time, but without learning new categories or labels. Before learning, both groups showed stronger CP in the RVF for distinctions between stimuli crossing the preexisting green–blue linguistic boundary. In the visual search task after learning, the experimental group additionally exhibited stronger CP in the RVF for the new linguistic boundaries, whereas there was no change in the control group. The authors concluded that the acquisition of lateralized CP can thus be attributed to language.

In the study by Holmes and Wolff (2012), participants learned to sort silhouettes of four previously unfamiliar objects into two categories. The objects were either labeled with pseudowords or learned without labels. Subsequently, participants showed acquired CP lateralized to the RVF in a visual search task. Notably, this effect occurred in both learning conditions (i.e., with or without the acquisition of verbal labels). The authors concluded that lateralization of CP to the left hemisphere may not be based on language, but may instead reflect a general preference of the left hemisphere for categorical processing. This finding is in contrast to other studies demonstrating facilitated learning of new categories by arbitrary verbal labels in infants (Waxman & Markow, 1995) and adults (Lupyan, Rakison, & McClelland, 2007). Clearly, further research is needed to elucidate learning mechanisms, and the use of previously unfamiliar stimuli is a promising approach for investigating learned CP.

1.2. The meaning of verbal categories

One factor that still awaits systematic investigation is the specific influence of semantic contents of verbal categories in CP. It is unclear whether and to which extent categorical perception is influenced by the contribution of semantic knowledge about verbal categories. Because virtually all existing linguistic categories entail a minimal amount of meaning (see below), this question can only be addressed in a learning paradigm with initially unfamiliar stimuli and verbal labels.

During language acquisition the speaker or hearer implicitly establishes a link between a verbal label and a number of objects that are referred to with this label in the respective language (Bloom, 2002). Initially, this link is made on the basis of perceivable properties, which are common to these objects. At a later stage of language acquisition a learner is able to individually apply a category label to a newly encountered object on the basis of this knowledge (Aitchinson, 2012, chap. 18). We suggest that this is the minimal amount of meaning that is represented by category labels (in the following also called bare labels). However, typically, additional semantic knowledge about the objects of a given category is acquired, e.g., semantic knowledge about the functional properties of the members of a certain object category. This knowledge goes beyond perceptual properties and has to be learned more explicitly. This is what shall be called semantically enriched verbal category labels within the present study.

To date it is unclear what the relative contributions of bare labels and semantically enriched verbal labels to CP are. Studies on CP, even those that include the learning of new category boundaries (e.g., Clifford et al., 2012), typically involve stimuli that are well-established in semantic memory, such as colors (Gilbert et al., 2006; Winawer et al., 2007), animal species (Gilbert et al., 2008) or verbal material (Lupyan, 2008). However, semantic knowledge has been shown to shape visual perception. For instance, Mitterer, Horschig, Müsseler, and Majid (2009) reported that declarative world knowledge influences the perceived color of objects. Furthermore, expert knowledge about specific object categories such as dogs and birds (Tanaka & Curran, 2001) and verbally transmitted object-related semantic information (Abdel Rahman & Sommer, 2008; Rabovsky, Sommer, & Abdel Rahman, 2012) can influence early stages of visual perception, as indexed by the P1 and N1/N170 components. Moreover, Gauthier, James, Curby, and Tarr (2003) have observed faster responses in a sequential object matching task with novel objects that were associated with arbitrary semantic features (e.g., fast, friendly, heavy) when the objects had distinct compared to overlapping (shared) attributes, suggesting that semantic knowledge has a genuine influence on visual discrimination. Thus, visual perception and perceptual discrimination have been shown to be affected by linguistic categories and by semantic knowledge, but the relative contributions of the two factors and their potential interplay remain elusive.

Taking into account that concrete semantic contents of verbal categories do not only stress common conceptual attributes of the category members but may also highlight their shared perceptual features, a direct influence of semantic information on CP seems likely. Specifically, as it has been argued that verbal labels affect perception and categorization by selectively activating perceptual features that are diagnostic of the category (e.g., Lupyan, 2012), such selective enhancements of diagnostic perceptual features might be augmented by semantic information on visual object properties.

1.3. Aim of the present study

To distinguish CP induced by bare labels from semantically enriched verbal categories we employed a learning paradigm with initially unfamiliar yet realistic objects that were associated with distinct or shared novel verbal labels. Additionally, half of the verbal labels were associated with enriched semantic information about object functions that related to the visual appearance of the objects. As discussed above, semantic content may be a major source of verbal category effects, giving rise to or augmenting categorical perception. Alternatively, the effects of verbal labels and semantic knowledge associated with the labels may be independent and located at different processing stages.

The learning of initially unknown objects and categories additionally allowed us to investigate whether findings on CP hold for newly learned object categories. As suggested above, during language acquisition the link between a category label and certain perceptual properties that are representative for a category is made implicitly and depends on perceptual experience. In the present study the use of unfamiliar yet realistic objects about which participants had no previous knowledge allowed for a systematic investigation of such implicit category assignments. At the same time, the assignment of objects to conditions can be fully counterbalanced in a learning paradigm, thereby assuring a control of previous knowledge and low-level stimulus features. If implicit categorization processes for those new objects take place just like during natural language learning, effects of CP comparable to those reported for color or animal perception should be induced by either bare or semantically enriched labels or both.

