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CONCEPTUAL REVIEW ARTICLE

Interactions Between Language and Mental Representations

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It has long been recognized that language interacts with visual and spatial processes. However, the nature and extent of these interactions are widely debated. The goal of this article is to review empirical findings across several domains to understand whether language affects the way speakers conceptualize the world even when they are not speaking or understanding speech. A second goal of the present review is to shed light on the mechanisms through which effects of language are transmitted. Across domains, there is growing support for the idea that although language does not lead to long-lasting changes in mental representations, it exerts powerful influences during momentary mental computations by either modulating attention or augmenting representational power.

Keywords language and thought; linguistic relativity; Whorf

Introduction

Languages differ in the way they divide up the world and encode, among other things, color, space, number, objects, and events. These crosslinguistic differences naturally lead to the question of whether speakers of different languages attend to different aspects of their environment and reason about the world in fundamentally different ways. This question has been addressed by several linguists, psychologists, anthropologists, and philosophers (for recent reviews, see Bowerman & Levinson, 2001; Casasanto, 2008; Gentner & Goldin-Meadow, 2003; Gleitman & Papafragou, 2005, 2012; Gumperz & Levinson,

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1996; Landau, Dessalegn, & Goldberg, 2010; Lupyan, 2012; Malt & Wolff, 2010; Wolff & Holmes, 2011; see also Sapir, 1924, and Whorf, 1956, for early discussions).

There is an obvious sense in which language affects the way cognizers think about the world: While communicating, speakers attend to the features of the world that they plan to speak about, and as a result, linguistic categories exert their influence on thinking during the process of transforming thoughts into language (Gleitman, January, Nappa, & Trueswell, 2007; Griffin & Bock, 2000; Slobin, 1996). To the extent that languages differ, this process should lead to language-specific patterns of conceptualizing the world. In support of this possibility, a recent study showed that English and Greek speakers allocated their attention to components of unfolding motion events differently as they prepared to describe these events, in accordance with the way the two languages encode motion (Papafragou, Hulbert, & Trueswell, 2008). Such production-driven shifts in attention allocation have been attested in children as young as 3 or 4 years of age (Bunger, Trueswell, & Papafragou, 2012; Bunger, Skordos, Trueswell, & Papafragou, in press). The issue, then, for most research on the language–cognition interface is whether speakers of different languages think differently even when they do not have to speak or understand speech in general.

Language Effects on Nonlinguistic Cognition

There are two broad types of potential language effects on nonlinguistic cognition that are particularly worth discussing. A first type of effect is selectivity. When language is available to be used as a means of encoding the perceptual world, it has the power to highlight certain aspects of the world by encoding those components and to deemphasize others by not encoding them. Thus, even when people are not required to communicate, the selective nature of linguistic encoding might affect the categories people entertain and bring to bear in a situation. In line with this hypothesis, language might act as a "lens" (Gentner & Goldin-Meadow, 2003) or "meddler" (Wolff & Holmes, 2011), and promote the "salience" (Gleitman & Papafragou, 2005) or "selection" (Landau et al., 2010) of certain categories over others. A second possible type of linguistic effect is the augmentation of computational or representational resources. When language is available as a means of encoding the perceptual world, then it offers an additional way of representing information from the world. This additional medium can create enhanced representations beyond the visual or spatial representations alone, thus augmenting representational power. Viewed within this potential role, language has been described in the literature as a "toolkit"

(Gentner & Goldin-Meadow, 2003) or "augmenter" (Wolff & Holmes, 2011), a type of "cognitive technology" (Frank, Everett, Fedorenko, & Gibson, 2008) or a means of "enrichment" (Landau et al., 2010).

Within these broad types of effects, there are more specific open possibilities about how and when language might exert its effects. For instance, selectivity can be instantiated through the modulation of attention, such that linguistic information exerts online, transient effects on cognitive processes within the context of a specific task. An alternative or additional possibility is that, over time, selective attention to certain conceptual distinctions over others might result in "a deep seated specialization of mind" (Levinson, 2003, p. 291); a kind of conceptual reorganization whereby speakers might lose sensitivity to those distinctions that are not captured by the semantics of their native language. This outcome would parallel the well-known phenomenon of perceptual reorganization in the domain of sound, whereby learners lose sensitivity to nonnative phonological distinctions after an initial period of being universal listeners (Werker & Tees, 1984; see also Göksun, Hirsh-Pasek, & Golinkoff, 2010; Majid, Bowerman, Kita, Haun, & Levinson, 2004; Slobin, 2006; Spelke & Hespos, 2002). Similarly, in cases where language acts as a tool, its role could be to help encode, store, and manipulate a representation more efficiently online as a task unfolds; alternatively or additionally, language could help deliver entirely novel representations that would not have been possible otherwise, thereby creating lasting effects on mental structure.

It is clear from the observations above that the question of whether language affects nonlinguistic cognition is too complex to be answered by a straight yes or no, and one needs to evaluate several fine-grained proposals to assess the specific conditions under which language interacts with cognition across different domains (see also Landau et al., 2010; Wolff & Holmes, 2011). At present, both the specifics of selectivity and augmentation and the classes of data that fall under each of these two processes are the topic of rigorous experimentation and theorizing. A key source of evidence about the workings of the two processes comes from probing whether linguistic effects persist across multiple methods and tasks. The idea here is that, if language exerts its influence online during cognitive processing in a certain domain (i.e., if people access verbal labels and use them to perform a task), such effects should be transient and highly task dependent. By contrast, if language has more stable effects on nonlinguistic perceptual-conceptual space (e.g., by inducing a form of narrowing of semantic distinctions similar to the narrowing of phonological distinctions), such effects should surface robustly across multiple tasks (Gennari, Sloman, Malt, & Fitch, 2002) and should be hard to obliterate (Gleitman & Papafragou, 2005).

A particularly clear instance of these contrasting predictions comes from interference tasks. If language exerts an online effect on some cognitive process, one should be able to block this influence by asking people to perform a concurrent task that engages the verbal code (verbal interference), but the role of language should resurface when people are asked to perform an equally distracting concurrent task that does not involve language (nonverbal interference; e.g., Frank, Fedorenko, Lai, Saxe, & Gibson, 2012; Hermer-Vasquez, Spelke, & Katsnelson, 1999; Trueswell & Papafragou, 2010; Winawer et al., 2007). By contrast, if language has reorganized the underlying nonlinguistic cognitive processes, then the effect should survive both verbal and nonverbal interference.

As an illustration, consider the study of motion mentioned earlier (Papafragou et al., 2008). In that study, English and Greek speakers displayed language-specific patterns of attention allocation to components of unfolding motion events as they prepared to describe these events. Further tests showed that these differences in attention allocation disappeared when people from the two language groups freely inspected the same events in preparation of a later memory task (Papafragou et al., 2008). However, differences among the groups emerged later as people tried to memorize the events, with people allocating attention more to aspects of the event that were not typically encoded in their native language. These linguistic intrusions disappeared when people were given a secondary task that prevented them from using language (repeating numbers) but not when they performed an equally taxing nonverbal interference task (tapping a rhythm; Trueswell & Papafragou, 2010). Furthermore, accuracy in the memory task did not differ between English and Greek speakers. Together, these findings suggest that languages do not reorganize the underlying perceptual or conceptual motion representations of speakers. Nevertheless, language can be used selectively as an online mechanism for the efficient and quick packaging of motion event information to aid a demanding memory task.

In this article, we discuss the conditions in which language interacts with the way people perceive, remember, and reason about the world in order to examine the nature of language–cognition interactions. We focus on four domains: color, spatial frames of reference, navigation, and number. These domains were chosen because (a) the mechanisms underlying nonverbal reasoning in these areas have been studied extensively and (b) there are well-documented crosslinguistic differences in these domains that have been linked to cognitive differences. Our goal is to examine empirical findings in order to uncover how the broad hypotheses proposed above relate to the role of language in cognition in these domains. Anticipating our conclusions, we suggest that language can strongly influence nonlinguistic representations; furthermore, much of this role is carried out online in the moment of performing a specific computation—even though in some domains, compared to others, language seems to have a more deeply transformative impact on cognitive structure.

