The Neural and Cognitive Bases of Ambiguous and Unambiguous Conceptual Combination

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Conceptual representations can be altered to align with the current context given learning and task goals. One cognitive process, known as conceptual combination, allows for a unique perspective for exploring how complex conceptual processing occurs and how this processing influences the underlying representations of concepts. During novel nominal conceptual combination, two constituent nouns, a modifier noun (e.g., lemon) and a head noun (e.g., flamingo) are creatively combined to form a novel meaning (e.g., a lemon flamingo might be a yellow flamingo). Different strategies can be taken up by combiners - typically being either attributive (as above) or relational (e.g., a lemon flamingo is a flamingo that consumes lemons). Importantly, few studies have directly examined more ambiguous combinations, which are more complex to process, having an equal likelihood of being combined attributively or relationally between individuals. This dissertation addresses two main aims for understanding nominal conceptual combination through a series of four studies. First, it explores the pathways driving different kinds of conceptual combination. In Study 1, I examine how easily conceptual combinations can be formed and subsequently remembered. In Study 2, I explore how individual differences in cognition predict ease of combining. The second aim explores how conceptual combination differently impacts the representations of the constituent concepts. In Study 3, I address whether and how the cognitive representations of the head noun in a conceptual combination are altered because of being conceptually combined. Finally, Study 4 addresses both aims using neuroimaging to explore how different types of conceptual combinations are processed and how the neural representations of concepts are altered because of their combination. The findings show representational change due to conceptual combination in early visual processing regions of the brain and suggest that conceptual combination may rely on additional cognitive processes throughout the lifespan. There is also an emerging theme of the importance of cognitive control in the ease of combining. Finally, the findings show differences in the processing of different types of conceptual combinations, both between attributive and relational combinations and between unambiguous and ambiguous, advocating for the inclusion of ambiguous compounds in future studies of conceptual combination.

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1.0 Introduction

The human memory system allows for the storage of a theoretically unlimited number of facts, or semantic information. This information is efficiently stored in the brain as mental representations of categories, known as concepts (e.g., *giraffe*, *ant*, *apple*), that are connected to their features. The concept of *giraffe*, for instance, is connected to features such as TALL, SPOTTED, and ANIMATE. The brain generalizes over each overlapping experience to store and organize these concepts (Barsalou, 2016). An organized conceptual system is the foundation for several higher-order cognitive processes, such as improved efficiency when making decisions or problem solving (Binder, et al. 2009; Lewellen, et al. 1993; Martin & Chao, 2001).

1.1 Conceptual Representations

Researchers have long debated the structure of the semantic memory system. One popular theory, known as the hub and spokes model, argues that concepts are organized in the brain such that feature information is distributed throughout the brain in spokes and integrated in a central hub (Lambon Ralph, et al. 2017; Patterson, Nelson, & Rogers, 2007). Though there is some disagreement between supporters of this model as to whether or not multiple hubs might exist, there is a consensus among supporters of the model that one of these hubs (or the only hub) is the anterior temporal lobe (ATL). The evidence for this originates from data collected from patients diagnosed with semantic dementia. These patients, who have a neurodegenerative disease that affects their anterior and inferior temporal lobes, experience impairment to their semantic processing, but little to no impact on other areas of cognition (Bonner, et al. 2009).

One study that demonstrates this model examined the neural representations elicited when one retrieves memory for a known item, such as a *carrot*. The study found, as expected, that the item's perceptual features, such as its shape and color information, were represented in the lateral occipital complex (LOC) and V4, respectively (Coutanche & Thompson-Schill, 2015). Importantly, at those same time points, *carrot* was being neurally represented at the item-level in the left ATL. In this example, V4 and the LOC behave as spokes, feeding color and shape information, respectively, to the ATL hub.

1.2 Manipulation of Concepts and Associated Representational Changes

Importantly, semantic concepts, once learned, are not unalterable. Instead, long-term and transient representational changes often aid in adapting to new contexts and modifying with higher-order processing. For example, upon learning that giraffes can hum, the brain does not entirely re-form the concept of *giraffe*, but instead, it can update the current concept with the new featural information. Evidence of the malleability of semantic knowledge can be observed both in the context of long-term learning and as a result of task conditions.

Representational changes as a result of long-term learning have been uncovered in the ATL, for instance. In one study, participants learned to associate pseudowords with one of six categories of words (monkeys, donkeys, elephants, hammers, wrenches, screwdrivers) for 8 training sessions (Malone, et al. 2016). As these were pseudowords, they cognitively and neurally should not reflect any sort of semantic relationships before training. After encoding, however, the representations of the pseudowords reflected the semantic relationships that are expected of the six categories, both at the basic (e.g., monkeys vs. donkeys) and superordinate (e.g., animals vs. tools) levels. The changes here reflect semantic-level structural changes. These long-term changes are not just reflected in the semantic hub but have also been uncovered in regions of the ventral temporal (VT) lobe, which are specialized for representing featural information, such as shape (LOC; Grill-Spector, Kourtzi, & Kanwisher, 2001), configural face representations (FFA; Kanwisher, McDermott, & Chun, 1997), and more. For instance, one study measured neural representational changes as a result of aversive learning (Dunsmoor, Kragel, Martin, & LaBar, 2013). In this study, participants were trained to fear certain types of stimuli (e.g., animals) and not other types (e.g., tools) using one category as an excitatory conditioned stimulus and the other as an inhibitory conditioned stimulus. After training, category-selective regions (localizer-defined) and the amygdala had more similar representations for items within categories that received aversive training than those within categories that did not receive aversive training.

In addition to long-term representational changes, the brain is capable of transient goal-related changes. Theories for how this process occurs originally suggested that task-relevant stimulus information would be expanded while task-irrelevant information would be collapsed while those tasks are being performed (Nosofsky, 1986). Past studies, which implemented multidimensional scaling (MDS) to measure representational space, found evidence of attention-based changes wherein similarity relationships changed in accordance with task goals (Nosofsky, 1986). More recent research has supported these theories. This hypothesis—that concepts contain multiple dimensions and that those dimensions can become more or less expanded according to task commands—is called the relevancy hypothesis (Bugatus, et al. 2017). This was shown in early visual cortex, for example, in one experiment where participants viewed colors and performed either a color-naming or a diverted attention task (Brouwer & Heeger, 2013). In the color-naming task, they were simply asked to name the color of the stimulus on screen. During the diverted-attention condition, however, attention was diverted away from color. Consistent with the relevancy hypothesis, regions showed categorical clustering of colors during the color-naming and not during the diverted attention task. These findings speak to the role of attention in reshaping these representational spaces. By attending to the specific feature of color, the representational spaces of regions involved with color processing were rearranged to better suit the task at hand. These findings have been shown in more complex tasks as well. One study found that one's behavioral goal can change how featural semantic information is processed in VT given the same perceptual stimuli (Nastase, et al. 2017). By asking participants to pay attention to either the taxonomy or behavior of animals on screen, the representational structure of VT was modified to more appropriately meet the task goals.