As the lateralization of CP effects to the RVF has been an important element in the literature, visual perception of the newly learned objects was tested with a lateralized oddball task in which two objects were presented simultaneously, one in the right and one in the left hemifield. In the frequent standard trials, identical objects were shown, whereas in the rare deviant trials, a different object was presented in the left or right hemifield. Although in the literature behavioral CP effects have most reliably been observed in visual search paradigms, we expected to replicate a similar behavioral effect in the present oddball task. Specifically, we expected an interaction of category boundaries and visual field, because targets that belong to different verbal categories (the between-categories condition) should be detected faster when presented in the right compared to the left visual field. Furthermore, if the semantic content of verbal labels has an effect on CP, this interaction should be strengthened by semantic information.

We used event related potentials to gain insight into the time course and functional loci of CP effects. A genuine influence of verbal categories on perceptual processes should be reflected in components that are associated with low and high level visual processing, namely, the P1 and/or N1 components. The P1 peaks about 100–130 ms after stimulus onset and reflects processing of low-level visual object features. The neural generators have been localized in dorsal extrastriate cortex of the middle occipital gyrus (early phase) and in the ventral extrastriate cortex of the fusiform gyrus (late phase; Di Russo et al., 2002). The N1 component (peaking at about 150 and 200 ms) is taken to reflect higher-level processing of visual features and their integration during holistic processing of objects and faces. The generators of the N1 family—that may vary depending on the specific materials and the source localization procedure—have been located in bilateral occipito-temporal cortex and the fusiform gyrus (e.g. Bötzel, Schulze, & Stodieck, 1995; Rossion, Joyce, Cottrell, & Tarr, 2003) or in the posterior superior temporal sulcus (Itier & Taylor, 2004; Watanabe, Kakigi, & Puce, 2003; for a recent review, see Eimer, 2011).

Irrespective of the precise loci of the neural sources of the P1 and N1, both components are generated in areas subserving the visual processing of features and whole objects. Crucially, given the assumption that shared features may be highlighted or warped by shared verbal categories (Lupyan, 2012; see discussion above), low and/or high-level aspects of visual feature processing, as indexed by the P1 and N1 components, should be modulated. This effect may be enhanced by additional semantic information relating visual and functional object features. Furthermore, if lateralized CP is replicable, category boundaries should modulate early visual ERP components for target stimuli presented in the RVF, but not (or to a lesser degree) in the LVF. Again, we assumed that this interaction would be strengthened by semantically enriched verbal labels if the semantic content of the labels has an influence on CP. In contrast, if linguistic categories and semantic knowledge affect distinct perceptual or post-perceptual processes, different components should be modulated at different points in time.

2. Method

2.1. Participants

Twenty-four right-handed native German speakers (21 women and 8 men aged $M = 24.62$ years, $SD = 5.14$) with normal or corrected to normal vision participated in the experiment. Five participants were replaced due to technical problems with one of the response keys. No participants were excluded based on learning or task inaccuracy (see Section 2.3). None of the participants knew any of the objects before the experiment. Informed written consent was obtained before the experiment. Participants received either payment or course credit.

2.2. Materials

Object stimuli were grayscale photographs of eight rare objects that were unfamiliar to all participants with functions that could not be derived from the visual appearance. The stimuli were selected such that pairs of two objects were perceptually similar enough to be plausibly grouped into one category, but also distinct enough to be assigned to different categories, yielding four pairs of similar looking objects (see Fig. 1).

Stimuli were presented on a 17-inch monitor with a resolution of 1280×1024 pixels and a refresh rate of 100 Hz. In the oddball task, object pictures appeared on both sides of a fixation cross with a horizontal distance of 4.5° visual angle (measured from the central fixation cross to the center of the object picture). The size of each object picture was $2.6° \times 2.6°$. All stimuli were presented on a light blue background.

Object names were pseudowords consisting of three syllables (e.g., "Plonidex"). Every syllable appeared only in one object name. The names did not reveal any meaningful information about functional properties. Eight spoken descriptions containing semantic information about the objects and twelve filler stories containing object-unrelated information (cooking recipes) were recorded (duration $M = 18.1 \pm 1.3$ s and 19.2 ± 0.9 s, respectively). The

