Précis of
Language, Meaning, and Visual Perception: Event-Related Potentials Reveal Top-Down Influences on Early Visual Processing

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Introduction

Language is assumed to transform human cognition—for instance, it may shape the way our cognitive systems represent knowledge about the world (Lakoff, 1987; Lupyan & Clark, 2015; Lupyan & Lewis, 2017). Crucially, language creates categories, for example when we divide the continuous spectrum of perceivable light using discrete color words (Boroditsky, 2012). Across languages, there is variation in how concepts are categorized linguistically, or whether a concept is put into words at all (Boroditsky, 2012; Lakoff, 1987). There is a long-standing and controversial debate in cognitive science on the idea of linguistic relativity (reviewed by Gumperz & Levinson, 1996). Are cross-linguistic variations associated with differences in cognition? Recently, the linguistic relativity hypothesis has gained new impetus from experimental work on the relation between linguistic categorization and perception (Maier, Glage, Hohlfeld & Abdel Rahman, 2014; Regier & Kay, 2009; Winawer et al., 2007). If language has the potential to influence how we see the world, this leads right to another, arguably even bigger current controversy in cognitive science: cognitive penetrability of perception (Firestone & Scholl, 2016; Raftopoulos & Lupyan, 2018). On one hand, cognitive factors like linguistic categorization and semantic knowledge might influence ongoing perceptual processing in a top-down fashion (e.g., Lupyan 2012, 2017a; 2017b). On the other hand, such effects may not concern perception itself, but only pre-perceptual shifts of attention or downstream processes, such as perceptual judgment (Firestone & Scholl, 2016; Raftopoulos, 2017). Progress on this question would improve our understanding of human sensation and perception and contribute directly to a variety of fields of cognitive science, including philosophy, psychology, psychophysics and cognitive neuroscience. This dissertation therefore approached linguistic relativity, along with influences of semantic knowledge, within the broader framework of top-down effects on perception. By combining novel and well-balanced experimental designs with electroencephalography (EEG), the individual studies directly addressed key arguments in the cognitive penetrability debate.

Competing perspectives on cognitive penetrability

Current influential accounts of perception underline the role of predictive processing (e.g., Clark, 2013). In this view, perception is seen as a process of active inference in which priors guide top-down predictions of sensory input. Both, language and semantic knowledge could be major sources of information for top-down predictions. Language, because of the way it evokes conceptual categories: verbal labels may transiently warp perceptual space, such that visual features that are diagnostic of a linguistic category are highlighted, while features unique to individual exemplars are discounted (Lupyan & Lewis, 2017). It has thus been proposed that linguistic relativity should be seen “through the lens of probabilistic inference” (Regier & Xu, 2017).

The first two studies of this dissertation were dedicated to categorical perception—the observation that stimuli from different linguistic categories are easier to discriminate than stimuli from the same category (e.g., Winawer et al., 2007). Regarding semantic knowledge, what we know about an object provides information about the context we usually encounter the object in and explains its visual appearance (e.g. characteristic details or its prototypical color), such that visual object features matching that semantic knowledge are predicted with higher certainty (e.g., Hohwy, 2013). This possibility was explored in Studies 1 and 3.

However, the idea that cognition affects perception at all is facing strong counterarguments (Firestone & Scholl, 2016; Raftopoulos, 2017). The first key argument is that empirically, no study so far has shown unequivocal evidence for top-down effects on perception, because all studies contain confounds in study design, such as bottom-up perceptual differences between conditions (Firestone & Scholl, 2015, 2016). The second key argument is that, although cognitive factors such as knowledge may change performance in perceptual tasks, this does not necessarily imply that perceptual processing proper is concerned. Rather, effects could reflect either pre-perceptual shifts in peripheral attention (i.e. before a stimulus is presented), changing the input perception acts upon, or downstream post-perceptual cognitive processing, such as judgments, memory, or response selection. This would leave early perceptual processing encapsulated (Firestone & Scholl, 2016; Pylyshyn, 1999; Raftopoulos, 2017).

Moving forward: a case for event-related potentials

The critical question concerning cognitive penetrability of perception appears to be about timing: In the impenetrability view, cognitive factors can modulate processing before and after perception only. Cognitive penetrability, in contrast, would allow for direct modulations of ongoing perceptual processing. My dissertation exploited the high temporal resolution of event-related potentials (ERPs) of the EEG to tackle this issue. Visual ERP-components with well-studied functional significance allowed locating effects at early perceptual vs. pre- or postperceptual processing stages.

