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Conceptual Combination

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Abstract

Much has been learned about how individual concepts and semantic dimensions are represented in the human brain using methods from the field of cognitive neuroscience; however, the process of conceptual combination, in which a new concept is created from preexisting concepts, has received far less attention. We discuss theories and findings from cognitive science and cognitive neuroscience that shed light on the processing stages and neural systems that allow humans to form new conceptual combinations. We review systematic and creative applications of cognitive neuroscience methods, including neuroimaging, neuropsychological patients, neurostimulation, and behavioral studies, that have yielded fascinating insights into the cognitive nature and neural underpinnings of conceptual combination. Studies have revealed important features of the cognitive processes central to successful conceptual combination. Furthermore, we are beginning to understand how regions of the semantic system, such as the anterior temporal lobe and angular gyrus, integrate features and concepts, and how they evaluate the plausibility of potential resulting combinations, bridging work in linguistics and semantic memory. Despite the relative newness of these questions for cognitive neuroscience, the investigations we review give a very strong foundation for ongoing and future work that seeks to fully understand how the human brain can flexibly integrate existing concepts to form new and never before experienced combinations at will.

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Our ability to construct complex concepts from simpler constituents, referred to as *conceptual combination*, is fundamental to many aspects of cognition. One can, often effortlessly, comprehend a novel utterance, event, or idea via the manipulation, integration, or synthesis of other simpler or more familiar concepts; for example, upon hearing a news report that as a result of climate change the Pacific Northwest robin hawk is under threat of extinction, you might construct one of several plausible interpretations of the meaning of *robin hawk* (see figure 71.1). In order to understand such novel concepts, one must recruit a series of cognitive processes that might include identifying combinable features of the attributing and receiving concepts; selecting which of these features are to be transferred between concepts; integrating the selected features into a unitary conceptual representation; and confirming the plausibility of the resulting concept. Methods of cognitive neuroscience can be deployed to investigate the neural signatures for combined concepts and the subprocesses that create them in order to understand conceptual combination more broadly. Investigating how individuals combine concepts can shed unique light on different aspects of conceptual knowledge, including the cognitive mechanisms that enable the generative and flexible use of language.

Figure 71.1 Two plausible interpretations of the novel concept *robin hawk*. *Top*, A hawk with the red breast of a robin. *Bottom*, A hawk that preys on robins.

One might protest that it is premature to attempt to explain the processes by which simple or familiar concepts are combined to form complex or new concepts, and the representations of the resulting combined concepts, prior to having a more developed understanding of the cognitive and neural architecture of their building blocks. Several of the other chapters in this volume describe the progress—and also the many, many open questions that remain—in our quest to understand the representation of concepts and the processes by which they are learned, stored, and retrieved. Why would one embark on a quest to understand how concepts are combined before we better understand the seemingly more fundamental questions about conceptual representation? We suggest that questions that arise when considering the processes and resulting representations of conceptual combination may help shed light on—or at least, suggest lines of fruitful inquiry into—more basic questions of conceptual representation. For example, what conceptual structures are flexible enough to allow for the decomposition and recomposition of features into novel combinations? In addition, some of the processes that govern the integration of simple concepts (such as *finger* and *lime*) into complex concepts (such as a *finger lime)* might also govern how simple sensory features (such as *round*, *tart*, and *green)* are integrated into so-called simple concepts (such as *lime).* In other words, combination occurs at multiple levels of semantic processing, even for so-called simple concepts. As such, we can potentially advance our understanding of conceptual processing of all sorts by asking questions about how concepts are combined. That is our undertaking in this chapter: How do we construct meaning out of ideas represented in, for example, noun-noun phrases such as *robin hawk*? What neural systems are recruited as we understand these newly combined concepts? We view these questions as critical to understanding not only one of the most fundamental and generative aspects of cognition but also basic questions about conceptual systems.