1.3 Conceptual Combination

Although studies have found instances of representational change as a result of long-term learning and task-related goals (e.g., Malone, et al. 2016; Nastase, et al. 2017; Nosofsky, 1986), few have examined how internally chosen strategies might produce similar changes. In addition, these studies of concepts often examine unitary concepts as opposed to paired or multiple concepts, which are how humans often more naturalistically interact with concepts. Finally, our understanding of concepts should not be considered only in terms of what they mean and how they are represented, but how they interact with other concepts. One cognitive process, conceptual combination, will likely be fruitful as we begin to confront these underexplored areas.

Conceptual combination is our ability to creatively compose and produce novel, complex conceptual representations from existing concepts (for review, see Coutanche, Solomon, & Thompson-Schill, 2019). During conceptual combination, constituent concepts (e.g., *ant* and *apple*) are combined to generate a new complex concept (e.g., *ant apple*). These combinations form the basis for communication, taking the form of not only noun-noun pairs but also adjective-noun pairs (e.g., *red boat*) and phrases. Conceptual combination has also been argued to be the basis of metaphor comprehension (e.g., "My *lawyer* is a *shark*."; Holyoak & Stamenković, 2018; Kintsch, 2000). The simplest form of conceptual combination takes the form of an adjective-noun pair, where the modifier concept (e.g., *red*) is applied to the head concept (e.g., *boat*). In these combinations, the presence of the concept *red* modifies the *boat*'s color attribute.

More complex processing occurs during the conceptual combination of nominal (i.e., noun-noun) compounds. Here, two main strategies are taken up by the combiner (Gagné & Shoben, 1997; Wisniewski, 1997; Wisniewski & Bassok, 1999; Wisniewski & Gentner, 1991; Wisniewski & Love, 1998). Some combinations are attributive, such that a feature (sometimes referred to as "property") of the modifier noun is attributed to the head noun (e.g., for *lemon cup,* one might imagine a yellow cup; Coutanche et al. 2019; Estes, 2003). Other combinations are relational, such that the modifier noun determines the relationship (sometimes referred to as the "function") between itself and the head noun (e.g., for *chocolate wreath*, one might imagine a wreath MADE OF chocolate; Coutanche, et al. 2019; Estes, 2003). Conceptual combination of nominal compounds requires the combiner to infer the relation between the modifier and head noun. Doing so often allows for a narrowing of the meaning and relevant properties of the head noun (e.g., a *circus lion* as a subclass of *lion* that is tamer than a typical lion; Estes, 2003).

There has been significant debate regarding whether this distinction of combination strategies actually reflects distinct processing (Estes, 2003; Gagné & Shoben, 1997; Spalding, et al. 2010; Wisniewski, 1996). Some argue for a dual-processing model in which relational and attributive combinations have distinct underpinnings. According to this model, features and relations are processed in parallel and one is ultimately selected to define the meaning of the combination (Estes, 2003). Others argue for a more parsimonious explanation in which both strategies undergo the same processing (Gagné & Spalding, 2013). This model states that relational and attributive processing occurs serially, with relations being processed prior to features. This theory is laid out by the Relational Interpretation Competitive Evaluation (RICE) model, which states that conceptual combination occurs in three steps: Relation Suggestion, Relation Evaluation, Elaboration (Gagné & Spalding, 2013). These stages largely depend on which types of relations the modifier and head nouns can make and how competitive the relation is for the noun (i.e., relational availability). For example, the noun *planet* has a dominant LOCATIVE relation compared to other relations it can make, such as DERIVED FROM. This model, stating that the relational availability of the modifier noun determines how a word pair will be conceptually combined, is an expansion of a previous theory (i.e., CARIN model; Gagné & Shoben, 1997). During **suggestion**, competition for interpretation begins with relational availability of the modifier noun. High competitors will limit future steps more than weak competitors. During **evaluation**, the relational availability and semantics of both the modifier and the head noun are considered. If a relation is winning from the suggestion phase but is not compatible with the relation structure of the head noun, another relation will likely dominate instead. Finally, during **elaboration**, a gist of the new relation is created so that one can deepen their semantic meaning of the new concept using real-world knowledge (e.g., a *snow man* interpreted as a man MADE OF snow will be cold and white, whereas a man FOR snow will be animate and may have a shovel; Gagné & Spalding, 2013). According to this model, attributive combinations are simply special instances of relational combinations where the relationship instantiated by the combination is RESEMBLANCE (e.g., a *zebra clam* is a *clam* that RESEMBLES a *zebra*; Gagné, 2000). Given that RESEMBLANCE is a relatively infrequent relation for most concepts, the relational theories also suggest that attributive combinations tend to be more challenging to combine and interpret.

Importantly, some combinations are more ambiguous to combine. These combinations take two forms where 1) they tend to be combined with some strategy that is not purely attributive or relational or 2) at a group level, they tend to be equally likely to be combined attributively and relationally. Most studies of conceptual combination examine attributive or relational combinations, with stimuli intentionally chosen to be strongly likely to be combined with the given strategy, but this leaves open the question of what happens when the possible strategy to be chosen is less clear. Again, it is not that these combinations will not ultimately be combined by any given individual using an attributive or relational strategy, it is that the path for deciding which strategy to implement is more challenging for these ambiguous combinations, as evidenced by the variety of strategies taken up across combiners. One study directly examined how this type of combination is processed and failed to find any neural effect of ambiguity (Boylan, et al. 2017). Importantly, this examination was not the main aim of the experiment. Instead, a norming study was implemented to select the most attributive and most relational combinations (Boylan, et al. 2017). To achieve a clearer picture of conceptual combination, I intentionally examine the processing of these ambiguous combinations, which are likely more demanding and require more complex processing than their unambiguous (relational, attributive) counterparts. I anticipate that this may alter which cognitive processes are recruited to achieve combination and have implications for how they influence the semantic network and how well they are remembered.