Experiments were carefully designed to avoid empirical pitfalls such as pre-perceptual shifts of attention, bottom-up visual differences between conditions, or response bias. Given these premises, effects of linguistic categories and semantic knowledge on ERP components that reflect early visual processing can be interpreted as genuine top-down effects on visual perception. Components taken to reflect early visual processing were the posterior P1 and N1 components (Foxe & Simpson, 2002; Raftopoulos, 2017). The P1, peaking around 100 ms after stimulus onset, is mostly sensitive to low-level stimulus properties, such as lightness and contrast (Luck, 2014; Pratt, 2011). The N1 peaks around 135–200 ms after stimulus onset and is taken to reflect an early stage of configural visual processing (Rossion, 2011; Tanaka & Curran, 2001).

Aims of the studies

The aim of Studies 1 and 2 was to critically test if categorical perception can be a genuine top-down effect on perception. Study 1 tested if learning new linguistic categories for unfamiliar objects influences visual discrimination in a visual search paradigm.

Additionally, to better understand the nature of linguistic representations that induce categorical perception, categories were learned either based on bare verbal labels, object-related semantic knowledge, or both. Study 2 used a cross-linguistic approach and the attentional blink paradigm to investigate whether categorical perception of colors has previously unknown consequences for the access to visual consciousness. Does our native language influence what we can and can't see?

The aim of Study 3 was to take a different perspective on top-down effects of semantic knowledge and to directly "observe" top-down predictions by investigating mental imagery, i.e. visual processing in the absence of the appropriate sensory input (Kosslyn, Ganis & Thompson, 2001). Can top-down predictions carry knowledge effects all the way into early visual processing?

Studies 1–3 used recently developed single-trial-based analyses of ERP-components using linear mixed effects models (LMMs). Study 4 describes the analysis of ERPs with LMMs in detail and explains their advantages over other widely used methods. The EEG analysis pipeline was made freely available to the scientific community. Studies 1–4 are summarized in the following section.

SUMMARY OF STUDIES

My dissertation consists of four manuscripts that were submitted to peer-reviewed journals and a synopsis that collectively introduces and discusses the individual studies. The current references for each manuscript are:

Study 1

Maier, M., & Abdel Rahman, R. (2019). No matter how: Top-down effects of verbal and semantic category knowledge on early visual perception. *Cognitive, Affective, & Behavioral Neuroscience*. doi:https://doi.org/10.3758/s13415-018-00679-8

Study 2

Maier, M., & Abdel Rahman, R. (2018). Native Language Promotes Access to Visual Consciousness. *Psychological Science, 29*(11), 1757-1772. doi:10.1177/0956797618782181

Study 3

Maier, M., Frömer, R., Rost, J., Sommer, W., & Abdel Rahman, R. (2018). *Mental imagery and visual perception: shared cognitive mechanisms and similar time course*. Manuscript submitted for publication.

Study 4

Frömer, R., Maier, M., & Abdel Rahman, R. (2018). Group-Level EEG-Processing Pipeline for Flexible Single Trial-Based Analyses Including Linear Mixed Models. *Frontiers in Neuroscience, 12*(48), 1-15. doi:10.3389/fnins.2018.00048

No matter how: Top-down effects of verbal and semantic category knowledge on early visual perception (Study 1)

Linguistic categories differ in semantic richness—and semantic knowledge, in turn, can affect perception of objects and written words (Abdel Rahman & Sommer, 2008; Lupyan, 2017b; Rabovsky et al., 2012a). Knowledge effects have been observed in ERP-signatures of early visual processing (P1 component) and higher-level semantic processing (N400 component; Abdel Rahman & Sommer, 2008; Rabovsky et al., 2012a). So both, linguistic categories and semantic knowledge may entail top-down modulations of visual perception, but research is only beginning to explore their interaction (Maier et al., 2014).

To better understand the nature of linguistic representations involved in categorical perception, this study tested three alternatives. First, verbal labels might take on a special role in categorical perception because of a unique suitability to evoke categorical representations (Lupyan, 2012). For instance, priming visual perception with verbal labels (e.g., "cat") works better than priming with semantically related cues (e.g., meowing; Boutonnet & Lupyan, 2015). Accordingly, typical categorical perception effects might be observed only for categories learned with a singular, consistent label, but not (or to a lesser extent) for categories without a consistent category label. Second, the depth of semantic knowledge associated with a linguistic category might make a difference. According to embodied approaches to linguistic representations, meaning is grounded in perception, action, and emotion (e.g., Glenberg & Gallese, 2012). Categorical perception could result from the combined meaning of category labels and associated semantic knowledge, such that semantically richer, more palpable categories should lead to stronger effects. Third, the driving factor could be that there is a category at all, such that any information allowing categorization (e.g., a label or semantic knowledge without a label) should lead to categorical perception. This view is supported by one behavioral study suggesting that categories need not be labeled in order to induce CP and that it is sufficient to learn that two objects "go together" (Holmes & Wolff, 2012).