Color

The color space is made up of two million perceivable differences in hue that fall along a continuum, but the range of color terms available in any language is limited. Even though across languages named color categories tend to cluster around universal focal colors (i.e., prototypes in the color space similar to best examples of English black, white, red, yellow, green, and blue or the corresponding terms in other languages; Berlin & Kay, 1969; Regier, Kay & Cook, 2005), languages also differ in the way they divide up the color space. Some languages like Dani only have two color terms (one corresponding to light and one corresponding to dark), other languages like French organize colors in more differentiated categories (e.g., blue, red, green), and yet others like Greek, Korean, or Russian make even more fine-grained distinctions (e.g., between light blue and dark blue). How does the availability of certain color terms affect the perception of hue?

A series of early, pioneering studies by Rosch argued for universal color concepts despite variability in color typology: These studies reported that members of the Dani tribe, despite the fact that their language had only two basic color terms, performed just like English speakers in a color memory task (Heider & Olivier, 1972; Rosch Heider, 1972, 1973). However, later studies pointed out several methodological and conceptual issues with these findings (Lucy, 1997; Ratner, 1989; Saunders & van Brakel, 1997; van Brakel, 1993; Roberson, Davies, & Davidoff, 2000). Furthermore, later studies failed to replicate Rosch's findings using visual discrimination tasks, which reflect in-the-moment processing instead of memory. Roberson and her colleagues compared speakers of English and speakers of Berinmo, a language that does not have different words for English *blue* and *green*, but make a distinction between two colors that do not exist in English, *nol* (corresponding to a greenish blue) and *wor* (corresponding to a yellowish green). The two groups demonstrated different visual search performance patterns depending on whether the color distinctions were encoded in their native language (Roberson et al., 2000; see also Davidoff, Davies, & Roberson, 1999; Roberson, Davidoff, Davies, & Shapiro, 2005, for replications with Himba speakers).

Two lines of evidence suggest that language-driven effects on color discrimination do not indicate a permanent change in the perceptual processes underlying color discrimination. First, such effects are disrupted by preventing speakers from using language while performing a color discrimination task. For instance, Winawer et al. (2007) demonstrated that Russian but not English speakers were faster to discriminate differences between lighter and darker shades of blue which correspond to different color words (*goluboy* and *siniy*, respectively) in Russian but not English. However, this difference disappeared when participants performed a verbal interference task (and persisted when they performed a nonverbal spatial interference task), suggesting that the reaction time difference in the prior study was an outcome of using language while performing the color discrimination task.

Second, language-driven effects on visual color discrimination are stronger for stimuli in the right visual field, and lateralized categorical perception is also selectively prone to interference. Gilbert, Regier, Kay, and Ivry (2006) demonstrated that English speakers had faster visual search times when searching for an odd color that crossed the category boundary between blue and green compared to equally spaced differences within the boundaries of blue and green when the targets were in the right visual field, but not when they were in the left visual field. This pattern disappeared when participants performed a concurrent verbal interference task, but not when they performed a nonverbal spatial interference task (see also Drivonikou et al., 2007, for similar results with other visual discrimination tasks, and Paluy, Gilbert, Baldo, Dronkers, & Ivry, 2011, for the reverse lateralized categorical perception effect in aphasia patients). This was because information presented to the right visual field was processed by the left hemisphere and had more immediate access to the verbal codes in the left hemisphere. Indeed, when participants took longer to complete the search, the categorical perception effect also emerged in the left visual field due to crosscallosal transfer (Roberson, Pak, & Hanley, 2008). Therefore, color discrimination performance is open to feedback from the verbal codes at the moment of visual discrimination.

How early do the effects of language on color discrimination emerge? In a recent ERP study, Thierry, Athanasopoulos, Wiggett, Dering, and Kuipers (2009) compared speakers of English to speakers of Greek, which has different color terms for lighter and darker shades of blue (*ghalazio* and *ble*, respectively). Participants pressed a button as soon as they saw a square shape presented in a stream of circles, some of which deviated from others in luminance, while their electrical scalp activity was being recorded. In each stimulus block, the most frequent stimuli were either green or blue circles, and the deviant stimuli were circles with a contrasting luminance. The brain potential of interest was visual mismatch negativity (vMMN), which is elicited within the first

200 milliseconds in response to deviant stimuli and can arguably be used as an index of preattentive change detection. The vMMN for blue contrasts was greater than it was for green contrasts for Greek, but not for English speakers. This was because the difference between light versus dark blue for Greek is not just a luminance difference, but a color difference. In a follow-up study with the same Greek speakers, who were Greek-English bilinguals recruited in the United Kingdom, Athanasopoulos, Dering, Wiggett, Kuipers, and Thierry (2010) demonstrated that this effect was modulated by how long the Greek speakers had lived abroad. In a finding reminiscent of the lateralized categorical perception effect found in behavioral studies, a later study by Mo, Xu, Kay, and Tan (2011) found that the vMMN for crosscategory color deviants was larger when the deviant stimuli were presented to the right visual field than in the left visual field. Thus, crosslinguistically varying vMMN indicates that color categories in language have effects on early stages of the perceptual processing of color.[1]

In a similar vein, further work shows that the brain areas associated with color judgments are modulated by language (Tan et al., 2008). Participants had to judge whether two colored squares briefly presented on a grey background for 100 milliseconds were the same color or not. Half of the squares showed easy-to-name colors (blue, red, and green), and the other half showed hard-to-name colors (light brown, greenish blue, and yellowish green). Behavioral performance did not differ for easy-to-name and hard-to-name colors. Easy-to-name and hard-to-name colors also evoked similar levels of activation in areas associated with color vision. However, activity in areas related to word finding and lexical access was stronger for the easy-to-name compared to the hard-to-name colors. The fact that behavioral performance did not differ across easy-to-name and hard-to-name colors suggests that, instead of language shaping color perception, color stimuli that have stronger associations to lexical items recruit the language system more readily than those stimuli that have weaker associations to lexical items.

To summarize, studies addressing the interface between language and color processing reveal meaningful language-driven differences at the behavioral level. Furthermore, language influences appear at early stages of visual processing, as shown by ERP studies. Neuroimaging work also leaves open the possibility that even early stages of color processing might be susceptible to rapid linguistic feedback. We attribute these effects to rapid recruitment of verbal codes online. Verbal interference data from multiple studies support the conclusion that linguistic color categories affect cognition through online access to verbal labels and fail to provide evidence for language-driven changes to low-level sensory input.

Spatial Frames of Reference

Humans and animals rely on multiple flexible systems for navigating space and locating objects (Gallistel, 1999). Languages make use of three systems (frames of reference) for encoding spatial relations between two objects (Brown & Levinson, 1993; Levinson, 1996, 2003; Pederson et al., 1998). The *intrinsic* frame of reference describes the location of a figure object in relation to the inherent properties of a ground object (e.g., *The cat is in front of the boy*). The *relative* frame of reference describes the relation between a figure and a ground object with respect to a viewpoint—usually the one belonging to the speaker (e.g., *The cat is to the left of the tree*). Finally, the *absolute* frame of reference describes spatial relations with respect to fixed cardinal directions (e.g., *The cat is south of the tree*).[2] Languages differ in terms of the availability or habitual use of these different frames of reference, especially for encoding locations of everyday objects in small-scale environments. For instance, speakers of Tzeltal, Arandic, and Longgu predominantly adopt an absolute frame of reference, whereas speakers of Dutch, Japanese, and English predominantly use a relative frame of reference (Pederson et al., 1998). These crosslinguistic differences in the habitual encoding of spatial relations raise the question whether speakers of languages with different frames of reference might think about space in different ways.