As with any cognitive process, ease and success in performance can vary both between individuals and, at times, within individuals. In the case of conceptual combination, one cause of within-individual variation may result due to changes in context in which the number of available competitors for combining varies. According to the RICE model, the suggestion phase can be lengthened when there are more competitors present. In addition, we might anticipate that the ease with which one can combine may vary by individual due to differences in related cognitive processes.

This dissertation will examine how conceptual combination occurs and consider its implications for semantic memory. Here, I will use *cognitive representations* to indicate representations held at the cognitive level and *neural representations* to indicate voxel-wise representations. In addition, as conceptual combination comes in many forms, it is necessary to restrict my exploration. Here, to allow for the generation of novel combinations that rely on creative processing, I will restrict my examination to nominal combinations.

1.4 Aims

This work contains 4 main studies, each designed to understand two high-level questions: 1) how does conceptual combination occur, and 2) in what ways does conceptual combination rely on and influence the semantic network? Studies 1 and 2 address this first aim. Study 1 examines how a state change in which additional competitors are activated before conceptual combination might influence the ease with which these combinations can be performed. Study 2 exists as a preliminary exploration of the possible individual differences that may aid conceptual combination. Study 3 will address the second aim by examining whether there are cognitive representational changes as a result of conceptual combination. Finally, Study 4 addresses both aims using neuroimaging data. First, Study 4 aims to uncover the neural underpinnings of performing conceptual combination, focusing in particular on differences between types of combinations. Second, it examines neural representational changes to concepts as a result of combining.

Ultimately, this work demonstrates a cognitive divergence in the processing of ambiguous and unambiguous conceptual combinations. It also shows evidence of the importance of cognitive control while conceptually combining, speaks to the relationship between visualizing and subsequent retrieval, and demonstrates the flexibility of the semantic network. Findings also show aging-related changes in processing of conceptual combinations. Additional discussion of the methods, results, and implications of these studies follow below.

2.0 Study 1: Ease and Recall of Attributive, Relational, and Ambiguous Conceptual Combination

Rapid semantic processing requires efficiently organized semantic networks. During conceptual combination, the importance of efficiency is particularly prominent during the suggestion phase. According to the RICE model, during this phase, multiple features and relations compete to aid in defining the new word pair (Gagné & Soben, 1997; Gagné & Spalding, 2013). Two factors determine the speed and ease with which one can combine: 1) the number of competitions to be resolved and 2) the efficiency with which each competition is resolved. Study 1 is aimed at understanding how these factors interact with each strategy for combining.

Elaboration techniques can induce a state change wherein people can enter a more flexible cognitive state – one that is capable of faster activation of semantic networks (Morelli, et al. 2011). The technique can provide additional activation of semantically related information. Though state change has not been induced in past studies of conceptual combination, there is evidence that recent experiences can modify the interpretations of new conceptual combinations such that prior activation of relations through priming can bias relation selection (Gagné, et al. 2001; Gagné & Shoben, 2002). For instance, when people are given an example of a MADE OF relation before combining a relational combination, they are more likely to use that same relation when presented with a new pairing.

To understand the impact of a state change of deeper semantic processing on conceptual combination, participants were randomly assigned into one of two conditions before combining. To induce deep semantic processing before conceptual combination, participants assigned to this group were asked to perform an elaboration task. This task was designed to elicit a state change wherein participants experience increased semantic activation during combination. Shallow semantic processing was induced by asking people to compare the frequency at which they encounter two words.

According to the RICE model, additional competitors could hinder combination due to an increase in the number of competitions that need to be resolved before combination. However, it is also possible that, with additional activation of semantic processing, one could more quickly and efficiently navigate their semantic spaces. Although having more competitors during this phase may initially seem as though it may make combining more challenging by creating more possible futures, it may also allow for the rapid discovery of a strong competitor, ultimately decreasing effort in subsequent combining stages. I anticipate that the type of combination being made is important to consider. The suggestion phase can be an important limiting factor for subsequent combining. During relational and attributive combinations, where there are already salient relations or features to be selected, I expect that an increase in competitors would not make combining more challenging. In fact, in a task where people practice exploring their semantic space before combining, I hypothesize that I would see a benefit relative to a task with less focus on increasing semantic processing because it would be easier to find a strong competitor. On the other hand, in a combination task with ambiguous combinations, I expect that the increased activation of weak competitors would make combining more challenging.

In addition to understanding how a semantic state change might influence the ease with which people perform conceptual combination, there is reason to believe that this manipulation may also influence how well these newly associated word pairs are subsequently remembered. A recent study found that conceptual combination improves associative memory performance in a recognition memory task relative to other forms of encoding that require less holistic linguistic processing (Lucas, et al. 2017). This same study found that combinations that were easier to combine produced better subsequent memory. The study, which found that recall performance did not differ between tasks, concluded that conceptual combination creates unitized associative memories. Here, we examine whether these unitized memories are consistent across strategies (relational, attributive, ambiguous) and states (deep/shallow semantic processing) during combining. We hypothesize that, consistent with this past study, pairs that are more easily combined will be better remembered. In addition, I expect that participants will be more engaged with their semantic network after completing the deep processing task, which will aid in forming stronger associative memories. As such, I expect that participants who complete this task will have better associative memory performance than those who complete the shallow processing task.

2.1 Methods

2.1.1 Participants

Data were collected online via Qualtrics from 100 students attending the University of Pittsburgh who were compensated with partial course credit. Exclusion criteria were applied to ensure participants met language eligibility requirements and sufficiently completed the tasks. Language criteria were implemented to ensure that each participant's most proficient language was American English: 1) their native country was the US, 2) English was at least one of their first languages, 3) and they rated their most proficient language as English. Exceptions to these criteria were made only when the other language responses given strongly indicated that American English was their most fluent language (e.g., did not indicate a most fluent language, but described their other language experience as “none” or “some in school”). These language requirements eliminated 15 participants from the sample. In addition, each task was checked for responses indicating engagement in the study (see Results). By including these quality checks, 16 additional participants were removed, leaving us with a sample of 69 participants (age M = 18.6; 48 female, 21 male), 30 in the deep semantic processing group and 39 in the shallow semantic processing group.