One note before we begin: Familiar phrases that are now treated as “simple concepts,” such as *doorstop* or *straightjacket*, were at one time novel combinations of existing concepts. As certain conceptual combinations fall into common use, they can become integrated into language as unitary lexical entities (*compound words*). When examining the process of conceptual combination, we will not consider these established phrases, which might be treated as a singular word after repeated use. Indeed, some investigations explicitly regress out the natural frequency of combinations to ensure that any identified neural substrate is not driven by the familiarity of a compound word or phrase (e.g., Graves, Binder, Desai, Conant, & Seidenberg, 2010). This is not to say that once a combination becomes familiar, it ceases to act in a combinatorial manner. Though familiar and novel combinations differ in their lexical retrieval, their respective patterns of response times suggest that both undergo similar computations (Estes & Jones, 2008; Gagné & Spalding, 2004). But we have found that studies of novel combinations provide a unique opportunity to explore critical questions about conceptual processing, and for this reason these studies are the focus of this chapter.

The Structure of Conceptual Combinations

The two interpretations of *robin hawk* depicted in figure 71.1 illustrate a potentially useful distinction: certain conceptual combinations (*canary crayon*) are feature-based (or *attributive*), which are understood by selecting a property from a modifier noun (yellow from *canary*), mapping this onto a dimension of the head noun (the color of a crayon), and then integrating them to form the combined concept (a yellow crayon). Schema-based theories of conceptual structure frame this process in terms of each concept containing a set of different dimensions into which alternative properties can be placed (in this case, through a modifier noun; e.g., Murphy, 1988). Comprehending a combined concept involves understanding the transference of a correct property into the other concept's appropriate dimension. Other conceptual combinations (*crayon box*) are *relational*. For these combinations, understanding the relation between items (e.g., containment) is crucial and allows a person to understand that a crayon box is a box that contains crayons. The precise relationship between attributive and relational combinatorial processing has been a topic of debate in the field of cognitive science (e.g., Estes, 2003; Gagné & Shoben, 1997). One contribution of cognitive neuroscience has been to shed new light on questions such as this (e.g., Boylan, Trueswell, & Thompson-Schill, 2017, discussed later in this chapter).

A large variety of relations can exist between constituent concepts, and the precise relation between two concepts is extremely significant. *Bird nest* involves one concept (bird) inhabiting another (nest); *flower girl* involves the temporary possession of an object (flower) by an agent (girl). Work in this area shows that we represent the relation between concepts in a relatively precise way. Concept combinations with particular combinatorial relationships can prime other concept compounds that are represented in the same way (e.g., *bird nest* primes *fish pond*; Estes, 2003; Estes & Jones, 2006; Gagné, 2001). Yet the priming combinations can be remarkably specific. For example, *bird nest* does not prime *toy box* (Estes & Jones, 2006). Though the relationships involved in *bird nest* and *toy box* are superficially similar, the presence of a *potential* common relation (such as containment) is not sufficient to induce priming. Instead, *bird nest* is more accurately characterized by the relationship of habitation, allowing it to prime *fish pond* but not *toy box*. This example illustrates the broader idea that conceptual combinations are represented as very particular interactions between composing concepts. The identification of these precise interactions often requires the empirical study of behavioral responses in carefully designed tasks.

Cognitive Processes in Conceptual Combination

The cognitive process of combining concepts appears to be automatic and implicit, without requiring top-down instruction. This is well illustrated by behavioral priming, in which a person's behavioral response speeds up after perceiving two items that share a particular stimulus characteristic in quick succession. The presence of a priming effect based on a particular stimulus dimension informs theories of cognitive and neural architecture (Churchland, 1998); for example, priming based on word phonology or meaning indicates an organization of language and memory systems that reflects those characteristics. A priming effect has also been identified based on the compatibility of two concepts for being combined (Estes & Jones, 2009). Specifically, presenting a word that starts a potential conceptual combination (e.g., *farm*) speeds subsequent judgments of combination-compatible words (*mouse*), with a similar magnitude and prevalence to more common forms of priming, such as that based on semantic meaning (*mouse*—*rat*; Estes & Jones, 2009). The presence of priming based on conceptual combination suggests that the plausibility of potential combinatorial relationships is automatically calculated during language comprehension.