Levinson and his colleagues (Levinson, 1996; Pederson et al., 1998; cf. Majid et al., 2004) explored this possibility by comparing the spatial reasoning skills of Dutch- and Tzeltal-speaking participants using a series of rotation problems. All problems involved studying an array of objects on a tabletop and reproducing the array on a second table after being spatially reoriented (facing the opposite cardinal direction), as shown in Figure 1. For instance, in the Animals-in-a-Row task, participants were presented with four small animals arranged head to toe on a table. After a brief delay, participants rotated 180 degrees and were asked to make the same array. Participants could reproduce the array in two different ways, preserving either the same cardinal direction (e.g., facing south) or the same relative direction (e.g., facing the participant's right). Notice that the cardinal direction remains the same after the rotation, but the relative direction (e.g., what is right or left) does not. Almost all Dutch speakers preferred a relative strategy when solving the Animals-in-a-Row task; by contrast, the majority of Tzeltal speakers preferred an absolute strategy. These patterns were replicated in a recognition memory task.

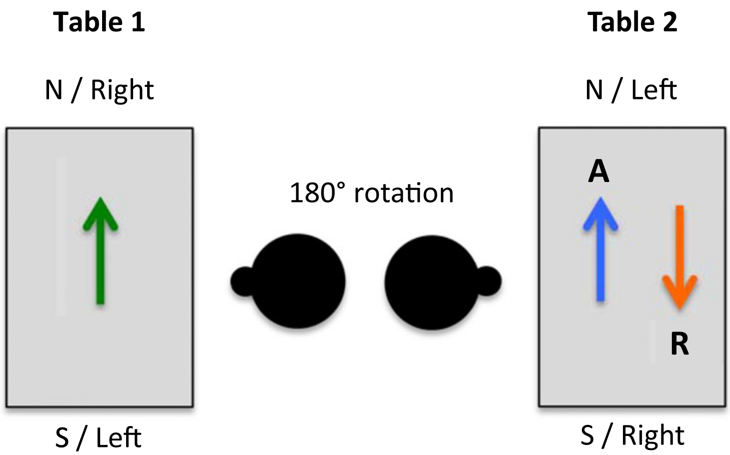

Figure 1 Underlying reasoning in rotation problems (adapted from Levinson, 1996).

Levinson (1996) concluded that "the frame of reference dominant in the language, whether relative or absolute, comes to bias the choice of frame of reference in various kinds of nonlinguistic conceptual representations" (p. 125).

Additional demonstrations pointed to the same conclusion. In Haun, Rapold, Call, Janzen, and Levinson (2006), 4-year-old German-speaking children and primates first saw an object being hidden under one of three identical cups. Then, they had to search for the object in a second table that had another set of three identical cups. Where the object was hidden in the first table served as a cue as to its location in the second table and the hiding place favored the use of either a relative or an absolute strategy. Learning the absolute rule was much easier than learning the relative rule for both 4-year-olds (who were in the process of acquiring relative frame of reference terms in German) and primates. Subsequent experiments with adults and older children who had acquired the relevant spatial vocabulary in their language showed that these groups were much better at learning the strategy that was consistent with the way their language encoded space. Based on these findings, Haun and colleagues concluded that the crosslinguistically varying performance in rotation problems indicates that human spatial cognition has "an inherited primate basis, which may be masked by language and culture" (p. 17572). In another study, Haun, Rapold, Janzen, and Levinson (2011) found that Dutch-speaking children, who prefer a relative (left/right) reference frame when describing spatial relationships, and Haillom-speaking children, who use an absolute (north/south) frame of reference in their language, had difficulty recreating from memory small-scale spatial arrays using a frame of reference that was incongruent with their language.

This set of findings and their interpretation has been widely discussed and debated in literature (see Li & Gleitman, 2002; Levinson, Kita, Haun, & Rasch, 2002). For instance, in a recent demonstration (Rosati, 2015), Bonobos (a primate that was also tested by Haun et al., 2006) received treats for searching for food hidden in one of two locations (relative: left/ right; absolute: north/south). Bonobos had an easier time searching for food in a second table after rotation in the absolute condition, but not in the relative condition, thus confirming the bias reported in Haun et al. However, in a subsequent experiment that used the same task as in Haun et al. but increased the distance between the first and the second table, Bonobos favored a relative strategy (presumably because, as the distance travelled increased, the visibility of the stable features of the environment that favored absolute representations decreased, and so the animals relied more on encoding space with reference to their own body). This finding casts doubt on the idea that there is an inherited bias to represent space using an absolute frame of reference and underscores the role of task demands in frame selection. In a related study, Li and Abarbanell (2016a) also replicated the preference for the absolute frame reported in Haun et al. with 4- and 6-year-old English speakers using two adjacent tables that were separated by a screen; however, when the distance between the tables was increased, the bias to prefer the absolute strategy disappeared.

One problem with rotation tasks (e.g., Animals-in-a-Row) that have been used across literature is that they are ambiguous, with the relative and absolute solutions being equally plausible. According to Li, Abarbanell, Gleitman, and Papafragou (2011), such tasks might require speakers to infer what the experimenter means by "make the same" and encourage a communicative choice that is consistent with the way their language habitually describes spatial relations. In that case, the observed differences between language groups might be due to the spontaneous recruitment of language to encode spatial relations and might disappear if task demands were clearer. An alternative possibility is that the use of the more habitual, language–congruent strategy would persist regardless of the ambiguity of rotation problems (Levinson, 2003; Levinson et al., 2002). In order to test these possibilities, Li et al. tested Tzeltal speakers on a series of unambiguous rotation problems. In the Maze Task (adapted from Brown & Levinson, 1993), participants observed the experimenter demonstrate a path on a maze placed on a table and had to reproduce the path on a maze on a second table (as shown in Figure 2). Participants were placed in one of two

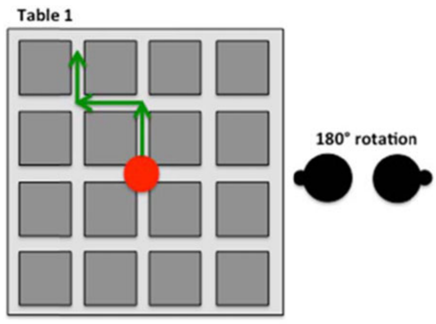

Figure 2 Absolute and relative solutions for the maze task (redrawn from Li, Abarbanell, Gleitman, & Papafragou, 2011).

groups. In the relative group, participants picked up the maze, and then rotated 180 degrees and walked to the second table. In the absolute group, participants rotated 180 degrees, and then picked up the maze and walked to the second table. Notice that in the relative, but not the absolute group, the maze also rotated with the participant. For later trials, participants did not carry the maze over, but used an identical maze on the second table to demonstrate their answer (Leave-Maze trials). For all trials, accuracy was higher in the relative versus absolute group. Furthermore, Li and colleagues manipulated path length in order to test whether increased memory load would make participants more likely to adopt the linguistically dominant absolute strategy, as suggested by Levinson et al. (cf. Haun et al., 2011). However, this prediction was not confirmed: The difference between relative and absolute groups increased as path length increased. Further manipulations in Li et al. confirmed the conclusion that Tzeltal speakers are flexible in their spatial reasoning and can solve spatial rotation problems using either a relative or an absolute frame of reference depending on task requirements.[3]

Finally, in a study comparing English- and Tzeltal-speaking children's spatial reasoning, Li and Abarbanell (2016b; see also Abarbanell & Li, 2015) sought to revisit children's resistance to adopt language-incongruent frames of reference reported in Haun et al. (2011). As in Haun et al., both language groups performed better when using the language-congruent strategy. In addition, English-speaking children could flexibly switch to an absolute strategy, but the Tzeltal-speaking group had some difficulty switching to a relative strategy. Importantly, the instructions asking the Tzeltal-speaking group to use the relative strategy were in Tzeltal, but included the Spanish terms for left and right since these terms do not exist in Tzeltal (similar instructions were used by Haun et al.). Follow-up experiments showed that many Tzeltal-speaking children did not know the Spanish words for left and right, thus raising the possibility that children's limited flexibility in this and other studies might be related to limited understanding of verbal instructions which involved these words.[4] In fact, when Tzeltal-speaking children were given instructions that conveyed the relative frame of reference through nonverbal means (and thus did not require knowledge of the Spanish words for left and right), the group of children were able to flexibly shift to a relative strategy.