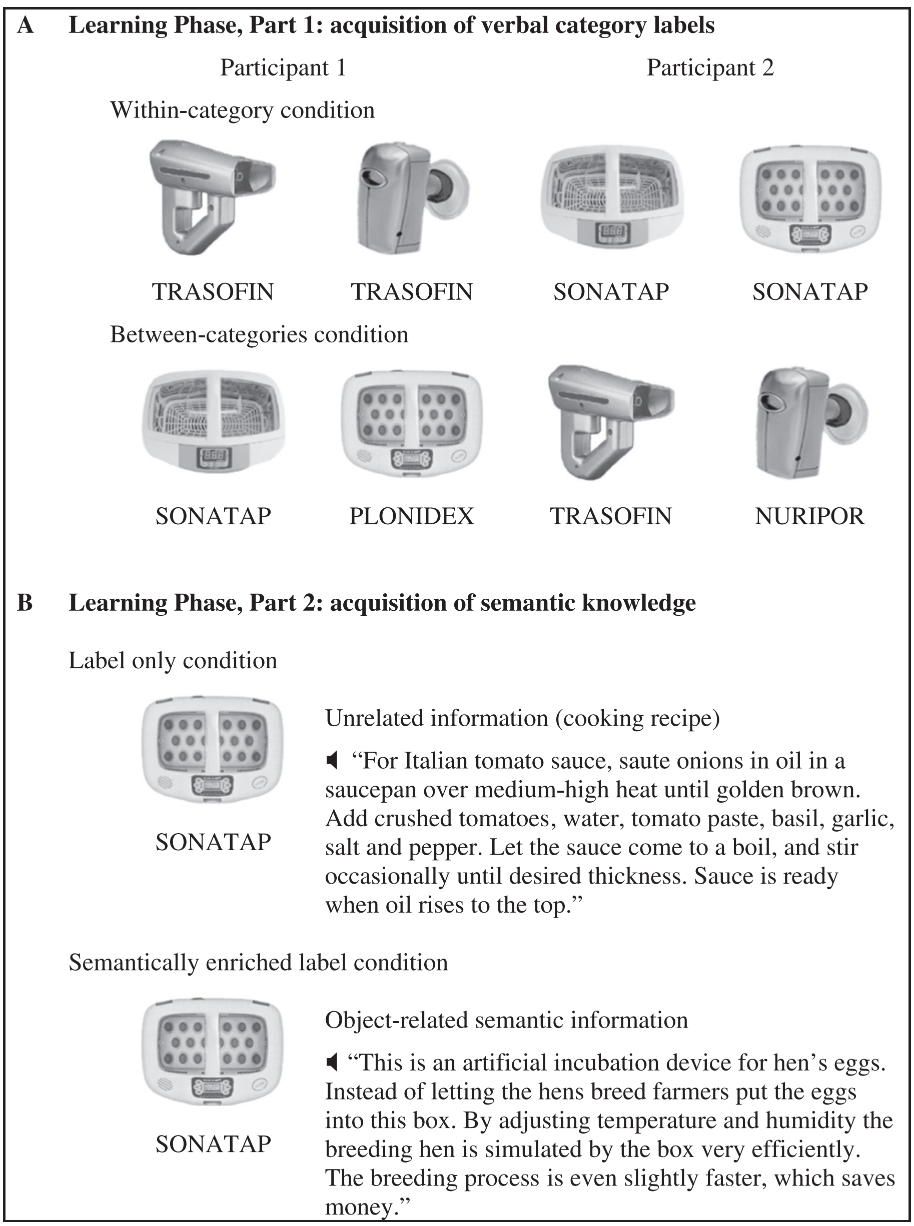

Fig. 1. Illustration of the learning conditions. (A) In Part 1, verbal labels were acquired. In the within-category-condition, objects were labeled with the same name. In the between-categories condition, objects were labeled with different names. The figure shows an example for two participants. Note that the category assignment of the four depicted objects is counterbalanced across Participants 1 (left) and 2 (right). With Participants 3 and 4 (not shown) full counterbalancing was achieved for all eight objects. (B) In Part 2, semantic knowledge was learned for half of the objects (semantically enriched label condition), whereas unrelated information was presented for the other half of the objects (label only condition). The factors *category* and *semantic knowledge* were manipulated orthogonally. Furthermore, the assignment of objects to learning conditions was counterbalanced such that, across participants, each object was presented equally often in each condition. Hence, visual experience during learning was equal for all participants.

semantic information referred to functional object attributes, mostly describing the use of the objects, thereby explaining perceptual object features (see Fig. 1 for examples).

Two object pairs were associated with the same and two were associated with different verbal labels, and one pair each was additionally associated with semantically enriched information in the form of the short stories described above. For the object pair sharing the same name, identical semantic information was given. In contrast, different semantic information was associated with objects that had different names. Thus, verbal category boundaries and semantic content of the categories were manipulated orthogonally. The assignment of the objects to conditions was such that, across all 24 participants, each object appeared equally often in each condition.

2.3. Procedure

The experiment consisted of a learning session and a test session two to three days after learning.

2.3.1. Learning session

In the learning session, participants first acquired the object names and subsequently the functional properties of the objects. With this stepwise procedure we aimed to avoid any influence of the semantic information on the initial learning of objects and names. The entire learning procedure lasted for about 45 min.

Before learning, a familiarity test was conducted. All eight objects were presented and participants were instructed to indicate whether they knew any of the objects. If all objects were unknown the learning session was started (see Table 1 for a summary of the learning session). In Part 1 the participants were familiarized with all eight rare objects and their names. Each object was presented for 3 s with the to-be learned name written next to it. Additionally the name was presented auditorily. After a fixation interval, the object picture reappeared with a question mark next to it, indicating that the name should be produced for rehearsal. Feedback about the correct object name was given by displaying the name again. After all eight objects were presented once in random order, there was a short self-paced break. This procedure was repeated four times (see Table 1). At regular intervals, the participants saw an overview of all eight objects with their associated names. At each new presentation of the overview, objects were presented at different random positions.