We employed a learning paradigm in which participants associated unfamiliar objects with their names (pseudowords, e.g., "Calimat"), their function (e.g., egg breeding device), or both. Each bit of information was shared by one pair of objects, thus creating linguistic categories with varying degrees of semantic content. Across participants, the assignment of objects to the same vs. different category condition and the three semantic knowledge conditions was fully counterbalanced, eliminating low-level visual differences between conditions. Two days after the learning session, visual discrimination was tested with a visual search task while EEG was recorded. Visual search displays were presented in randomized order to rule out pre-perceptual shifts of attention.

Results showed that when two objects belonged to different categories, they stood out more against each other, leading to faster visual search. ERPs revealed an influence of linguistic categorization on early visual processing, observed in both, the P1 and N1 components. This early categorical perception effect was restricted to visual search targets presented in the right visual field (Maier et al. 2014; Regier & Kay, 2009). Further, a nonlateralized category effect was observed in the N2 component, reflecting attentional selection. Interestingly, the different types of semantic knowledge did not significantly modulate category effects. This suggests that any linguistic categorization can lead to categorical perception.

In sum, due to the carefully balanced learning design and the control for pre-perceptual shifts of attention, the categorical perception effect observed in early visual processing demonstrates a genuine top-down effect on perception. Lateralization of the early stage of this effect to the right visual field suggests a stronger involvement of the language-dominant left hemisphere of the brain (Regier & Kay, 2009). This speaks for an online effect of language on perception.

Native Language Promotes Access to Visual Consciousness (Study 2)

Study 2 aimed to break new ground by investigating the consequences of categorical perception for the access to visual consciousness. Do linguistic categories influence what we can and can't see? The experimental design capitalized on cross-linguistic differences in color naming (Athanasopoulos, Dering, Wiggett, Kuipers, & Thierry, 2010; Drivonikou, Davies, Franklin, & Taylor, 2007; Roberson, Davidoff, Davies, & Shapiro, 2005; Roberson, Pak, & Hanley, 2008; Thierry et al., 2009; Winawer et al., 2007). This bears the advantage that identical stimuli are tested in different groups (e.g., speakers with and without a certain linguistic category boundary), precluding bottom-up visual differences between conditions.

Over three experiments, three groups of speakers were tested: Greek and Russian native speakers, who distinguish categorically between light and dark shades of blue, and German native speakers who use only one basic level category for blue (Androulaki et al., 2006; Athanasopoulos et al., 2010; Thierry et al., 2009; Winawer et al., 2007). We tested three color contrast conditions: blue (light versus dark), green (light versus dark) and mixed (light or dark blue versus light or dark green). The blue and green contrasts were based on previous studies and measured to be equally salient according to the Munsell color system (Athanasopoulos et al., 2010; Munsell & Munsell, 1929; Thierry et al., 2009).

Participants performed an attentional blink task in which two targets, T1 and T2, and 11 distractors were presented in a rapid serial visual presentation stream. T1 was a semi circle (pointing up or down), T2 was a triangle (pointing left or right), and the distractors were other geometric shapes (task demonstrations can be found at https://osf.io/sqp6z/wiki). Color contrast was manipulated in the T2 stimuli (e.g., dark blue triangle on a light blue background). Due to the attentional blink effect, detection rates of T2 typically vary as a function of the lag between T1 and T2, with better performance at long relative to short lags (reviewed by Martens & Wyble, 2010).

We predicted the following pattern of results: since more salient color contrasts should help to overcome the attentional blink (Chua, 2005; Itti & Koch, 2001), hit rates should be highest in the mixed condition in all participants, given that this contrast had a higher bottom-up saliency due to the relatively higher chromatic difference. Crucially, Greek and Russian speakers should perform better in the blue compared to the green condition, helped by the top-down contrast of the linguistic category boundary. German speakers, however, should perform equally with green and blue targets. We recorded EEG data in the first two experiments with Greek and German speakers, while Experiment 3 with Russian speakers was a preregistered replication study of the behavioral effects. Concerning ERPs, we predicted that categorical perception would affect early perceptual processing in the P1, as well as the subsequent stage of attentional selection reflected in the N2 component.