In sum, the findings reviewed above fail to provide evidence for the proposal that linguistic frames of reference influence how speakers represent space even when language is not explicitly involved. Rather these findings are compatible with the position that language is one of the many ways to encode spatial frames of reference and is often recruited online as a tool while solving spatial problems. As a result, speakers prefer to solve rotation problems using language-consistent strategies. Previously documented crosslinguistic differences might originate from the speakers' need to infer the experimenter's intent when solving the rotation task. When the experimenter's communicative intent is clear, and the task has a truly correct solution, speakers can flexibly choose among reference frames to solve rotation problems.

Navigation

Preverbal infants and nonhuman animals (e.g., rats) are able to maintain a sense of their relative location in an environment and update their spatial representations by attending to the geometric properties of the environment, such as the shape or the lengths and angles of the walls making up an enclosed space (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994, 1996). As a result, human infants and animals can navigate their environment and complete everyday tasks such as finding food or objects. In one demonstration, after being disoriented, 18- to 24-month-old infants searched for an object hidden in one of the corners of a rectangular room with white walls in the two geometrically appropriate corners of the room: the correct corner and the rotationally opposite corner (Hermer & Spelke, 1994, 1996), as illustrated in Figure 3 (panel a). When the room had a salient landmark (e.g., one blue wall), infants ignored this cue and continued to search for the object in the two geometrically appropriate corners (Figure 3, panel b). Similarly, when rats had to reorient themselves to search for food in a familiar environment (i.e., a rectangular chamber made up of walls differing in brightness and patterns), they ignored nongeometric features

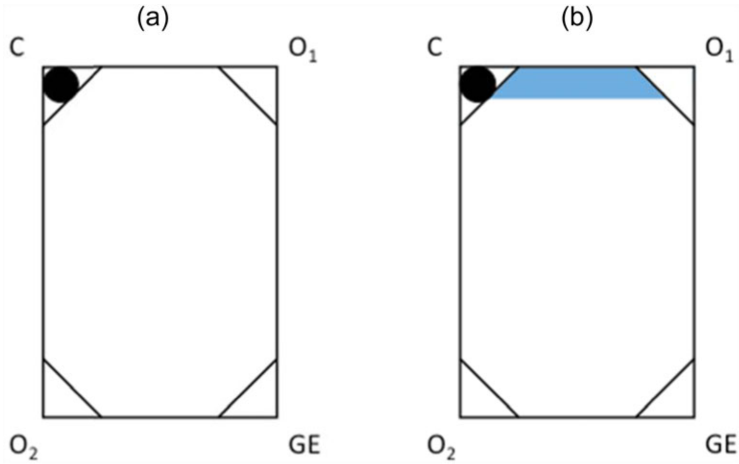

Figure 3 Layout of the environment in reorientation experiments with infants and adults. Panel (a) represents rectangular room with white walls; panel (b) represents room with landmark information/blue wall; C = correct location, GE = geometrically equivalent opposite location, O1, O2 = other locations (adapted from Hermer & Spelke, 1996).

of the environment and searched for food in the geometrically appropriate locations (Cheng, 1986).

Unlike preverbal infants and nonhuman animals, adult humans are able to use a wider range of information to represent the spatial layout of their environment, including both geometric and landmark information. In a study by Hermer-Vazquez and colleagues (1999), adults saw an experimenter hide an object in one of the corners of a rectangular chamber with white walls and had to find the hidden object after being disoriented. Adults searched for the object in the two geometrically appropriate corners more often than the other two corners—a fact suggesting that they were able to use the geometric properties of the chamber to reorient and localize the hidden object. Another group of adults tested with the same procedure in a chamber with one blue wall also overwhelmingly searched for the hidden object in the correct location. Thus adults can flexibly combine different types of information for navigation and spatial representation.

Of importance for present purposes, this process of integrating different types of representation seems to benefit from language. Other groups of participants in Hermer-Vazquez et al. (1999) underwent the same procedure while performing either a verbal interference task (in which they repeated aloud a prerecorded passage) or a nonverbal interference task (in which they reproduced a prerecorded set of drumbeats by tapping). The verbal interference group was unable to use the landmark information when tested in the chamber with one blue wall and instead searched in the two geometrically appropriate corners. By contrast, the nonverbal interference group performed exactly as the participants who did not perform a secondary task: They searched in the two geometrically appropriate corners when tested in the white room and used the landmark information when tested in the room with one blue wall.

These findings have been interpreted as evidence for two domain-specific core knowledge systems underlying navigation: a geometric system representing the spatial layout of the environment and a landmark system representing small, movable objects (Spelke & Tsivkin, 2001; Spelke, 2011). According to this proposal, language enables adults to flexibly conjoin domain-specific representations (e.g., to the left of the blue wall) to reorient themselves and localize objects in space. When prevented from using language to encode object location, adults fall back to the core knowledge systems that are shared with preverbal infants and nonhuman animals.

More recent studies have challenged the idea that navigation involves separate domain-specific mechanisms (see Cheng, Huttenlocher, & Newcombe, 2013, for a review). For example, Ratliff and Newcombe (2008a) showed that adults' flexibility in choosing geometric versus landmark cues depends on both the salience of these cues (e.g., in small rooms, landmark use is dispreferred) and the adults' history of success with a particular type of cue. Thus, adults utilize geometric and landmark information in varying degrees depending on the certainty and variance with which the two kinds of information are encoded, along with their salience and perceived usefulness. Furthermore, this line of work has shown that language does not play a central role in allowing the use of landmark cues during reorientation. Ratliff and Newcombe (2008b) asked adults to perform a reorientation task modeled after Hermer-Vasquez et al. (1999). When reorientation occurred in a small room (where the use of landmarks was dispreferred) and without explicit information about the nature of the task, verbal interference disrupted adults' reliance on landmarks; after participants gained additional experience and were given more specific instructions, they successfully completed the task using both landmarks and geometry. When orientation occurred in a large room (where landmarks were presumably more distal and thus salient), verbal interference had no effect on reorientation. Interestingly, and contrary to the original proposal of Hermer-Vasquez et al., nonverbal (spatial) interference also disrupted orientation performance in the small room, and to an equal degree. This shows that, under those conditions, any secondary task destroys an already fragile process of cue combination that does not rely exclusively on language. Furthermore, nonverbal interference (unlike verbal interference) disrupted performance in the large room, underscoring the fact that the integration of landmarks and geometry in those contexts relies on spatial, rather than linguistic, mechanisms. These results suggest that language is not necessary for combining landmarks and geometry, even though it can provide an efficient tool to store and recall information about the location of an object.

Numerical Reasoning

Studies with adults, preverbal infants, and nonhuman animals have revealed two core systems underlying numerical reasoning: one that precisely represents discrete objects for up to four items and one that approximately represents large numerical quantities, where the error in magnitude estimation increases for larger quantities in accordance with Weber's law (Feigenson, Dehaene, & Spelke, 2004). These two core systems are thought to be innate. A third system that is responsible for exact representation of large quantities (e.g., the quantity denoted by 17) is unique to human adults. Some researchers have argued that natural language is the central vehicle through which this last system is learned (Carey, 2009; Spelke & Tsivkin, 2001; Spelke, 2011).