In Part 2 of the learning session, participants acquired semantic background information about half of the objects' use and origin. For the other half of the objects, randomly assigned unrelated information (cooking recipes) was presented. No cooking recipe was presented twice to avoid possible associations between objects and recipes. By presenting auditory input with all objects, perceptual similarity between conditions was maintained and differences in the learning phase were minimized. The sequence was analogous to Part 1, but this time the objects remained on the screen for 21 s while related or unrelated information was presented auditorily. After listening to each story, participants rehearsed the object name and received feedback as in Part 1. Fig. 1 illustrates the knowledge acquired during Parts 1 and 2. In Parts 3 and 4, participants further rehearsed the acquired object names, with Part 4 including no more feedback about the correct object name (see Table 1).

At the end of the learning session, a naming test was conducted. The test consisted of eight blocks with all objects presented in each block once in randomized order. Naming latencies were measured with a voice key. As soon as the naming response was registered, the object picture disappeared. Participants were instructed to name the pictures as fast and accurately as possible. The data of one participant had to be excluded due to technical problems with the voice key. Naming latencies were shorter in the within-category condition (M = 819.36 ms, SD = 224.31 ms) compared to the between-categories condition (M = 942.70 ms, SD = 306.35 ms), $F(1,22) = 22.52$, $p < .05$, $\eta_p^2 = .51$. This effect is most probably due to the fact that the labels in the within-category condition have been associated with two instead of only one object and therefore have been presented and learned twice as often. Error rates (ERRs) were low (mean percentage over all conditions: M = 3.87%, SD = 1.86%) and not further analyzed.

2.3.2. Test session

The test session took place two to three days after learning and lasted about 90 minutes. Before starting the test session participants were familiarized with the task by completing a short training session with commonly known objects (chairs and tables). We employed a lateralized visual oddball task. Two object pictures were presented simultaneously on the left and right side of a central fixation cross. In 70% of the trials object pictures were identical on both sides (standard trials), but in 30% a different object appeared on one side and served as a target stimulus (deviant trial). The target stimulus appeared equally often in the LVF and the RVF. Participants were instructed to maintain central fixation and to respond as accurately and fast as possible to the target stimulus by pressing the left or right button with the index finger corresponding to the presentation side of the target. Importantly, the information acquired in the learning session was irrelevant for task performance.

Each trial started with a fixation cross at the center of the screen for 300 ms. Next, object pictures were shown on both sides of the fixation cross for 200 ms. Manual responses were recorded from the onset of object presentation until 800 ms after offset. The duration of a single trial was 1.3 s. Each object served once as a standard and once as a target stimulus, resulting in eight combinations of standard stimulus and target stimulus. Accordingly, the test session was subdivided into eight blocks presented in random order. Each block consisted of 200 trials, which comprised 60 deviant and 140 standard trials. The trials within each block were randomized, yet each block started with the presentation of at least four standard trials. The object serving as target was shown once in the instruction displayed prior to each block. The test session consisted of a total of 1600 trials, containing 1120 standard trials (70%) and 480 deviant trials (30%), i.e., 60 deviant trials per condition.

Note that all participants were tested with the same displays, but had acquired different knowledge during learning. While two

Table 1
Summary of stages in the learning session.

Parameter	Part 1	Part 2	Part 3	Part 4	Part 5 (test)
Content	L	SEM, L	L	L	L
Verbal information type	Auditory + written	Auditory (SEM) + written (L)	–	–	–
Object presentation duration	3 s	21 s	3 s	3 s	Until response
Feedback	Yes	Yes	Yes	No	No
Repetitions	4	3	8	8	8
# Overview	1	1	4	4	–

Note. In Parts 1 and 2 labels and semantic information were introduced, respectively. In Parts 3 and 4, labels were rehearsed. L = labels; SEM = semantic information (object function or unrelated information).

objects had different labels for Participant 1 (between-categories), they had the same label for Participant 2 (within-category). Furthermore, for Participants 3 and 4, the labels were semantically enriched (with a between-categories and a within-category assignment, respectively). Hence, there were no visual differences between the experimental conditions in the test session.

After the test session, participants filled in a questionnaire assessing whether they could remember the object names and keywords describing the background information acquired in the learning session. Concerning the names, accuracy was M = 88.54% (SD = 18.72%). Spelling errors (e.g., "Fenebec" instead of "Fenipec") did not lead to any exclusions because the category assignment was not compromised, i.e. the same names were given to objects in the within-category condition and different names in the between-categories condition. Concerning the semantic background information, accuracy was M = 95% (SD = 10%). 20 participants remembered all pieces of background information and 4 participants partially remembered the information. Because in no case was the between-categories assignment severely compromised, we decided to keep all participants. In sum, we considered recall accuracy of verbal labels and semantic information after the test session as acceptable for subsequent analyses, and no participant was excluded based on the questionnaire.

2.4. EEG data recording and analysis

The electroencephalogram (EEG) was recorded with sintered Ag/AgCl electrodes at 64 scalp sites according to the extended 10–20 system. The sampling rate was 500 Hz. During recording, a low-cutoff filter (.032 Hz), a high-cutoff filter (70 Hz) and a notch filter (50 Hz) were applied. All electrodes were initially referenced to the left mastoid. Electrode impedance was kept below 5 kΩ. Electrooculograms (EOGs) were recorded from the left and right outer canthi and from above and below the left eye. Prototypical eye movements for later artifact correction were obtained in a calibration procedure. Offline, the continuous EEG was re-referenced to a common average reference and low-pass filtered at 30 Hz. Eye movement artifacts were removed with a spatio-temporal dipole modeling procedure using the BESA software (Berg & Scherg, 1991). Remaining artifacts were eliminated with an automatic artifact rejection procedure (amplitudes exceeding ±200 μV or changing by more than 50 μV between two successive samples or by 200 μV within intervals of 200 ms). Error- and artifact-free EEG data were segmented into epochs of 1.4 s, starting 400 ms prior to object picture onset, including a 100 ms pre-stimulus baseline interval. ERPs were time-locked to stimulus onset.