2.1.2 Procedure

All participants provided informed consent before participating. Participants were randomly assigned to the deep or shallow semantic processing group. Each group began the study with a task lasting 5.25 minutes. For the deep semantic processing task, participants were presented with 7 words, each for 45 seconds, and asked to perform a free association task in which they typed out all words they associated with the cue they could in the allotted time. For the shallow semantic processing task, participants were presented with 63 words, each for 5 seconds, and asked to indicate whether the word presented was larger or smaller than a shoebox. While both tasks require the use of semantic knowledge to be completed, the deep semantic processing task was meant to engage this network more deeply, putting participants into a highly semantically active state.

After this initial manipulation, all participants completed the same tasks. They next completed a conceptual combination task with 60 word pairs (20 attributive, 20 relational, 20 ambiguous; see Appendix for norming details). Before beginning, they were given some examples of word pairs and definitions (equal examples of attributive and relational) and told that their goal for this part of the study was to imagine the definition that they felt fit best for each word combination. For each trial of the conceptual combination task, participants viewed the word pair for 2 seconds, viewed an “I” for 4 seconds when they were instructed to imagine the definition for the word pair, and then were prompted to indicate how well they could define the word combination on a scale of 1 (very well) to 7 (not well at all) for 4 seconds. Participants were encouraged to use the full range of the scale and were told to use 7 when they could not come up with any definition at all.

After combining, participants completed a cued recall task during which they were presented with the modifier noun and asked to type the associated head noun for the pair. Finally, participants were asked to provide their preferred definition for each word pair and answer basic demographic and language history questions (adapted from Tokowicz, Michael, & Kroll, 2004).

2.1.3 Analyses

To aid in interpretability of the results, the polarity of ease was swapped, such that 1 indicated the least ease and 7 the most ease in combining. Two models were run to analyze the results, one predicting ease of combining and another predicting recall performance. Ease of combining was analyzed using a linear mixed-effects model. In the model predicting ease, the interaction of a between-subjects categorical fixed variable (Level: deep, shallow) and a within-subjects categorical fixed variable (Combination Type: attributive, relational, ambiguous) was examined. Orthogonal contrasts were created, one examining the contrast of attributive and relational combination and the other examining the contrast of ambiguous and unambiguous (relational and attributive) combination. Item and subject were included as random effects and a random slope of combination type by subject was included. Recall was predicted using a generalized linear mixed-effects model, examining the interaction of Level, Combination Type, and Ease, a within-subjects continuous variable. Ease was included as a random slope by subject as well in this model. The bobyqa optimizer was implemented in the models to help them converge. For both dependent variables, a model was also run without the random slopes. AIC values were compared to select the model with the best fit.

Finally, to further examine whether deep semantic processing before combining aids in the combining process or subsequent memory for the pairs, I ran two correlations, one between the number of features generated by the deep semantic processing group and their average ease and another between the number of features and the average recall performance.

2.2 Results

2.2.1 Task Performance

Some participants were removed from analyses due to poor task engagement. For participants who completed the deep semantic processing task, I ensured that at least one word listed was semantically related to the cue. For those in the shallow semantic processing task, I checked two criteria: 1) that the participants' responses were variable (removed if < 3 SDs below average SD) and 2) for 10 questions with clear answers (e.g., Is a blimp larger or smaller than a shoebox?), participants got least 9 correct. Recall answers were checked for reasonable responses (e.g., responses should be letters, not numbers). Participants were excluded due to performance on the definition phase if, on multiple trials, they repeated the word associate (e.g., writing "lawyer" when prompted with "piranha lawyer"), and/or they typed a single character. Finally, responses were checked for the combination task (< 3 SDs below average SD; > ⅓ responses blank). As indicated in the Methods, with these quality checks, 16 additional participants were removed, leaving us with a sample of 69 participants. Overall, in the final sample, participants reported combinations as somewhat easy to combine on average (*M* = 4.89, *SE* = 0.04) and remembered about 40% of the word combinations (*M* = .40, *SE* = 0.01).

2.2.2 Ease

AIC comparisons of models with and without random slopes indicated a better fit for the model containing random slopes ($\Delta AIC = 8$, $\chi^2 = 17.43$, $p = .004$), so results reported here reflect that model (see Table 1).

There was a significant effect of combination type for the contrast of ambiguous relative to unambiguous compounds, $\beta = 0.95$, $SE = 0.25$, $t(64) = 3.86$, $p < .001$. Examining means indicated that it is easier to combine unambiguous (i.e., attributive (*M* = 5.05, *SE* = 0.05) and relational (*M* = 5.34, *SE* = 0.05)) nouns relative to ambiguous nouns (*M* = 4.27, *SE* = 0.06). In addition, there was a marginal effect of combination type (unambiguous vs. ambiguous) by level of processing, $\beta = 0.28$, $SE = 0.16$, $t(68) = 1.78$, $p = .080$. There was no correlation between the number of features generated by the deep semantic processing group and their ease of combining ratings ($r = -0.07$, $p = 0.705$).

Table 1. Fixed effect estimates for linear mixed effects regression of ease of combining.

Fixed effects	**Estimate**	**SE**	***t***	***p***
Intercept	4.86	0.14	35.47	< .001
Level (Deep vs. Shallow)	0.10	0.16	0.60	0.549
Ambiguity (Unambiguous vs. Ambiguous)	0.95	0.25	3.86	< .001

Unambiguous (Attributive vs. Relational)	-0.27	0.29	-0.93	0.354
Level x Ambiguity	0.28	0.16	1.78	0.080
Level x Unambiguous	0.28	0.18	1.55	0.127
Random effects	**Variance**			
Subject	0.39			
Item	0.73			

Note. Unambiguous consists of relational + attributive. Model: lmer(ease ~ 1 + level*comboType + (1|item) + (1+comboType|sub), REML = F, data = state_data, control = lmerControl(optimizer = "bobyqa", optCtrl = list(maxfun=20000)))

2.2.3 Recall

AIC comparisons of models with and without random slopes indicated no statistically significant differences between the two models (ΔAIC = 3.5, χ^2 = 14.5, p = .106). Numerically, the AIC was slightly lower for the model without the random slopes (AIC = 3834.4) than the model with (AIC = 3837.9), so that model is reported below (see Table 2).