A strong test of this hypothesis was provided by a study conducted by Peter Gordon of the Piraha, an Amazonian tribe whose language has a "one-two-many" counting system (Gordon, 2004). Linguistic tasks confirmed that the Piraha did not have any exact number words; furthermore, the words for one and two (*hoí* and *hói*, respectively) were not consistently used to designate those quantities. In nonlinguistic tasks, participants had to make an array of objects the same as in the experimenter's array. The Piraha were highly accurate when the arrays consisted of up to three objects; however, their accuracy dropped in accordance with Weber's law as the number of items increased and as tasks became more demanding (see Pica, Lemer, Izard, & Deheane, 2004, for similar results with Munduruku speakers). Gordon concluded that speakers of languages that lack exact number words to refer to large quantities are not able to entertain the concept of exact quantities beyond two or three items.

Building on Gordon's tasks, Frank and colleagues (2008) showed that language is particularly critical for memory of large exact quantities: When the Piraha were presented with a line of objects and asked to create, from a new collection of objects, a second line that matched it, they placed objects from the new collection opposite those in the first collection by one-to-one correspondence; however, their accuracy dropped drastically in matching tasks where they could no longer see the original array.[5]

In a later study, Frank and colleagues (2012) tested adult English speakers with the same tasks while having people perform a secondary task involving either verbal interference (searching for the letter L or T in a string of letters appearing in the same location on a screen) or nonverbal interference (reproducing the locations of a blue square appearing on a screen by clicking on the screen with the mouse). The difficulty level of the secondary tasks was matched. English speakers performed just like the Piraha under verbal interference, but not under nonverbal interference. A subsequent experiment showed that verbal interference impaired memory for cardinality when it was introduced during only encoding or both encoding and retrieval, but not when it was introduced during only retrieval, suggesting that the information about cardinality was encoded in the preferred (verbal) code in memory. Thus, language offers a representational tool for storage and manipulation of large exact quantities. However, speakers need to have access to this tool in the moment of accessing large exact quantities.

Further evidence for the idea that language is one of the representational tools that complements nonverbal numerical representations comes from work on mental abacus—a technique that relies on visuospatial working memory to represent large exact quantities (e.g., the number 49). Frank and Barner (2011) tested students who were enrolled in a mental abacus training program in India while they performed arithmetic computations under verbal interference, nonverbal interference (i.e., tapping their fingers), and no interference conditions. Nonverbal interference impaired performance more than verbal interference in mental abacus users; however, a control group of English speakers who did not have any mental abacus training were affected by verbal interference and unaffected by nonverbal interference. Together, these findings suggest that the representation of large exact quantities can be carried out in the absence of access to verbal codes, but only if speakers have learned to represent them in another, nonlinguistic medium.

To summarize, research on the interface between language and numerical cognition suggests that language provides the means to encode, store, and manipulate information about exact number representations across time, space, and modalities. Speakers are likely to spontaneously recruit language as a tool to create exact number representations and increase efficiency in arithmetic and numerical reasoning tasks. Perhaps most strikingly, in the absence of productive linguistic encoding, the ability to represent large, exact quantities does not seem to emerge. Furthermore, knowledge of a language with exact number words does not allow one to be able to represent large exact quantities offline in the absence of access to language or to some nonlinguistic medium, such as the mental abacus. When the ability to use the verbal code is blocked, humans rely on the core systems of number, universally shared with preverbal infants and nonhuman primates, and can represent either small quantities exactly or large quantities approximately.

Discussion and Conclusions

At the outset of this article, we asked whether one's native language affects cognition. Here we reviewed empirical findings about the language-and-thought relation in four domains: color, spatial frames of reference, navigation in space, and number. Overall, across different domains, the empirical findings point to some behavioral and/or neural differences among speakers of different languages that can be tied to crosslinguistic differences in encoding aspects of the visual world. Typically, these differences decrease or disappear when speakers are prevented from accessing verbal codes or are presented with other conceptual cues, a fact suggesting that language-driven differences are produced by temporary interactions between linguistic and mental representations. In other cases (especially number), language seems to be more deeply intertwined with cognition, with language potentially changing the underlying mental structure.

We can now revisit the two proposals about how language and mental processes interact in light of evidence from the domains we reviewed. The first type of mechanism is selectivity. When language is available to be used as a means of encoding the perceptual world, it has the power to selectively direct attention to certain aspects of the world by encoding those components and to deemphasize other components by not encoding them. The empirical findings in the domains of color and spatial reasoning can be explained by this mechanism. In both of these domains, selectivity creates an online, highly transient change in attention and does not lead to a reorganization of the underlying perceptual-conceptual space. For instance, recruiting language-specific color codes might create a momentary shift in the color continuum, such that the boundaries of color categories align with verbal codes. This does not mean that the ability to perceive certain categorical distinctions is lost (e.g., two colors that fall within the boundaries of blue in English), but attention is preferentially directed to those categorical distinctions encoded by language (e.g., two colors that cross the boundary between green and blue in English). Thus within a specific task cross-category color distinctions may become more salient than within-category distinctions. Similarly, crosslinguistic investigations of spatial reasoning reveal that, while solving rotation problems, speakers might recruit language to encode a particular location and therefore attend to the dominant frame-of-reference system in their language. However, this momentary change in attention does not permanently impede the capacity to conceptualize space in line with another frame of reference system.

The second mechanism is the augmentation of representational power. When language is available as a means of encoding the perceptual world, then it offers an additional way of representing the information in the world. This additional medium can create enhanced representations that go beyond the visual or spatial representations alone, thus augmenting representational power. The domains of navigation and number offer two somewhat different examples of this process. In navigation, language provides an efficient packaging to encode the location of a hidden object (e.g., left of the blue wall), creating an enhanced and possibly more durable representation of the relation between the object and its location by combining both landmarks and geometric cues in the environment. In numerical cognition, having language as a tool introduces a new level of representation, allowing the computation, storage, and manipulation of complex numerical concepts. When language is suppressed, or its number vocabulary is imprecise, people are limited in how they handle large exact numbers. In the domain of navigation, language acts as a flexible online tool that helps cognition, but does not seem to create truly novel representations. However, in the case of number, the rapid online use of verbal codes provides an important piece of cognitive machinery that may not otherwise become available (in the absence of other specialized computational tools such as a mental abacus). The precise details of how language might create novel representational resources in the number domain are still developing (see Carey, 2009, and Spelke, 2011, for two different proposals).

Several issues at the language–cognition interface are ripe for future research. First, in the domains we surveyed, language seems to reliably accompany many cognitive processes, even when people appear to not engage in overt linguistic communication. This fact speaks to the importance of language within human mental life: Even when people do not have to speak or comprehend speech, language is spontaneously recruited online and produces important and multifaceted changes in cognition. At the same time, the online involvement of language in nonlinguistic tasks is clearly malleable and context-bound (especially in findings from the domains of frame of reference and navigation). This conclusion converges with studies on motion summarized earlier in this article, showing that effects of language on cognitive processes are task dependent and do not always surface in ordinary contexts (Papafragou et al., 2008; Trueswell & Papafragou, 2010; see also Gennari et al., 2002; Papafragou & Selimis, 2010). This conclusion is also consistent with studies of the role of language in further domains, such as the object/substance distinction (Li, Dunham, & Carey, 2009), positional information in spatial scenes (Bosse & Papafragou, 2010), and source monitoring (Ünal, Pinto, Bunger, & Papafragou, 2016). Thus, available findings suggest that linguistic categories exert their influence on how speakers cognize the world in a flexible way. The parameters of this flexibility currently await a full synthesis.