Differences between conditions were analyzed for 50 ms time windows with repeated measures ANOVAs. Analyses focused on activity related to early visual processing (i.e., P1 and N1 components), for which we selected regions of interest (ROIs). For the P1, the ROI comprised the electrodes O1, O2, and Oz, analyzed in the time window 100–150 ms. For the N1, the ROI consisted of electrodes P7, PO7, O1, P8, PO8, and O2 between 150 ms and 200 ms. Furthermore, we conducted an overall analysis across all electrodes which additionally included the factor *electrode site* (62 levels). Because an average reference was used, only interactions with the factor *electrode site* are reported as main effects in the overall analyses. Huynh-Feldt corrections (Huynh, 1976) were applied where appropriate.

3. Results

3.1. Behavioral results

Mean RTs and ERRs for all experimental conditions are presented in Fig. 2. RT differences between conditions were tested with a repeated measures ANOVA with the factors *category* (within-category vs. between-categories), *semantic knowledge* (label only vs. semantically enriched label), and *visual field* (LVF vs. RVF). Responses were faster to deviants in the RVF (M = 415.86 ms) than in the LVF (M = 440.86 ms), as confirmed by a main effect of *visual field*, $F(1,23) = 32.65$, $p < .05$, $\eta_p^2 = .59$. Concerning the crucial interaction between the factors *category* and *visual field*, RTs in between-categories condition were slightly slower in the between-categories condition (M = 444.97 ms) than in the within-category condition (M = 436.76 ms) in the LVF. In the RVF, there was virtually no difference between *category* conditions (M = 417.00 ms in the between-categories condition vs. M = 414.72 ms in the within-category condition). However, the interaction between *visual field* and *category* did not reach significance, $F(1,23) = 3.51$, $p = .07$, $\eta_p^2 = .13$. Concerning the factor *semantic knowledge*, RTs were faster for targets in the label only than in the semantically enriched label condition (M = 426.55 vs. 430.17 ms; $F(1,23) = 4.41$, $p < .05$, $\eta_p^2 = .16$), suggesting that additional functional knowledge slowed down the visual discrimination of objects—irrespective of verbal category boundaries. No further effects reached statistical significance. Notably, there was no interaction between *visual field, category* and *semantic knowledge*. Error rates (ERRs) were low (M = 0.87%, SD = 0.48%) and not further analyzed.

3.2. EEG results

Although not the main focus of the study, standard and deviant trials were compared in order to characterize the oddball response. Differences were tested using a repeated measures ANOVA with the factors *trial type* (standard vs. deviant) and *electrode site* (62 levels). In order to match the number of standard and deviant trials entering the ANOVA, a random sample of 450 standard trials was selected from every participant's dataset. The ERP responses to deviant and standard trials started to diverge around 150 ms after stimulus onset, with a more negative-going curve for deviants between 150 and 350 ms, $Fs > 3.01$, $ps < .05$, $\eta_p^2 > .12$. This was followed by a more positive-going P3 for deviants compared to standards, yielding a statistically significant difference (between 350 and 600 ms: $Fs > 27.27$, $ps < .05$, $\eta_p^2 > .46$). These effects suggest that deviant trials elicited reliable target responses typical for visual oddball paradigms requiring an overt response (e.g., Herrmann & Knight, 2001).

ANOVAs on deviant trials included the factors *semantic knowledge* (label only vs. semantically enriched label), *category* (within-category vs. between-categories) and *visual field* (LVF vs. RVF). For deviants in the RVF, P1 amplitudes were higher in the between-categories compared to within-category condition, whereas there seemed to be no difference in the LVF. This was confirmed by a significant interaction between *category* and *visual field* in the P1 ROI, $F(1,23) = 10.05$, $p < .05$, $\eta_p^2 = .30$ (see Fig. 3). Separate comparisons for the RVF and the LVF, with the factors *category* and *semantic knowledge* yielded a significant effect of *category* in the RVF, $F(1,23) = 7.73$, $p < .05$, $\eta_p^2 = .25$, and no effect in the LVF, $F(1,23) = 1.56$, $p = .23$, $\eta_p^2 = .06$. No interaction between *category* and *semantic knowledge* was observed in either visual field ($F(1,23) = 0.76$ and $F(1,23) = 0.17$ in the RVF and LVF, respectively). ERPs and topographies illustrating the P1 results are presented in Fig. 3. Furthermore, semantic knowledge appeared to increase the P2 amplitude, as illustrated in Fig. 4. Accordingly, the ANOVA across all electrodes revealed a main effect of *semantic knowledge* between 200 ms to 250 ms, $F(61,1403) = 2.32$, $p < .05$, $\eta_p^2 = .092$, i.e. in the time window corresponding to the P2 component. Concerning the N1 component, the analysis revealed no effects.