Results confirmed the predicted pattern: hit rates were highest in the mixed condition in all groups. Hit rates in the blue condition were increased compared to the green condition in Greek and Russian speakers. Electrophysiological signatures of categorical perception were found in the P1, as well as the N2 in Greek speakers. The categorical perception effect observed in the P1 predicted hit rates, establishing a crucial link between the modulation of early visual processing and task performance. As expected, German speakers showed no differences between the green and the blue condition.

Taken together, linguistic enhancement of color contrast saliency in Greek and Russian speakers provided blue targets with a head start in the access to visual consciousness. Consistent with cognitive penetrability of perception, the onset of this effect was indeed in early visual perception (P1 component), before attentional selection or visual working memory encoding (N2 component). Our native language can thus influence perception and promote access to visual consciousness.

Mental imagery and visual perception: similar time course and shared cognitive mechanisms (Study 3)

The results of Studies 1 and 2 are at least compatible with the predictive processing framework and the assumption that language and knowledge inform perceptual predictions that influence early vision. To seek stronger evidence for a role of predictive processing, Study 3 aimed to directly "observe" top-down predictions. We therefore tested the influence of semantic knowledge on mental imagery, that is, visual experience generated by top-down simulation (Kosslyn, Ganis, & Thompson, 2001). If previously reported effects of semantic knowledge on early visual processing in object recognition are due to predictive processing, then the same effects should be replicable in mental imagery (Abdel Rahman & Sommer, 2008; Rabovsky, Sommer & Abdel Rahman, 2012).

Imagery and perception engage overlapping neural circuits, as established by functional neuroimaging (Cichy, Heinzle, & Haynes, 2012; Dijkstra, Bosch, & van Gerven, 2017; Kosslyn, 2005; Kosslyn et al., 1993; Kosslyn, Ganis, & Thompson, 2001). However, due to their relatively low temporal resolution, PET and fMRI cannot disentangle whether recruitment of early visual cortex is an early, fundamental building block of imagery or an epiphenomenon occurring late in the imagery process. Therefore, this study employed ERPs to better understand temporal aspects of mental imagery.

We used a learning paradigm established by Abdel Rahman and Sommer (2008), in which participants learned information about unfamiliar objects. In the subsequent test session, there were three knowledge conditions: in-depth knowledge (names and spoken descriptions of the objects' functions, e.g., an egg-breeding device), minimal knowledge (object names only, e.g., "Calimat") and well-known objects (familiar objects, e.g., a TV set). Counterbalancing the assignment of objects to the in-depth versus minimal knowledge conditions across participants prevented low-level perceptual differences between conditions. A novel imagery task was designed to control the onset of imagery and time-lock ERPs: After a cue showing a small part of an object, participants performed a demanding visual search trial. Then, they either saw or imagined the cued object (each in 25 % of the trials), or saw a different object (filler trials, 50% overall). This ensured that participants only started imagining objects when prompted.

The results showed that imagery proceeds faster with increasing semantic knowledge (in-depth vs. minimal knowledge condition) and perceptual experience (well-known vs. previously unfamiliar objects). Crucially, effects of semantic knowledge on early visual perception were observed in the P1 component in both, perception and imagery. This demonstrates a surprisingly early, perception-like modulation of low-level visual feature processing during imagery. Imagery-specific configural processing began within the first 250 ms, as shown in a delayed and enhanced N1 in imagery compared with perception.

In conclusion, top-down predictions may indeed carry top-down effects into early vision. Taken together with the results from Studies 1 and 2, this provides converging evidence that top-down effects on early visual perception are implemented through predictive processing.

Group-Level EEG-Processing Pipeline for Flexible Single Trial-Based Analyses Including Linear Mixed Models (Study 4)

With this paper, we made an EEG-analysis pipeline as used in Studies 1–3 available to the scientific community. Its major advantage is the implementation of recently developed analyses of single-trial EEG data with linear mixed models (LMMs).