Second, many of the studies across literature that address the nature of the effects language has on cognition rely on evidence from interference tasks. However, there are several unresolved issues with the use of such tasks. As Perry and Lupyan (2013) point out, studies have used various types of verbal interference tasks (e.g., digit or letter repetition, answering questions, etc.) and nonverbal interference controls (e.g., visual memory, tapping, etc.); moreover, the two types of task were not always matched in difficulty. Furthermore, we do not have a fully developed theoretical account of verbal interference (see also Lupyan, 2012; Regier, Kay, Gilbert, & Ivry, 2010). These are issues that the field needs to address.

Third, at present, little is known about how the online involvement of language in cognitive processes emerges in childhood and changes with age. Existing evidence points to developmental differences: Adults, but not young children, use language online to enhance working memory (e.g., Dessalegn & Landau, 2008, 2013; Hitch, Halliday, Schaafstal, & Heffernan, 1991; Palmer, 2000). Other work shows that, for children, explicit language may highlight the relevant dimensions for solving a task. In a study of 4-year-olds' spatial navigation in a disoriented search task (Shusterman, Lee, & Spelke, 2011), spatial verbal expressions (e.g., *I'm hiding the sticker at the red wall*) were more effective than verbal expressions that merely mentioned the landmark object (e.g., *Look at the pretty red wall*) or control cues (e.g., *I'm hiding the sticker over here*) in facilitating children's use of landmark cues. Importantly, verbal expressions that emphasized the relevance of the landmark for the task (e.g., *The red wall can help you get the sticker*) were as effective as spatial verbal expressions, suggesting "language guides children's construal of landmarks as relevant for navigation" (p. 200). It is likely that this role generalizes beyond the domain of navigation in ways that have not yet been fully explored.

Final Thoughts

The studies reviewed here point to a complex and nuanced pattern of relations between linguistic–semantic distinctions and mental representations. In some domains, such as color and spatial frames of reference, language can impact visual or spatial processes by modulating attention. In other domains, such as navigation and number, language can help augment or handle already available representations. These effects unfold online, as language interfaces with human perceptual-conceptual systems, and are malleable (e.g., they do not lead to permanent narrowing of underlying visuospatial representations). Nevertheless, in some cases (most notably, number) language may make a deeper and more long-lasting representational contribution. We conclude that language is an efficient, powerful, and flexible resource that can influence cognitive processing during mental computations.

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Notes

1 One might be tempted to conclude from these data that verbal color categories are automatically recruited during color perception (see also Winawer et al., 2007). This conclusion is challenged by the well-known Stroop effect (see Trueswell & Papafragou, 2010, for discussion). When naming the color that a word is printed in, color terms interfere with the task (Stroop, 1935). This shows that strings of letters automatically trigger the computation of linguistic information. However, the opposite does not hold true: When reading color words aloud, text printed in incongruent colors does not interfere with word naming times. This suggests that colors do not automatically trigger the computation of linguistic information (MacLeod, 1991; Stroop, 1935). If accessing color words had become an automatic part of perceiving color, we should see interference in both directions.

2 The terms for frames of reference are fraught with difficulty, and different authors use different terminology (e.g., egocentric vs. allocentric in place of relative vs. absolute). We maintain the original terms for ease of reference.

3 One might argue that Haun et al. (2006) used a rule-learning paradigm with minimal verbal instructions and a single objective correct answer, so their task was not subject to the same criticism concerning ambiguity as the Animals-in-a-Row task. Nevertheless, even in Haun et al., participants had to guess a rule that the experimenter had in mind, and these guesses were subject to communicative inferences just like ambiguous tasks in prior literature. Li et al. (2011, Experiment 4) used a similar rule-learning task with minimal verbal instruction, but participants did not have to make communicative inferences, because the display either rotated 180 degrees with the participants (absolute condition) or did not rotate (relative condition). In that task, Tzeltal speakers performed better in the relative compared to the absolute alignment. This finding is not explained by Haun et al.'s account. We thank Peggy Li for discussion of this section.

4 Haun et al. (2011) did not directly test children's understanding of these words. Furthermore, in that study, children needed more training in the relative than absolute trials in order to correctly align only two animals, a finding consistent with the possibility that they had difficulty with left/right language.

5 Frank et al. (2008) suggest that the discrepancy between their own and Gordon's (2004) findings, when no memory was involved, might be due to "theoretically unimportant aspects of the testing materials and environment" (p. 822). More specifically, Gordon's studies included a very small sample (four individuals, all male) and the items that were to be matched were AA batteries that could easily roll on an uneven surface creating an additional source of difficulty. Frank et al. used a larger sample (14 individuals, with an equal number of males and females) and improved testing materials and conditions. Notice, however, that when no memory of quantity is necessary, it is possible for participants to pass Frank et al.'s matching task without representing the numerical equality of the two sets.

References

Abarbanell, L., & Li, P. (2015). Left-right language and perspective taking in Tseltal Mayan children. In E. Grillo & K. Jepson (Eds.), *Proceedings of the 39th Annual Boston University Conference on Language Development* (pp. 1–13). Somerville, MA: Cascadilla Press.

Athanasopoulos, P., Dering, B., Wiggett, A., Kuiper, J. R., & Thierry, G. (2010). Perceptual shift in bilingualism: Brain potentials reveal plasticity in pre-attentive colour perception. *Cognition*, *116*, 437–443. doi:10.1016/j.cognition.2010.05.016

Berlin, B., & Kay, P. (1969). *Basic color terms: Their universality and evolution*. Berkeley: University of California Press.

Bosse, S., & Papafragou, A. (2010). Spatial position in language and visual memory: A cross-linguistic comparison. In S. Ohlsson & R. Catrambon (Eds.), *Proceedings of the 32nd Annual Meeting of the Cognitive Science Society* (pp.1052–1057). Hillsdale, NJ: Erlbaum.

Bowerman, M., & Levinson, S. C. (2001). *Language acquisition and conceptual development*. Cambridge, UK: Cambridge University Press.

Brown, P., & Levinson, S. C. (1993). "Uphill" and "downhill" in Tzeltal. *Journal of Linguistic Anthropology*, *3*, 46–74. doi:10.1525/jlin.1993.3.1.46

Bunger, A., Skordos, D., Trueswell, J., & Papafragou, A. (in press). How adults and children encode causative events cross-linguistically: Implications for language production and attention. *Language, Cognition and Neuroscience*. doi:10.1080/23273798.2016.1175649

Bunger, A., Trueswell, J., & Papafragou, A. (2012). The relation between event apprehension and utterance formulation in children: Evidence from linguistic omissions. *Cognition*, *122*, 135–149. doi:10.1016/j.cognition.2011.10.002

Carey, S. (2009). *The origin of concepts*. Oxford, UK: Oxford University Press.

Casasanto, D. (2008). Who's afraid of the big bad Whorf? Cross-linguistic differences in temporal language and thought. *Language Learning*, *58*, 63–79. doi:10.1111/j.1467-9922.2008.00462.x

Cheng, K. (1986). A purely geometric model in rat's spatial representation. *Cognition*, *23*, 149–178. doi:10.1016/0010-0277(86)90041-7

Cheng, K., Huttenlocher, J., & Newcombe, N. S. (2013). 25 years of research on the use of geometry in spatial reorientation: A current theoretical perspective. *Psychonomic Bulletin and Review*, *20*, 1033–1054. doi:10.3758/s13423-013-0416-1

Davidoff, J., Davies, I., & Roberson, D. (1999). Colour categories of a stone-age tribe. *Nature*, *398*, 203–204. doi:10.1038/18335

Dessalegn, B., & Landau, B. (2008). More than meets the eye: The role of language in binding visual properties. *Psychological Science*, *19*, 189–195. doi:10.1111/j.1467-9280.2008.02066.x

Dessalegn, B., & Landau, B. (2013). Interaction between language and vision: It's momentary, abstract, and it develops. *Cognition*, *127*, 331–344. doi:10.1016/j.cognition.2013.02.003