Table 2. Results of logit model predicting correct recall.

Fixed Effects	**Coefficient**	***SE***	**Wald *z***	***p***
Intercept	-1.64	0.22	-7.54	< .001
Level (Deep vs Shallow)	0.09	0.34	0.28	0.781
Ambiguity (Unambiguous vs Ambiguous)	0.03	0.37	0.07	0.945
Unambiguous (Attributive vs Relational)	1.10	0.45	2.45	0.014
Ease	2.45	0.03	9.68	< .001
Level x Ambiguity	-0.20	0.47	-0.43	0.666

Level x Unambiguous	1.25	0.62	2.01	0.044
Level x Ease	0.01	0.05	-0.14	0.892
Ambiguity x Ease	0.05	0.05	1.09	0.277
Unambiguous x Ease	-0.14	0.06	-2.38	0.017
Level x Ambiguity x Ease	0.04	0.09	0.47	0.636
Level x Unambiguous x Ease	-0.24	0.11	-2.16	0.031

Note. Fixed effect estimates (top) and variance estimates (bottom) for logit model of correct recall (N = 3401, log-likelihood: -1903.2.). Model: glmer(recall ~ 1 + level + comboType + ease + level*comboType*ease + (1|item) + (1 + comboType + ease|sub),REML = F, data = state_data, family=binomial, control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=20000)))

There was an effect of combination type, where attributive combinations (M = .46, SE = 0.013) were better remembered than relational (M = .41, SE = 0.013), β = 1.10, SE = 0.45, z = 2.45, p = .014. Additionally, in line with previous research, there was an effect of ease, where combinations that were easier to combine were better remembered, β = 2.45, SE = 0.03, z = 9.68, p < .001. There was a significant 3-way interaction of level, ease, and unambiguous compounds, β = -0.24, SE = 0.11, z = -2.16, p = .031, see Figure 1. The model showed that this same contrast interacted with ease (β = -0.14, SE = 0.06, z = -2.38, p = .017) and with the level of semantic processing due to the state change manipulation, β = 1.25, SE = 0.62, z = 2.01, p = .044. The number of features generated by the deep processing group did not correlate with recall performance, r = 0.302, p = 0.105.

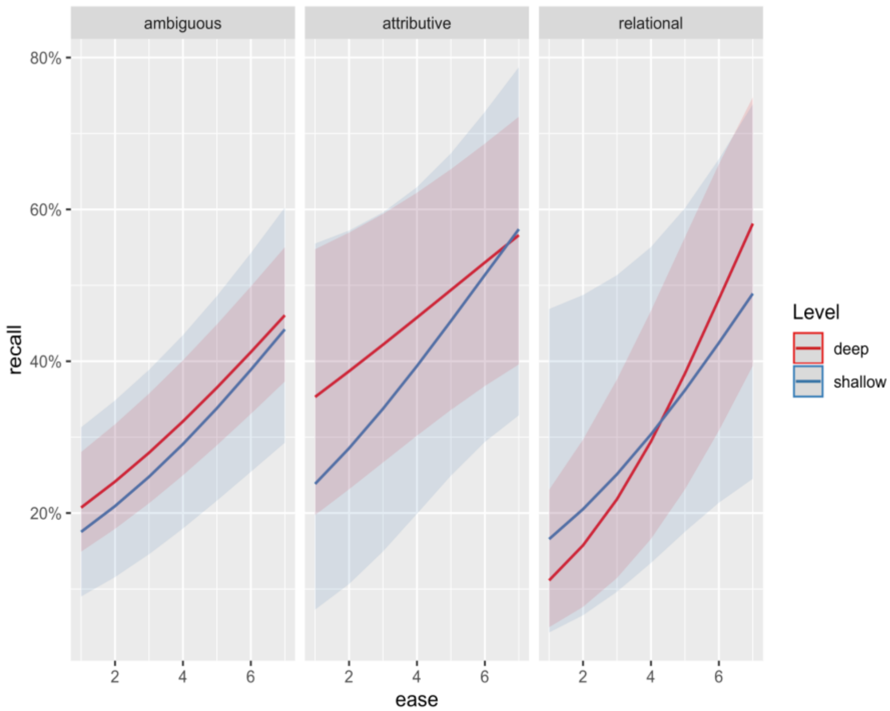

Figure 1. Predicted probabilities of recall by ease.

Ease (1 = cannot combine at all, 7 = can combine very well), grouped by people who deeply and shallowly processed semantic information before conceptually combining the word pairs.

2.3 Discussion

This study was aimed at understanding the impact of deep semantic processing on conceptual combination. I anticipated that deeply engaging the semantic network before combining would make combining more challenging for ambiguous combinations where more competitions would need to be resolved but would aid combining for attributive and relational combinations where the easily resolved competitions could be more quickly settled. Contrary to my hypotheses, my study found no significant influence of level of semantic processing on ease of combining. Instead, I found only that unambiguous combinations were easier to combine than ambiguous combinations. In addition, I examined how these level of processing differences, as well as the ease of combining, might predict how well the combinations of each type were subsequently remembered. I anticipated word pairs that were easier to combine would be better remembered, especially for deeply processed combinations. Results showed evidence for the benefits of easy combining, but only showed a stronger relationship between ease and recall for deep relative to shallow processing for relational combinations.

The differences in ease between ambiguous and unambiguous combinations are not entirely surprising based on how I defined my conditions. Strongly unambiguous combinations (i.e., relational, attributive) were intentionally identified in the norming process. These strong combinations likely have a relatively strong competitor that makes combining easier and less time-consuming whereas ambiguous combinations do not. It is interesting to note here the heterogeneity that likely exists between ambiguous combinations. Though these combinations are more challenging to combine than unambiguous combinations, the reason for one ambiguous combination being challenging may be different from another. For instance, combinations can be ambiguous because features and relations are both being similarly activated, but they may also be ambiguous because their ultimate strategy does not quite reflect attributive or relational combining strategies. Examining the divergence between these cases will be interesting for future studies to consider.

This study found no evidence that the deeper semantic processing before conceptual combination impacted the ease with which people could combine word pairs. This did not support my hypothesis that deep semantic processing would be detrimental to ambiguous combinations and beneficial to unambiguous combinations. Upon further investigation of the manipulation's interaction with combination type, it does seem that whatever effect is present is being driven by a change in ease of combining attributive combinations. These results may hint that semantic activation may be uniquely important for attributive combinations.