At what point during word processing does combinatorial processing occur? A number of investigations converge on an important time frame of approximately 400 ms after presenting combining words. This matches the poststimulus delay that has long been associated with the integration of meaning during typical sentence processing, reflected in the N400, an event-related potential (ERP) that is observed 400 ms after a person encounters a word that is unexpected relative to its surrounding sentence (Kutas & Hillyard, 1980). The attenuation of the brain's electroencephalographic signal at 400 ms poststimulus indicates the successful integration of a compound word's meaning (El Yagoubi et al., 2008). Interestingly, a reduction in neural activity is also observed at approximately 400 ms after plausible, compared to less plausible, compounds (Koester, Holle, & Gunter, 2009), suggesting that this stage of conceptual combination is more than a signal of familiarity. Instead, cognitive processes during this time frame include those necessary to calculate a combination's plausibility.

What is the nature of the cognitive processes that underlie conceptual combination? Historically, conceptual combinations have been framed as resulting from amodal operations in predicate-like structures (Fodor & Pylyshyn, 1988; Smith, Osherson, Rips, & Keane, 1988). For example, *red cup* is the result of binding the relevant value (red) to an argument (color) within *cup*, which is composed of many different arguments (color, shape, volume, and more). These arguments are not independent: changing an argument's value can propagate correlated values to other arguments. For example, *large bird* not only affects a bird's expected size but also changes its beak shape from straight to curved (Medin & Shoben, 1988). Connectionist approaches provided an alternative explanatory framework for conceptual combination by replacing predicate-like processes with statistical mechanisms (Pollack, 1990; Smolensky, 1990). A further alternative has drawn on simulation theory to suggest that people combine multimodal simulations (with associated perceptions, beliefs, and emotions) of individual concepts into larger, more complex simulations so that *red* and *cup* simulations are combined to successfully simulate *red cup* (Barsalou, 1999; Wu & Barsalou, 2009).

To test this last idea, Wu and Barsalou (2009) have investigated how the generated characteristics of items change after conceptual combination by having participants read combined concepts (e.g., *rolled-up lawn*) and generate features for each combination. Their results showed that the act of combining concepts shifted the features that participants generated in a way that respected visual occlusion even though the actual features remained largely unchanged in the concept. For example, a lawn has features that include blades, dirt, green, is played on, and more. The features generated by participants to the cue *lawn* shifted from being dominated by external features (blades) to being dominated by internal features (dirt) once presented as a combined concept (*rolled-up lawn*). The generated features were similar to those generated when participants were explicitly told to engage in imagery, which is consistent with the idea that participants were spontaneously deploying perceptual simulation when they processed the combined concepts. The shift in generated features was not simply a function of the modifier: features generated for *rolled-up snake* did not differ from *snake*, suggesting the shift is driven by a recombination of features within the head concept (*lawn*), rather than simply the addition of new features by a modifier (*rolled-up*). Shifts in generated features were observed for known (*convertible car*) and novel (*glass car*) conceptual combinations, suggesting it was not simply a product of how conceptual combinations are represented in memory. Nevertheless, an open question remains of whether simulation plays a role in the construction of combined concepts or is part of a postcombination process. One such process could be the automatic calculation of a combination's plausibility, which (based on priming) appears to occur even in the absence of explicit plausibility judgments (Estes & Jones, 2009). A fascinating direction for future work will be to characterize the cognitive processes that are unique or shared across different steps toward successful conceptual combination.

The Neural Basis for Conceptual Combination

Cognitive neuroscience theories of semantic knowledge suggest a number of alternatives for how conceptual combination is instantiated in the brain. Some theories represent semantic knowledge as distributed patterns of semantic features across areas of neocortex (Martin, 2007); these theories would suggest that a combined concept is similarly represented across the same neural regions that represent its constituent concepts and corresponding features. On the other hand, theories of semantic knowledge that posit integration sites or semantic "hubs" (Damasio, 1989; Patterson, Nestor, & Rogers, 2007) suggest that processing combined concepts involves additional neural regions involved in the integration or abstraction of conceptual information. Cognitive neuroscience investigations have repeatedly highlighted two cortical sites as being particularly involved in conceptual combination: the anterior temporal lobe (ATL) and the angular gyrus (AG). We explore how these regions (among others) relate to conceptual combination in the remainder of the chapter.