Drivonikou, G. V., Kay, P., Regier, T., Ivry, R. B., Gilbert, A. L., Franklin, A., et al. (2007). Further evidence that Whorfian effects are stronger in the right visual field than the left. *Proceedings of the National Academy of the Sciences*, *104*, 1097–1102. doi:10.1073/pnas.0610132104

Feigenson, L., Dehaene, S., & Spelke, E. S. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 307–314. doi:10.1016/j.tics.2004.05.002

Frank, M. C., & Barner, D. (2011). Representing exact number visually using mental abacus. *Journal of Experimental Psychology: General*, *141*, 134–149. doi:10.1037/a0024427

Frank, M. C., Everett, D. L., Fedorenko, E., & Gibson, E. (2008). Number as a cognitive technology: Evidence from Pirahã language and cognition. *Cognition*, *108*, 819–824. doi:10.1016/j.cognition.2008.04.007

Frank, M. C., Fedorenko, E., Lai, P., Saxe, R., & Gibson, E. (2012). Verbal interference suppresses exact numerical representation. *Cognitive Psychology*, *64*, 74–92. doi:10.1016/j.cogpsych.2011.10.004

Gallistel, C. R. (1999). Coordinate transformations in the genesis of directed action. In B. M. Bly & D. E. Rumelhart (Eds.), *Cognitive science handbook of perception and cognition* (2nd ed., pp. 1–42). San Diego, CA: Academic Press.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.

Gennari, S. P., Sloman, S. A., Malt, B. C., & Fitch, W. T. (2002). Motion events in language and cognition. *Cognition*, *83*, 49–79. doi:10.1016/S0010-0277(01)00166-4

Gentner, D., & Goldin-Meadow, S. (2003). *Language in mind: Advances in the study of language and thought*. Cambridge, MA: MIT Press.

Gilbert, A., Regier, T., Kay, P., & Ivry, R. (2006). Whorf hypothesis is supported in the right visual field but not the left. *Proceedings of the National Academy of Sciences*, *103*, 489–494. doi:10.1073/pnas.0509868103

Gleitman, L. R., January, D., Nappa, R., & Trueswell, J. C. (2007). On the give and take between event apprehension and utterance formulation. *Journal of Memory and Language*, *57*, 544–569. doi:10.1016/j.jml.2007.01.007

Gleitman, L., & Papafragou, A. (2005). Language and thought. In K. Holyoak & R. Morrison (Eds.), *Cambridge handbook of thinking and reasoning* (pp. 633–661). Cambridge, UK: Cambridge University Press.

Gleitman, L., & Papafragou, A. (2012). New perspectives on language and thought. In K. Holyoak & R. Morrison (Eds.), *The Oxford handbook of thinking and reasoning* (2nd ed., pp. 543–568). New York: Oxford University Press.

Gordon, P. (2004). Numerical cognition without words: Evidence from Amazonia. *Science*, *306*, 496–499. doi:10.1126/science.1094492

Göksun, T., Hirsh-Pasek, K., & Golinkoff, R. M. (2010). Trading spaces: Carving up events for learning language. *Perspectives on Psychological Science*, *5*, 33–42. doi:10.1177/1745691609356783

Griffin, Z. M., & Bock, K. (2000). What the eyes say about speaking. *Psychological Science*, *11*, 274–279. doi:10.1111/1467-9280.00255

Gumperz, J. J., & Levinson, S. C. (1996). *Rethinking linguistic relativity*. Cambridge, UK: Cambridge University Press.

Haun, D. B. M., Rapold, C. J., Call, J., Janzen, G., & Levinson, S. C. (2006). Cognitive cladistics and cultural override in Hominid spatial cognition. *Proceedings of National Academy of Sciences*, *103*, 17568–17573. doi:10.1073/pnas.0607999103

Haun, D. B. M., Rapold, C. J., Janzen, G., & Levinson, S. C. (2011). Plasticity of human spatial cognition: Spatial language and cognition covary across cultures. *Cognition*, *119*, 70–80. doi:10.1016/j.cognition.2010.12.009

Heider, E. R., & Olivier, D. C. (1972). The structure of the color space in naming and memory for two languages. *Cognitive Psychology*, *3*, 337–354. doi:10.1016/0010-0285(72)90011-4

Hermer, L., & Spelke, E. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*, 57–59. doi:10.1038/370057a0

Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, *61*, 195–232. doi:10.1016/S0010-0277(96)00714-7

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive Psychology*, *39*, 3–36. doi:10.1006/cogp.1998.0713

Hitch, G. J., Halliday, M. S., Schaafstal, A. M., & Heffernan, T. M. (1991). Speech, "inner speech," and the development of short-term memory: Effects of picture-labeling on recall. *Journal of Experimental Child Psychology*, *51*, 220–234. doi:10.1016/0022-0965(91)90033-O

Landau, B., Dessalegn, B., & Goldberg, A. M. (2010). Language and space: Momentary interactions. In P. Chilton & V. Evans (Eds.), *Language, cognition, and space: The state of the art and new directions* (pp. 51–78). London: Equinox Publishing.

Levinson, S. C. (1996). Frames of reference and Molyneux's question: Cross-linguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 385–436). Cambridge, MA: MIT Press.

Levinson, S. C. (2003). *Space in language and cognition: Explorations in linguistic diversity*. Cambridge, UK: Cambridge University Press.

Levinson, S. C., Kita, S., Haun, D. B. M., & Rasch, B. H. (2002). Returning the tables: Language affects spatial reasoning. *Cognition*, *84*, 155–188. doi:10.1016/S0010-0277(02)00045-8

Li, P., & Abarbanell, L. (2016a). Alternative spin on phylogenetically inherited spatial reference frames. Manuscript submitted for publication. Retrieved from http://scholar.harvard.edu/files/peggyli/files/liabarbanell_cups.pdf?m=1447550138

Li, P., & Abarbanell, L. (2016b). Competing perspectives: Frames of reference in language and thought. Manuscript submitted for publication. Retrieved from http://scholar.harvard.edu/files/peggyli/files/liabarbanellanimals.pdf?m=1447550630

Li, P., Abarbanell, L., Gleitman, L., & Papafragou, A. (2011). Spatial reasoning in Tenejapan Mayans. *Cognition*, *120*, 33–53. doi:10.1016/j.cognition.2011.02.012

Li, P., Dunham, Y., & Carey, S. (2009). Of substance: The nature of language effects on entity construal. *Cognitive Psychology*, *58*, 487–524. doi:10.1016/j.cogpsych.2008.12.001

Li, P., & Gleitman, L. (2002). Turning the tables: Language and spatial reasoning. *Cognition*, *83*, 265–294. doi:10.1016/S0010-0277(02)00009-4

Lucy, J. (1997). The linguistics of "color." In C. L. Hardin & L. Maffi (Eds.), *Color categories in thought and language* (pp. 320–346). Cambridge, UK: Cambridge University Press.

Lupyan, G. (2012). Linguistically modulated perception and cognition: The label-feedback hypothesis. *Frontiers in Psychology*, *3*, 1–13. doi:10.3389/fpsyg.2012.00054

MacLeod, C. M. (1991). John Ridley Stroop: Creator of a landmark cognitive task. *Canadian Psychology*, *32*, 521–524. doi:10.1037/h0079012

Majid, A., Bowerman, M., Kita, S., Haun, D., & Levinson, S. C. (2004). Can language restructure cognition? The case for space. *Trends in Cognitive Science*, *8*, 108–114. doi:10.1016/j.tics.2004.01.003

Malt, B. C., & Wolff, P. M. (Eds.). (2010). *Words and the mind: How words capture human experience*. Oxford, UK: Oxford University Press.