It is interesting to consider why the expected results were not found. One possibility is that a manipulation capable of influencing the conceptual combination process must be more specific to the combinations at hand than a general state change. One study, for instance, found that priming of conceptual combinations must be very specific (Estes and Jones, 2006). For instance, whereas *bird nest* primes *fish pond* (through a HABITAT relation), it does not prime *crayon box*. Although there is an element of CONTAINMENT relation for all combinations, only the specificity of sharing the HABITAT relation could prime the next combination's definition. In this study, the manipulation did not consist of the words to be combined, but other, unrelated nouns. Perhaps a stronger, more specific manipulation of the constituent nouns might manipulate the semantic space more effectively. Another possibility goes back to the initial hypotheses. It was expected that entering the deep semantic processing state would have 2 consequences relative to the shallow state: 1) people would have a more easily activated semantic network, where more competitors could be activated, and 2) people would be able to more efficiently navigate their semantic network, making settling competitions easier. Although initially hypothesized to have different effects on the different combination types, allowing us to parse how these combining strategies differ from one another, it is possible that, instead, these effects canceled one another out. In other words, it is possible that entering a state change actually benefited and harmed combining equally such that the impact of each consequence was impossible to dissociate. Future studies may want to explore this possibility by isolating these effects, engaging participants in one task where more competitors are activated but processing efficiency is not impacted and another task where the opposite is true.

Another factor, ease of processing, was shown to be a significant predictor of recall, consistent with prior studies. The finding shows that, when combinations are more easily formed, they are also remembered better. By processing combinations more easily, it is likely that more complex, integrated, and well-defined associations can be formed. When memories are better integrated, they are better remembered. Interestingly, this relationship was found to be particularly strong for relational combinations, especially when they were deeply processed. These findings may therefore suggest a divergence between relational and attributive combining where attributive combinations manipulate features and require less focus on relational history and relational combinations process in the opposite manner. This divergence is consistent with parallel processing models of conceptual combination (Estes, 2003). Perhaps, for challenging combinations, it is helpful to manipulate and visualize featural information instead of considering the relational history of the modifier noun. Whereas attributive combinations would receive this multimodal processing benefit to aid in defining the combination, relational combinations would not, or at least would experience this to a lesser extent. Likewise, deeper processing of these challenging relational combinations might lead to poorer memory because the relational history might be expanded in this state, it is more challenging to form a well-defined definition for the combination.

Conceptual combination has been shown to produce a more unitized associative memory than other strategies where the associates remain arbitrarily related (Ahmad, et al. 2014; Lucas, et al. 2017; Lucas, et al. 2019). Whereas other pairs need to be retrieved using the relational processing system in the hippocampus, conceptually combined pairs may be able to bypass this system and be remembered better. This study speaks to the importance for future studies to uncover the systems and strategies used when conceptual combination is more easily achieved, as these compounds will be best remembered. Our study shows enhanced subsequent memory for combinations formed using an attributive strategy relative to a relational strategy. Given the finding that there seems to be a strong relationship between ease and recall for relational combinations, but no overall benefit to combining relationally, it may be advisable to combine using an attributive strategy unless the relational combination is particularly easy.

3.0 Study 2: Individual Differences in Conceptual Combination throughout the Lifespan

Past studies have shown that there may be a mnemonic benefit of completing conceptual combination while encoding associative pairs relative to other strategies lacking meaningful associations between the words (Lucas, et al. 2017). Study 1 showed that this benefit is enhanced when people can combine words more easily. One way to begin unpacking how to optimize the memory benefits of conceptually combining associates during encoding is to understand how other cognitive processes contribute to ease of combining. The question of why some individuals find conceptual combination more challenging than others has not been extensively explored. Most likely, there are several cognitive processes that can impact one's ability to conceptually combine. This study is aimed at exploring which cognitive individual differences might predict differences in ease of performing conceptual combination. When deciding which factors to measure, I considered which would aid in the suggestion and evaluation phases of combining. As such, I aimed to identify factors that might aid in faster navigation of the semantic space and the enhanced separation of competitors (making competition easier). Ultimately, I identified semantic processing, cognitive control, divergent and convergent thinking, and visualization as possible predictors of ease while completing conceptual combination.

In many areas, older adults tend to cognitively differ from younger adults. Relative to younger adults, for example, older adults tend to have larger vocabularies (Dubossarsky, De Deyne, & Hills, 2017), but also have semantic networks that are less connected, less organized, and less efficient (Cosgrove, et al. 2021; Dubossarsky, et al. 2017). This area of research on the "aging lexicon" has been extensively researched and debated (for review, see Wulff, et al. 2019). Given the reliance of conceptual combination on the semantic network, the influence of individual differences on ease of combining may change throughout the lifespan. At the present, very few studies have investigated aging-related differences in conceptual combination, but it seems clear that these differences do exist, characterized by the production of fewer properties (Taler, et al. 2011), production of more unusual combinations (Taler, et al. 2011), difficulty in maintaining the role of the head noun compared to the modifier noun (Taler, et al. 2005), and poorer memory for new combinations (Lucas, et al. 2019) relative to younger adults. Importantly, of these studies that have investigated aging-related changes in conceptual combination, none have directly compared performance on the task with individual difference measures (Lucas, et al. 2019; Taler, et al. 2005; Taler, et al. 2011). In this study, I also examine how variation in these cognitive processes relates to conceptual combination performance in both younger and older adults. I anticipated that older adults, whose semantic networks are less efficiently organized than those of young adults (Cosgrove, et al. 2021; Dubossarsky, et al. 2017), would be more dependent on the individual differences measured, showing stronger relationships between the measures and ease of combining than younger adults.

Humans are capable of complex higher-order thinking but have limited working memory space (Baddeley, 1992). As such, an organized conceptual system is the foundation for several important cognitive processes. This organization can improve efficiency when making decisions or problem solving (Binder, et al. 2009; Lewellen, et al. 1993; Martin & Chao, 2001), and improve memory for newly learned information (Bruett, et al. 2018). As conceptual combination requires the navigation of one's semantic space to identify competitors, semantic processing is likely one individual difference measure that will predict ease of combining. I expect this to be a universal relationship, benefiting combinations created with all strategies.