The anterior temporal lobe Classical and recent findings in cognitive neuroscience have established that the properties often combined during conceptual combination, such as color (Zeki et al., 1991), shape (Tanaka, 1996), size (Coutanche & Koch, 2018; Konkle & Oliva, 2012), and manipulation (Buxbaum, Kyle, Tang, & Detre, 2006), are represented across distributed areas of neocortex. How are such features integrated? The process of integration itself is nontrivial, as the same property can vary when combined with different noun concepts: for example, *red* takes on different values when integrated with *face*, *fire*, or *truck* (e.g., Halff, Ortony, & Anderson, 1976). Cognitive neuroscience studies implicate both the ATL and AG in conceptual integration. The ATL is known to be a key brain area underlying semantic knowledge (Patterson et al., 2007). The processing of semantic associations has been linked to ATL activity through multiple neuroimaging methods, including functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG; Lau, Gramfort, Hämäläinen, & Kuperberg, 2013). Importantly, the ATL appears to play a key role in integrating features to form semantic representations, potentially acting as a "hub" that links and integrates information between feature-specific regions across sensorimotor cortex (Lambon Ralph, Jefferies, Patterson, & Rogers, 2017). For instance, to study how features converge to form object concepts, Coutanche and Thompson-Schill (2015) identified the ATL as a potential *convergence zone* (Damasio, 1989) for the shape and color of known objects. Coutanche and Thompson-Schill scanned participants with fMRI as they held a known object in mind (e.g., tangerine) during a top-down visual detection task. Using multivariate techniques, the specific shape (e.g., sphere) and color (e.g., orange) of the retrieved objects were decodable in regions involved in shape (lateral occipital complex) and color (V4) processing, respectively. In an exploratory analysis, the only region with activity patterns for the identity of the retrieved object (e.g., tangerine) fell within the left ATL. Furthermore, a time series analysis showed that significant ATL object decoding was best predicted by significant feature decoding in shape and color regions. In other words, feature information in visual cortex predicted object representations in the ATL, consistent with the ATL acting as a site for integration.

A current area of debate and investigation is whether the ATL is specialized for the visual modality or if it also acts as an amodal hub for concepts with limited visual relationships (e.g., *truth*; Bonner & Price, 2013). Given its large size, one possibility is that ATL subregions have differential roles for visual and nonvisual combinations. For example, a meta-analysis has suggested that ventral ATL regions are more likely to be recruited during visual object processing, whereas lateral ATL areas are employed in auditory processing (Visser, Jefferies, & Lambon Ralph, 2010).

If the ATL is a semantic hub where conceptual features are integrated to form more complex conceptual representations (Lambon Ralph et al., 2017; Patterson, Nestor, & Rogers, 2007), it should respond more to combinations that involve integration, versus those that do not. In an MEG study, Bemis and Pylkkanen (2011) contrasted integrative and nonintegrative combinations to find brain regions sensitive to property integration. Specifically, they isolated regions whose activity was more strongly modulated by the comprehension of integrative combinations (e.g., *red boat* vs. *xkq boat*) than by nonintegrative combinations (e.g., *cup boat* vs. *xkq boat*). The use of adjective-noun combinations, rather than noun-noun combinations, can be a valuable way to isolate the integration process, independent of the additional processes of property selection (required for noun-noun combinations). The left ATL was specifically sensitive to integrative combinations, with related activity occurring approximately 200–250 ms after stimulus presentation. In a similar MEG study, the left ATL was found to be sensitive to conceptual integration during the basic comprehension of visual and auditory stimuli (Bemis & Pylkkanen, 2013). Furthermore, an integration-sensitive response occurs in the ATL when the task does not explicitly require integration, even if the order of concepts is flipped (e.g., *boat red*), suggesting that ATL integration is automatic and reflects semantic, rather than syntactic, composition (Bemis & Pylkkanen, 2013).