Mo, L., Xu, G., Kay, P., & Tan, L. H. (2011). Electrophysiological evidence for the left-lateralized effect of language on preattentive categorical perception of color. *Proceedings of National Academy of Science*, *108*, 14026–14030. doi:10.1073/pnas.1111860108

Palmer, S. (2000). Working memory: A developmental study of phonological recoding. *Memory*, *8*, 179–193. doi:10.1080/096582100387597

Paluy, Y., Gilbert, A. L., Baldo, J. V., Dronkers, N. F., & Ivry, R. B. (2011). Aphasic patients exhibit a reversal of hemispheric asymmetries in categorical color discrimination. *Brain and Language*, *116*, 151–156. doi:10.1016/j.bandl.2010.11.005

Papafragou, A., Hulbert, J., & Trueswell, J. (2008). Does language guide event perception? Evidence from eye movements. *Cognition*, *108*, 155–184. doi:10.1016/j.cognition.2008.02.007

Papafragou, A., & Selimis, S. (2010). Event categorisation and language: A cross-linguistic study of motion. *Language and Cognitive Processes*, *25*, 224–260. doi:10.1080/01690960903017000

Pederson, E., Danziger, E., Wilkins, D., Levinson, S., Kita, S., & Senft, G. (1998). Semantic typology and spatial conceptualization. *Language*, *74*, 557–589. doi:10.2307/417793

Perry, L. K., & Lupyan, G. (2013). What the online manipulation of linguistic activity can tell us about language and thought. *Frontiers in Behavioral Neuroscience*, *7*, 1–4. doi:10.3389/fnbeh.2013.00122

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science*, *306*, 499–503. doi:10.1126/science.1102085

Ratliff, K. R., & Newcombe, N. S. (2008a). Reorienting when cues conflict: Evidence for an adaptive-combination view. *Psychological Science*, *19*, 1301–1307. doi:10.1111/].1467-9280.2008.02239.x

Ratliff, K. R., & Newcombe, N. S. (2008b). Is language necessary for human spatial reorientation? Reconsidering evidence from dual task paradigms. *Cognitive Psychology*, *56*, 142–163. doi:10.1016/j.cogpsych.2007.06.002

Ratner, C. (1989). A sociohistorical critique of naturalistic theories of color perception. *Journal of Mind and Behavior*, *10*, 361–373.

Regier, T., Kay, P., & Cook, R. (2005). Focal colors are universal after all. *Proceedings of the National Academy of Sciences*, *102*, 8386–91. doi:10.1073/pnas.0503281102

Regier, T., Kay, P., Gilbert, A., & Ivry, R. (2010). Language and thought: Which side are you on, anyway? In B. Malt & P. Wolff (Eds.), *Words and the mind: How words capture human experience* (pp. 165–182). New York: Oxford University Press.

Roberson, D., Davidoff, J., Davies, I. R. L., & Shapiro, L. (2005). Colour categories in Himba: Evidence for the cultural relativity hypothesis. *Cognitive Psychology*, *50*, 378–411. doi:10.1016/j.cogpsych.2004.10.001

Roberson, D., Davies, I., & Davidoff, J. (2000). Color categories are not universal: Replications and new evidence from a stone-age culture. *Journal of Experimental Psychology: General*, *129*, 369–398. doi:10.1037/0096-3445.129.3.369

Roberson, D., Pak, H., & Hanley, J. R. (2008). Categorical perception of color in the left and right hemisphere is verbally mediated: Evidence from Korean. *Cognition*, *107*, 752–762. doi:10.1016/j.cognition.2007.09.001

Rosati, A. G. (2015). Context influences spatial frames of reference in bonobos (*Pan paniscus*). *Behavior*, *152*, 375–406. doi:10.1163/1568539X-00003189

Rosch Heider, E. (1972). Universals in color naming and memory. *Journal of Experimental Psychology*, *93*, 10–20. doi:10.1037/h0032606

Rosch Heider, E. (1973). Natural categories. *Cognitive Psychology*, *4*, 328–350. doi:10.1016/0010-0285(73)90017-0

Sapir, E. (1924). The grammarian and his language. In D. Mandelbaum (Ed.), *Selected writings of Edward Sapir in language, culture, and personality* (pp. 150–159). Los Angeles 1: University of California Press.

Saunders, B. A. C., & van Brakel, J. (1997). Are there non-trivial constraints on coulour categorization. *Behavioral and Brain Sciences*, *20*, 167–178.

Shusterman, A., Lee, S. A., & Spelke, E. S. (2011). Cognitive effects of language on human navigation. *Cognition*, *120*, 186–201. doi:10.1016/j.cognition.2011.04.004

Slobin, D. I. (1996). From "thought and language" to "thinking for speaking." In J. Gumperz & S. C. Levinson (Eds.), *Rethinking linguistic relativity* (pp. 70–96). Cambridge, MA: Cambridge University Press.

Slobin, D. I. (2006). What makes manner of motion salient? Explorations in linguistic typology, discourse, and cognition. In M. Hickmann & S. Robert (Eds.), *Space in languages: Linguistic systems and cognitive categories* (pp. 59–81). Amsterdam: John Benjamins.

Spelke, E. (2011). Natural number and natural geometry. In S. Dehaene & E. Brannon (Eds.), *Space, time and number in the brain: Searching for the foundations of mathematical thought* (pp. 287–317). London: Academic Press.

Spelke, E. S., & Hespos, S. J. (2002). Conceptual development in infancy: The case of containment. In N. L. Stein, P. J. Bauer, & M. Rabinowitch (Eds.), *Representation, memory, and development: Essays in honor of Jean Mandler* (pp. 223–246). Hillsdale, NJ: Erlbaum.

Spelke, E. S., & Tsivkin. S. (2001). Initial knowledge and conceptual change: Space and number. In M. Bowerman & S. C. Levinson (Eds.), *Language acquisition and conceptual development* (pp. 70–97). Cambridge, UK: Cambridge University Press.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662. doi:10.1037/h0054651

Tan, L. H., Chan, A. H. D., Kay, P., Khong, P. L., Yip, L. C. K., & Luke, K. K. (2008). Language affects patterns of brain activation associated with perceptual decision. *Proceedings of National Academy of Sciences*, *105*, 4004–4009. doi:10.1073/pnas.0800055105

Thierry, G., Athanasopoulos, P., Wiggett, A., Dering, B., & Kuipers, J. (2009). Unconscious effects of language-specific terminology on pre-attentive colour perception. *Proceedings of the National Academy of Sciences*, *106*, 4567–4570. doi:10.1073/pnas.0811155106

Trueswell, J. C., & Papafragou, A. (2010). Perceiving and remembering events cross-linguistically: Evidence from dual-task paradigms. *Journal of Memory and Language*, *63*, 64–82. doi:10.1016/jml.2010.02.006

Ünal, E., Pinto, A., Bunger, A., & Papafragou, A. (2016). Monitoring sources of event memories: A cross-linguistic investigation. *Journal of Memory and Language*, *87*, 157–176. doi:10.1016/j.jml.2015.10.009

van Brakel, J. (1993). The plasticity of categories: The case of color. *British Journal of the Philosophy of Science*, *44*, 103–135. doi:10.1093/bjps/44.1.103

Werker, J. F., & Tees, R. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, *7*, 49–63. doi:10.1016/S0163-6383(84)80022-3

Winawer, J., Witthoft, N., Frank, M. C., Wu, L., Wade, A. R., & Boroditsky, L. (2007). Russian blues reveal effects of language on color discrimination. *Proceedings of the National Academy of Sciences*, *104*, 7780–7785. doi:10.1073/pnas.0701644104

Wolff, P. M., & Holmes, K. J. (2011). Linguistic relativity. *Wiley Interdisciplinary Reviews: Cognitive Science*, *2*, 253–265. doi:10.1002/wcs.104

Whorf, B. L. (1956). Language, thought and reality. In J. B. Carroll (Ed.), *Selected writings of Benjamin Lee Whorf* (pp. 35–278). Cambridge, MA: MIT Press.