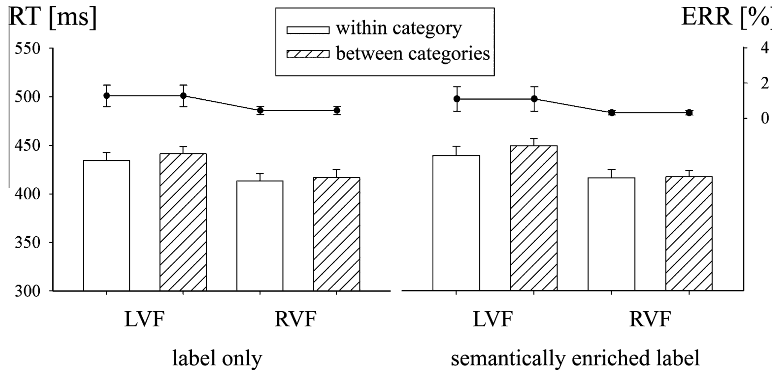

Fig. 2. Behavioral results. Mean reaction times in ms (RTs; bars) and error rates (ERRs; dots) in the oddball task, with the factors *semantic knowledge* (left: label only; right: semantically enriched label), *visual field* (left part: LVF; right part: RVF) and *category* (white: within category; striped: between categories). Error bars represent one standard error of the mean.

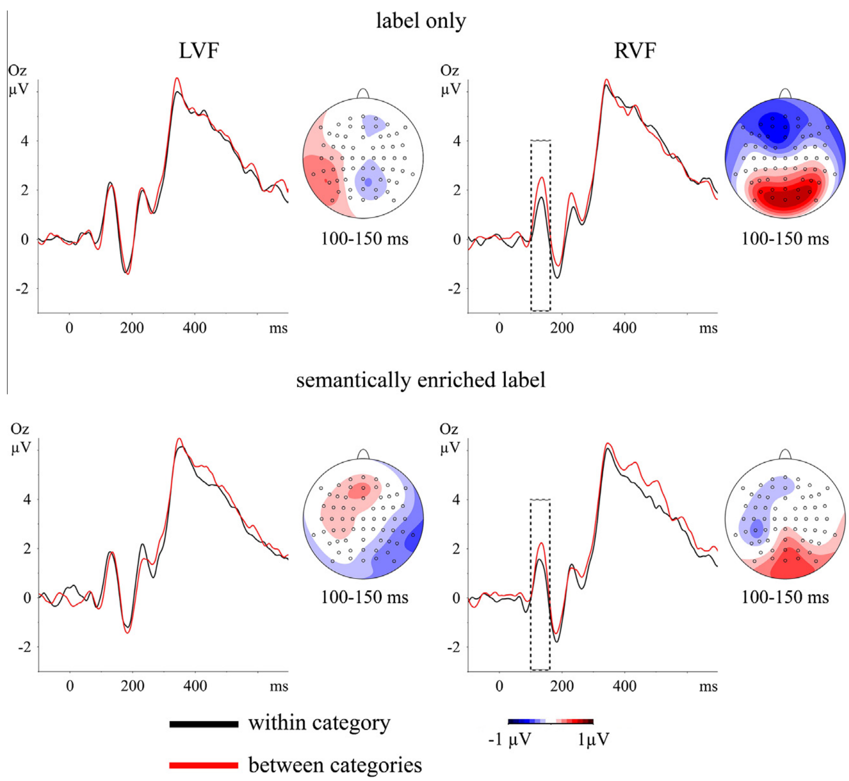

Fig. 3. P1-effect. Effect of the factor *category* in the P1 time window (100–150 ms) with the factors *semantic knowledge* (top: label only condition; bottom: semantically enriched label condition) and *visual field* (left: LVF; right: RVF). ERPs represent grand means at electrode Oz. Positive is plotted upward. Topographies represent difference maps of between- minus within-category deviants in each condition.

4. Discussion

In the present study we extend findings on CP to newly learned categories, investigating the time course of linguistic top-down effects on visual object perception while controlling for prior knowledge and low-level visual stimulus features. The main goal was to determine how semantic content of verbal labels contributes to CP.

In a learning phase participants acquired information about the verbal category label of initially unfamiliar objects. Additionally, we varied the semantic content of verbal categories which was learned either in the form of bare labels without accompanying explicit semantic information or as labels associated with semantically enriched information on functional object attributes relating to their visual appearance. It was assumed that confronting participants with objects that share some visual properties and a common verbal label would induce an implicit process of category forming, whereas the additional semantic knowledge given for some labels provided more explicit information, thus resulting in more explicit learning of categories that are anchored in the conceptual system.