Recent research shows that one area of cognition that may be particularly impacted by semantic memory structure is creativity, where individuals with more rigid, less connected semantic network structures are less creative than individuals whose structures are more flexible and interconnected (Kenett, et al. 2014; Kenett & Faust, 2019; Rossman & Fink, 2010). As conceptual combination inherently relies on the creative combination of novel concepts, I also examined how one's creativity might predict ease of combining. In particular, I focused on two facets of creativity, divergent and convergent thinking. Divergent thinking refers to the ability to flexibly recombine information in novel ways (Guilford, 1967), whereas convergent thinking refers to the ability to narrow down a single, well-defined, best solution (Cropley, 2006). I anticipated that both factors would predict the ease of combining, particularly for ambiguous combinations, which contain more competitors.

During conceptual combination, word pairs without strong competitors require greater inhibition of possible competitors for a final combination to be formed (Lucas et al. 2019). As such, researchers have hypothesized that cognitive control may be an important factor in conceptual combination. In my study, I anticipated most variation in competition among ambiguous combinations, which are less likely to be quickly narrowed down to a particular feature or relation. Healthy older adults, however, show decreased cognitive control relative to younger adults (Anderson et al. 2014). Given these aging differences, I expected to measure a full range of control performance that I might not get by examining only younger adults.

Finally, for some, a strategy for completing conceptual combination may be to visually imagine the new concept being created. There is evidence that visualizing can be important in aiding creative processing (Abraham, 2014; Abraham & Windmann, 2007). In addition, one study found evidence that participants might be engaging in spontaneous perceptual simulation as a result of conceptual combination (Wu & Barsalou, 2009). The study showed that participants generated similar features after conceptual combination with neutral instructions as they did when given imagery instructions for both known and novel word pairs (Wu & Barsalou, 2009). However, because the feature naming task took place after combining, they were unable to determine if the perceptual simulation occurred during or only after combining. Here, I examine this question of whether visualizing during conceptual combination aids in ease of combining using an individual differences approach. I anticipate that conceptual combination will be easier for those who can more easily visualize information, especially for attributive combinations for which feature resemblance is the relation driving the compound's meaning.

3.1 Methods

3.1.1 Participants

Data were collected online from 100 younger adults through the University of Pittsburgh's subject pool for partial course credit and from 100 older adults, who were recruited and paid through Prolific (https://prolific.co/). One older adult and 15 younger adults were removed from the sample because American English was not their most proficient language (see criteria in Study 1). In addition, participants were excluded for lack of task engagement (see Results). Ultimately, my sample consisted of 83 younger adults (39 Male, 44 Female, Age *M* = 18.55) and 87 older adults (37 Male, 50 Female, Age *M* = 69.63).

3.1.2 Procedure

In this study, participants completed a conceptual combination task in the same manner as the Study 1. Stimuli were normed prior to use (see Appendix for details). Following this combination task, participants completed a cognitive battery in a randomized order to measure individual differences that might predict performance on the conceptual combination task.

Participants completed two creativity tasks. One task, the alternate uses task (AUT), is designed to measure divergent thinking (Guilford, 1967). In this task, participants were given three minutes to write all creative uses they could think of for the cue object. Participants did this twice with two different cues: *brick* and *paperclip* (Stevenson, et al. 2020). Another task, the remote associations task (RAT), was implemented to measure convergent thinking (Taft & Rossiter, 1966). On each trial, participants viewed three words that were all related to a fourth word (e.g., cottage / swiss / cake: cheese). Participants completed 30 trials, where for each they were given 15 seconds to type out the correct related word. Stimuli were selected from a bank of 144 normed problems (Bowden & Jung-Beeman, 2003). Those selected were checked with a small sample (n = 8) of people aged across the lifespan for familiarity in 2020.

Participants completed a self-report battery, the Vividness of Visual Imagery Questionnaire (VVIQ), to measure their visual image vividness (Marks, 1973). The questionnaire contains 16 items that participants read and indicate how well they can visualize what is being described on a scale of 1 (Perfectly clear and as vivid as normal vision) to 5 (No image at all, you only "know" that you are thinking of the object). The questionnaire is reported to have a good test-retest reliability coefficient of .74 (n = 68) and split-half reliability coefficient of .85 (n = 150; Marks, 1973).

Participants also completed a Flanker task to measure their cognitive control. Stimuli were presented using jsPsych in Qualtrics (de Leeuw, 2015), which has been shown to be comparable to in-person response time collection (de Leeuw & Motz, 2016). Participants were instructed to indicate the direction of a central arrow among a string of 5 arrows. The central arrow was either facing the same direction as the flanking arrows (congruent trial; <<<<< or >>>>>) or the opposite direction (incongruent trial; <<><< or >><>>). Each trial lasted 1500 ms with an ITI of 500 ms. Participants completed 240 trials total (120 congruent, 120 incongruent).

Finally, participants completed a semantic memory task. The task consisted of a 3-way alternative forced choice (3AFC) wherein they decided which word choice was semantically related to a cue word. Trials varied in difficulty in order to measure individual differences, where some trials were easier due to greater cue-target relatedness (e.g., tennis ball-racket) and others were more challenging with lower cue-target relatedness (e.g., butterfly-eggs). Trials lasted either a maximum of 3s or until the participant submitted their response. The task and stimuli were modified slightly for an American audience from a recent study (Sormaz, et al. 2017). In particular, some cues and choices were translated into American English (e.g., aubergine → eggplant) and three trials were removed entirely for comprehension (e.g., a trial where the cue was "runnerbean"). Ultimately, this left 56 trials of the task.

All participants ended their session by completing a short demographics and abbreviated language history questionnaire (adapted from Tokowicz, et al. 2004).

3.1.3 Analyses

AUT scores were generated online using SemDis (Beaty & Johnson, 2020). Higher values indicate larger semantic distance (i.e., more creativity) of response. Flanker reaction times (RTs) were transformed with the Box-Cox family transformation on a group level. Incorrect trials and those with RTs deviating more than 2.5 SDs from the cell means (separately for each participant) were removed prior to averaging. Flanker RT and error rate difference scores were created by subtracting congruent from incongruent values.