Is the ATL modulated by the form of the interactions between modifiers and object concepts? Westerlund and Pylkkanen (2014) varied the specificity of object concepts and observed whether the ATL integration response was affected. Brain responses were collected as participants processed combinations with low-specificity nouns (e.g., *blue boat*) or combinations with a highly specific counterpart (e.g., *blue canoe*). Other linguistic properties, such as frequency and the transition probability between adjective and noun, were carefully matched. The left ATL responded more strongly (250 ms after the noun presentation) for low-specificity combinations than for high-specificity combinations. This effect indicates that the left ATL's combinatorial response is influenced by semantic properties of the noun, such as conceptual specificity, nicely linking language-focused and semantic-hub accounts of the ATL's role in conceptual combination (Westerlund & Pylkkanen, 2014).

As well as assessing the magnitude of ATL activity during the comprehension of combined concepts, researchers can explore the content of the resulting representations. Baron, Thompson-Schill, Weber, and Osherson (2010) presented fMRI participants with images of faces varying in gender and age and collected multivoxel patterns that corresponded to each of the target properties (i.e., male, female, young, old) as well as combinations (e.g., young woman). The combined concepts resulted in multivoxel patterns in the left ATL that were predicted by the superimposition of the constituent concepts.

Taken together, these results suggest that the left ATL might represent the conjunction of concepts, in addition to representing the conjunction of basic perceptual features. An open question concerns whether the ATL neural computations that might bind features to form basic concepts overlap completely, or only partially, with neural computations used to bind concepts into conceptual combinations. This will be an important question for the field going forward.

The angular gyrus The AG is another region that has been consistently implicated in studies of conceptual combination. This region of inferior parietal cortex has widespread connections across cortex, including sensory and language networks (Caspers et al., 2011), supporting the idea that the AG lies at the top of a semantic processing hierarchy (Binder, Desai, Graves, & Conant, 2009). The AG has been linked to the combinatorial strength, or plausibility, of conceptual combination. In an fMRI study, Price, Bonner, Peelle, and Grossman (2015) found that the AG responds preferentially to combinations that form meaningful, compared to less meaningful, concepts (e.g., *plaid jacket* vs. *moss pony*) and that this did not depend on the kind of information being integrated (e.g., visual, tactile). Further, right AG cortical thickness predicted how people responded to combined concepts, such as the magnitude of their response-time advantage for phrases with higher combinatorial strengths (Price et al., 2015). Adding to evidence for the region's key role in combinatorial processing, neurological patients with damage to the left AG have shown impairments in combinatorial tasks, with larger impairments experienced by patients with greater AG atrophy (Price et al., 2015).

In a recent neurostimulation study, Price, Peelle, Bonner, Grossman, and Hamilton (2016) stimulated the AG of healthy participants to observe the behavioral consequences for combinatorial processing. Anodal high-definition transcranial direct current stimulation (tDCS) was used to excite left AG cortical sites, which led to faster responses to meaningful (*tiny radish*), compared to nonmeaningful (*fast blueberry*), adjective-noun combinations. The effect of stimulation on response times was correlated with the degree of semantic coherence between the adjective and noun in the combination. In contrast, stimulation of the right AG slowed responses to meaningful (vs. nonmeaningful) combinations.

As the studies discussed thus far illustrate, the relative roles of the left and right AG are not currently clear. Neurological damage and stimulation of the left AG both affect behavioral responses to combinatorial pairings, but cortical thickness in the right (but not left) AG has predicted individual differences in response times to combinable word pairings. In functional studies, AG activity is often lateralized. For instance, Graves et al. (2010) compared meaningful noun-noun combinations (e.g., *lake house*) to less meaningful reversals (*house lake*) during an fMRI scan and found that combinatorial comparisons activate the AG with a large right-sided bias, while lexical processing stimulated the left AG. They proposed that regions of the right hemisphere have larger semantic fields, enabling a broader array of conceptual links to be made during combinatorial processing (Beeman et al., 1994; Graves et al., 2010). Alternatively, the right AG might differ from the left in having access to *implicit* relational content in combinations (Boylan, Trueswell, & Thompson-Schill, 2017). The left AG instead might require the presence of explicit syntactic cues about a relation in order to process the corresponding combination.