Behaviorally, the expected pattern of slower RTs for between- compared to within-category deviants, in particular in the RVF, was not observed. This might be due to the employed learning design. In contrast to the majority of studies on CP that used well-known stimuli with established representations in long-term memory even if they were associated with novel labels, here we presented objects that were unfamiliar to the participants prior to the experiment. However, the effects of verbal category labels possibly depend to some degree on perceptual experience or

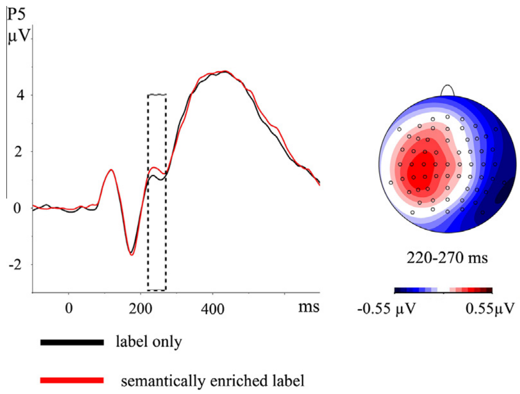

Fig. 4. Semantic knowledge effect. Illustration of the effect of *semantic knowledge* in the P2 time window. Left: Grand means of the label only condition (black line) and semantically enriched label condition (red line) at electrode P5. Positive is plotted upward. Right: Topography of the semantic effect (difference map of deviants in the label only minus deviants in the semantically enriched label condition).

training with those categories. Alternatively, the detection of lateralized targets in the oddball task might have been too shallow to reveal subtle behavioral CP effects compared to, for instance, a more demanding visual search task (Gilbert et al., 2006).

As an unexpected result, a general benefit for reacting to targets in the RVF was observed. We did not have a hypothesis concerning a main effect of this factor, but we attribute the observed RVF benefit to the fact that all participants were right-handed. As the task required manual reactions that were compatible to the side of the deviant stimulus, effector speed (a right hand advantage) is the most likely explanation for this pattern.

4.1. CP in early visual ERPs

With regard to ERPs, there were three main findings. First, verbal category boundaries modulated early visual processing of objects presented in the RVF, reflected in amplitude modulations of the P1 component. Second, concerning the semantic richness of verbal categories, minimal linguistic knowledge in the form of bare labels that are not explicitly associated with specific semantic information appears to be sufficient to induce such effects. They were not further enhanced by semantically enriched labels. Third, additional semantic information had a separate effect at subsequent processing stages that was independent of category boundaries.

Whereas the lateralization of color CP to the RVF (Witzel & Gegenfurtner, 2011), and the very existence of color CP under balanced perceptual conditions has been challenged (Brown, Lindsey, & Guckes, 2011), our ERP results concerning the P1 component are in support of lateralized CP in the domain of visual objects. Thus, given the perceptual control achieved with the present experimental design, our data strongly suggest that CP can be induced by linguistic conceptual knowledge. Because the P1 reflects low-level aspects of visual perception, our data can also be taken as evidence for a perceptual, rather than a post-perceptual, locus of CP, suggesting that perception of complex objects is susceptible to linguistic knowledge.

This finding is in line with recent accounts of visual perception that include feedback between higher cortical areas and areas supporting sensory visual processing (e.g., Gilbert & Li, 2013; Kveraga et al., 2007). In contrast to the clear distinction between "pure" early vision and separated subsequent post-perceptual cognitive processing (e.g., Pylyshyn, 1999) several studies have demonstrated that conceptual knowledge, predictions or expectations can modulate even very early stages of visual perception (see Gilbert & Li, 2013, for a review). Interactions between top-down and bottom-up processing via direct feedback connections between cortical areas and cascading top-down feedback can render object categorization extremely fast (Delorme et al., 2004; Grill-Spector & Kanwisher, 2005; Kveraga et al., 2007). A study by Foxe and Simpson (2002) circumscribed a possible time frame for interactions between "higher" cortical regions and occipital regions supporting visual sensory processing. Their results suggest that the P1 represents sustained visual activation that already includes several iterations of feedback from other cortical regions, rather than the initial volley of feed forward sensory processing. Thus, in general, given the functional architecture of the brain, top-down feedback may be a vehicle for linguistic categories to modulate—and improve—visual processing by generating predictions useful in guiding behavior (in this case object discrimination).

More specifically, we have based our predictions concerning visual ERP components on a theoretical account that includes the highlighting or warping of relevant visual features of within-category members (Goldstone et al., 2001; Lupyan, 2012), assuming that such changes in feature processing should be reflected in ERP components associated with high- and low-level feature analysis and integration. Indeed, we find an amplitude modulation of the P1 with a smaller amplitude in the within category condition. So in the present data, categorical warping could consist of a top-down driven sensory amplification of visual features via feedback involving language- and possibly also object-selective regions (Folstein, Palmeri, & Gauthier, 2013) that modulate sustained activation patterns in ventral extrastriate cortex, thus reflected in the P1.

To our knowledge, this study presents the first report of lateralized CP in P1 amplitude modulations, and while we have not made clear predictions on the direction of amplitude effects, a possible speculation about the underlying mechanism may be that the temporal warping or highlighting of categorically shared features results in facilitated processing of these common features, which in turn may be reflected in a reduction of P1/N1 amplitudes. In line with this idea of facilitatory effects, a recent study has demonstrated that the presentation of verbal labels results in an earlier (i.e., facilitated) detection of objects in a continuous flash suppression paradigm (Lupyan & Ward, 2013).

In our view the most likely possibility to solve the oddball task is to react to deviants by detecting an object change compared to the standard within the visual fields. In this scenario, the relative P1 amplitude reduction in the within-category condition can be readily explained in terms of the categorical warping framework: Targets in the within- compared to the between-categories condition elicit a weaker oddball response in the P1 because they appear more similar to the standard object due to categorical warping. This could be implemented in the brain by a priming mechanism: a bigger number of shared (warped) visual features is pre-activated by the standard for the within- relative to the between-categories deviant. As a consequence, neurons representing relevant visual features of the within-category deviant are primed and the perception of the stimulus is facilitated, reflected in reduced P1 amplitudes.