The paper explains specific advantages of ERP analysis with LMMs over traditional methods based on by-participant grand averages (e.g., repeated-measures ANOVA). First, the traditional averaging approach contains the implicit assumption that each participant's average per condition has the same quality, but often, datasets may not meet this assumption. In reality, participants' averages can be based on different trial numbers due to differences in performance or the amount of data removed during artifact rejection, such that group-level statistics could be biased. For example, in Study 2, a different amount of hit trials entered analysis for each participant because of individual differences in the strength of the attentional-blink effect. LMMs can deal with unequal observations per cell (Pinheiro & Bates, 2000). Second, LMMs allow estimating crossed random effects for participants and items, including random intercepts and random slopes (Bates, Mächler, Bolker, & Walker, 2015). Thus, LMMs can accommodate for differences in mean amplitude of a given component between participants (or items) and differences in how "well" an experimental manipulation works for different participants (or items). For instance, modeling random effects made the results of Studies 1 and 3 less dependent on the particular set of object pictures that was used. A third advantage of LMMs (but also standard linear regression) is the straightforward implementation of continuous predictors. For instance, single-trial ERP amplitudes were used as predictors for behavioral performance in Studies 1 and 2.

The modular structure of the pipeline makes it easy for other researchers to take pieces of code and adapt them for different needs.

Discussion and conclusions

This dissertation investigated how linguistic categories and semantic knowledge affect visual perception. Recently, there has been a controversial debate whether such influences are due to genuine top-down effects on perception. Studies 1 and 2 demonstrated that linguistic categorization affects perceptual performance and indeed modulates early visual processing. Study 3 showed effects of semantic knowledge on both, perception and mental imagery of visual objects.

The studies thoroughly addressed important challenges to empirical demonstrations of top-down effects. The experimental designs eliminated low-level visual differences between conditions, precluded pre-perceptual shifts of attention through unpredictable stimulus displays, and avoided response or memory biases by making linguistic categories and semantic knowledge task-irrelevant (Firestone & Scholl, 2016). Crucially, ERPs were used to disentangle effects on early visual processing from later cognitive processing stages in the brain. In all studies, the earliest effects were observed in the P1, a component associated with early visual processing (Foxe & Simpson, 2002; Pratt, 2011; Raftopoulos, 2017). By showing knowledge effects on the P1 not only during object perception, but also mental imagery, Study 3 provides novel direct evidence of top-down modulations of early visual processing.

Limitations remain concerning the exact mechanisms that implement modulations of perception "online". Linguistic categorization, for instance, is assumed to enhance the saliency of visual features that are diagnostic of a category (Lupyan, 2012). On one hand, this could happen synchronically with perception, such that the activation of a verbal label in the language system transiently biases ongoing visual processing. On the other hand, the effect could be diachronic, with linguistic categorization changing perceptual representations in long-term memory, which then becomes apparent in perception tasks. These mechanisms are not mutually exclusive. Importantly, there is converging evidence for online effects. First, lateralization of categorical perception to the right visual field in Study 1 can hardly be accounted for by changes to long-term representations (see also Maier et al., 2014). These should not affect only one half of the visual environment. Rather, the observed lateralization of categorical perception in early visual processing bears similarities with visual processing of linguistic material (Rossion, Joyce, Cottrell, &

Tarr, 2003), suggesting an online influence of language on object perception. More converging evidence for synchronicity comes from studies showing that verbal interference affects categorical perception online (Gilbert et al., 2006; Roberson & Davidoff, 2000; Winawer et al., 2007) and that Greek speakers' increased sensitivity to differences between shades of blue fades away as they live in the United Kingdom and speak English in everyday life (Athanasopoulos et al., 2010). Future research should aim to better understand the causal mechanisms at the synchronic level, that is, how exactly linguistic representations shape perception while it happens. This should take the neural dynamics between language areas and visual areas of the brain into account (Tomasello, Garagnani, Wennekers, & Pulvermüller, 2017).

Conclusions

Collectively, the present studies demonstrate that linguistic categorization and semantic knowledge can modulate perception. As illustrated by Study 2, under certain experimental conditions, calling two colors by the same or different names in our native language can make the difference between seeing and missing a stimulus. This project shows that effects of language and semantic knowledge can be located within early and automatic perceptual processing in the brain.

Investigating linguistic relativity within the broader framework of top-down effects on perception opens up a promising avenue for research that combines rigorous experimental designs with neuroscientific methods. Considering language-perception interactions as instances of cognitive penetrability of perception can help to resolve the theoretical conflict between universality and relativity (Regier & Xu, 2017). Seen through the lens of predictive processing, linguistic relativity does not have to be an extra principle, but follows from more general neurocognitive mechanisms of perception that allow taking linguistic categories into account as a top-down factor (Clark, 2013; Hohwy, 2013; Lupyan & Clark, 2015; Regier & Xu, 2017). This way, the assumption of a principally universal cognitive architecture in all humans and observations of linguistic relativity are no contradiction (Regier & Xu, 2017).

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