The left inferior frontal gyrus Processing less meaningful combinations has been associated with increased activity in left frontal cortex, including the left inferior frontal gyrus (LIFG; Graves et al., 2010), which is implicated in semantic selection (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). This LIFG activation might reflect attempts to select the appropriate information to integrate, which is a more effortful process for combinations with a less obvious meaning. The need for a selection process—for successfully comprehending conceptual combinations—is particularly apparent for feature-based combinations, in which a subset of features is selected and applied. For example, the intended referent of *canary crayon* does not involve an actual canary: rather, the person comprehending must select the property *yellow* from a set that includes *small*, *has wings*, and more. The selected property is then integrated with *crayon*. Similarly, *prune skin* does not involve actual prunes, and the term *piano key teeth* does not involve actual piano keys. These combinations are thus similar to metaphors (e.g., "His teeth are piano keys"), where the processes of selection and integration still apply. In order to study how appropriate features are selected during the comprehension of these attributive metaphors, Solomon and Thompson-Schill (2017) computed a metaphor-specific measure of property selection. They observed the extent to which certain properties became activated after metaphor comprehension by presenting participants with a metaphor (e.g., “Her skin is a prune”) and then asking how much faster participants agree that a metaphor-relevant property (e.g., wrinkly) applies to a modifier concept (e.g., *prune*), relative to a metaphor-irrelevant property (e.g., sweet). During an fMRI scan, this property-selection measure predicted activity in the LIFG, suggesting this region is involved in the selection of conceptual properties during metaphor comprehension. This same process might underlie property selection when processing noun-noun conceptual combinations.

Regional interactions and differences How does combinatorial processing in the ATL and AG relate to each other? Processing in the ATL occurs approximately 200 ms after relevant stimuli, followed by processing in the AG 200 ms later (Bemis & Pylkkänen, 2013). Molinaro, Paz-Alonso, Duñabeitia, and Carreiras (2015) examined how regions of lexical and semantic networks, particularly the ATL and AG, respond to differing levels of combinatorial processing. The authors examined concepts and attributes with differing degrees of typicality: prototypical (*wet rain*), contrastive (opposing the typical property: *dry rain*), and noncomposable (*blind rain*). Participants’ ATLs were sensitive to the typicality of the perceived word pairings, with greater responses to contrastive, compared to typical, combinations. The ATL also showed particularly strong coupling with the AG during the contrastive combination condition, suggesting coordination between these regions during difficult semantic integrations. This coupling occurred in the context of activation across the broader lexical-semantic network, with activation in the posterior middle temporal gyrus (a region involved in lexical/semantic processing; Lau, Phillips, & Poeppel, 2008) for all conditions and in the LIFG (possibly for the controlled retrieval of lexical-semantic information; Thompson-Schill, Aguirre, D’Esposito, & Farah, 1999) for complex constructions (*dry rain*/*blind rain*). The ATL was connected with both the medial temporal lobe and the IFG during these complex constructions but only with the AG during the contrastive combination. Coordination between these regions appears to play an important role in combinatorial processing.

The ATL and AG appear to respond differently based on the type of conceptual combination being processed. Boylan, Trueswell, and Thompson-Schill (2017) compared how the regions respond to attributive versus relational nominal compounds. The two regions responded to both types of compound, but the nature of the regions’ response differed based on the kind of combination. The AG responded more strongly to relational, compared to attributive, compounds. In contrast, the ATL responded with a similar magnitude to both but had an earlier response to attributive combinations. These findings shed light on a potential greater role for the AG when combinations require more relational processing and suggest that attributive combinations might be processed first in the ATL (Boylan, Trueswell, & Thompson-Schill, 2017).

Summary

As the work described in this chapter indicates, conceptual combination is a multifaceted process, involving feature selection, integration across concepts, and plausibility assessments. The human tendency to engage in conceptual combination is often automatic and implicit, leading to the processing of conceptual combinations 400 ms after combinable items are presented. The ATL and AG appear central to the combinatorial process. Interactions between these regions, and with other areas of the lexical and semantic networks, are crucial to successfully combining concepts. As the methods of cognitive neuroscience continue to be applied to explore how our brains combine and comprehend concepts, we move closer to understanding the place of conceptual combination within the operation of the semantic system more generally.

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