Although usually associated with ERP components of the N1 family (Keil & Müller, 2010), visual feature-sensitive processing may also be visible in the P1 (Zhang & Luck, 2009). For instance, Thierry et al. (2009) reported non-lateralized color CP in a cross-linguistic design in the visual mismatch negativity. Interestingly, their data also suggested that some part of the effect might start earlier, as revealed by mixed modulations of P1 peak latency and amplitude that differed between native Greek and native English participants. The fact that we find a modulation of the P1 rather than the temporally subsequent N1 may in part be due to the blocked presentation of the *category* conditions (Zhang & Luck,

2009) and the uniform rhythm of stimulus presentation in the present experiment, causing verbal labels to be constantly activated throughout each experimental block.

Finally, the present lateralized oddball task—even though frequently used in EEG studies on CP—may reflect aspects of stimulus detection more than discrimination. However, we consider the consequences of categorical perception on detection just as interesting as discrimination, and recent evidence indeed suggests that language can "boost otherwise unseen objects into visual awareness" (Lupyan & Ward, 2013).

4.2. Facilitation of lexical access vs. category boundaries

In addition to their constant activation, the accessibility of the labels as such may play a critical role for top-down effects on perception. In the present study, whereas care was taken during learning that all object pictures were presented equally often, the labels in the within-category condition were presented and rehearsed twice as often as in the between-category condition because each label was associated with two different object pictures. Besides generally strengthening the within-category lexical representations and lexical access, as indicated by faster naming times at the end of the learning session, this may result in a strong co-activation of the common label in the within-category condition when both objects are presented. Although this introduces a possible confound in the factor *category*, the manipulation still remains purely linguistic. In line with the discussed pre-activation of the labels due to the design of the experiment (see above), more easily accessible and more strongly active labels might induce enhanced "warping" of perceptual features compared to the ones with less accessible labels, resulting in reduced P1 amplitudes in the within-category condition.

4.3. The role of additional semantic knowledge

The lack of an interaction of verbal category boundaries and additional semantic knowledge is contrary to our hypothesis that semantically enriched verbal categories should have a greater influence on object perception. If anything, additional semantic knowledge weakened the effect of verbal category labels in the P1 component (see Fig. 3). Thus, as a core finding, our data suggest that categorization on the basis of an implicitly made link between a verbal label and perceptual properties can be sufficient to produce CP effects in early visual perception (see also Holmes & Wolff, 2012 for results pointing in the same direction).

Instead of the expected interaction with category boundaries, separate effects of explicitly learned additional semantic knowledge were observed in RTs and ERPs in the time range of the P2 component. Additional semantic knowledge had an inhibitory effect on RTs, with slower RTs for targets associated with semantically enriched labels. Semantic modulations of the visual P2, induced by sentence contexts, have been found in the processing of words (Federmeier, Mai, & Kutas, 2005) and pictures (Federmeier & Kutas, 2002). However, unlike in our data, this effect on the P2 was restricted to stimulus presentation in the RVF. Thus, this P2 effect might well reflect more general semantic mechanisms. Mental representations of objects in the semantically enriched label condition may be more complex than those of objects associated with bare labels, therefore inducing deeper semantic or more attentive processing. Yet, as can be seen in Fig. 4, the scalp distribution of the effect reported here is slightly left lateralized. This might indicate a general attention bias to the RVF that is enhanced for objects associated with semantically enriched verbal labels. Such a left-hemispheric attention bias would be in line with the lateralized early effects in the P1. Even though not directly predicted, these findings are interesting because they suggest that semantic knowledge may influence object detection despite the fact that this knowledge was entirely irrelevant for task performance. However, before drawing firm conclusions this effect should be replicated.

4.4. Conclusions

The lateralization of linguistic effects on visual perception to the right hemifield, in association with a special involvement of the left hemisphere of the brain in language processing, has been an important argument in the language and thought literature. Here, we present evidence for a lateralized CP effect in early ERP components, suggesting a perceptual locus of CP, demonstrating that CP, most often described for colors, can also be observed for complex objects even when they were unfamiliar prior to learning. Most importantly, the present results suggest that the association of objects with bare verbal labels is sufficient to modulate visual perception and that the enrichment of the labels with additional semantic information on conceptual attributes of the category members and semantic references to their visual features does not seem to significantly enhance categorical perception effects. Thus, a common verbal label can induce implicit learning of common perceptual properties that allow grouping of the respective objects into one category, and lead to CP. The fact that CP was observed several days after learning indicates that new category labels can alter perception in the long term, even without explicit perceptual category training (cf. training studies by Clifford et al., 2012; Goldstone, 1994; Notman et al., 2005; Özgen & Davies, 2002). Tentatively, the time course of linguistic effects on object perception can then be sketched like this: while verbal category boundaries modulate low-level perceptual processes, semantic knowledge has an impact on object-based or selective attention. This is in line with the notion that language exerts an on-line influence on perception, with different aspects of linguistic knowledge modulating distinct processing stages involved in object perception.

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