To account for missing data (see Results), a multiple imputation model was implemented to analyze young adult data in predicting ease of combining. A linear mixed effects model analyzed how individual differences predict ease of combining in older adults. In both models, six continuous fixed effects were included: visual imagery, semantic memory, divergent thinking, convergent thinking, Flanker RT, and Flanker error rate. These variables were all z-scored. In addition, a categorical fixed effects variable of combination type (attributive, relational, ambiguous) was included. Interactions between each individual difference measure and combination type were also included. Subject was included as a random effect.

3.2 Results

3.2.1 Task Performance

Twelve participants were excluded for poor task engagement during the conceptual combination (< 3 SDs below the average SD, > 33% of trials left blank), VVIQ (<3 SDs below the average SD), semantic (< 3 SDs below the average SD, > 33% of trials left blank), and/or RAT tasks (all trials left blank). One participant was also removed from the RAT task for misunderstanding the instructions (i.e., re-typing the cues). As mentioned in the Methods, my final sample consisted of 83 younger adults and 87 older adults. Basic performance for each task is reported in Table 3.

Table 3. Summary of performance on individual difference measures for both younger and older adults.

	Younger		Older			
	M	*SE*	*M*	*SE*	*t*	*p*
Flanker RT (inconsistent – consistent)	0.07	0.01	0.13	0.01	4.57	< .001
Flanker Error Rate (inconsistent – consistent)	0.33	0.03	0.08	0.01	-7.36	< .001
RAT	0.51	0.01	0.59	0.01	6.04	< .001
AUT	0.96	0.00	0.95	0.00	-3.33	.001
Semantic	0.82	0.01	0.81	0.00	-0.77	0.440
VVIQ	3.75	0.03	3.72	0.03	-0.71	0.480
Ease	4.65	0.07	5.20	0.07	5.62	< .001

Notes. RAT reflects accuracy (0 -1). AUT reflects creativity (0 = least creative, 2 = most creative). Semantic reflects average accuracy (0-1). VVIQ reflects average response (1 = most clear, 5 = least clear). Ease reflects average response (1 = not well at all, 7 = very well).

3.2.2 Younger Adults

Flanker data predicted the ease with which younger adults formed conceptual combinations. Lower differences both between incongruent and congruent RTs (β = -2.52, *SE* = 0.78, $t(116) = -3.24$, $p = .002$), and incongruent and congruent error rates, β = -0.91, *SE* = 0.33, $t(116) = -2.76$, $p = .007$ were related to greater ease of combining; see Figure 2. In addition, there was an interaction of Flanker error rate and combination type, β = -0.28, *SE* = 0.28, $t(116) = -2.03$, $p = .044$. No other effects approached significance (see Appendix C for full model).

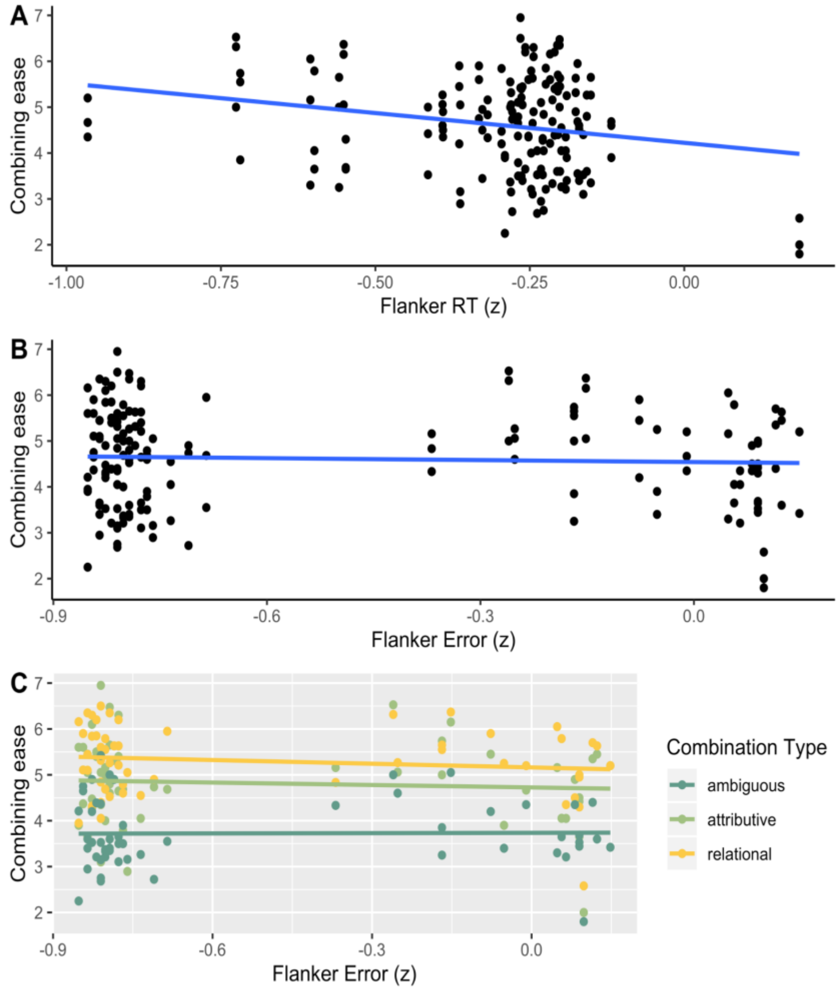

Figure 2. Individual difference measures predictive of ease of combining in younger adults.

3.2.3 Older Adults

Two variables predicted ease of combining in older adults: visualizing (β = 0.26, *SE* = 0.08, *t*(69) = 3.15, *p* = .002) and semantic memory, β = 0.25, *SE* = 0.09, *t*(69) = 2.94, *p* = .005. In addition, there were three significant interactions (see Figure 3). First, there was an interaction of visual imagery with combination type (attributive vs. relational), β = 0.157, *SE* = 0.08, *t*(138) = 1.99, *p* = .048. Next, there was an interaction of convergent thinking with combination type (unambiguous vs. ambiguous), β = 0.22, *SE* = 0.71, *t*(138) = 3.03, *p* = .003. Finally, there was an interaction of Flanker RT with combination type (unambiguous vs. ambiguous), $\beta = 1.88$, $SE = 0.91$, $t(138) = 2.07$, $p = .041$. No other effects approached significance (see Appendix D for full model).

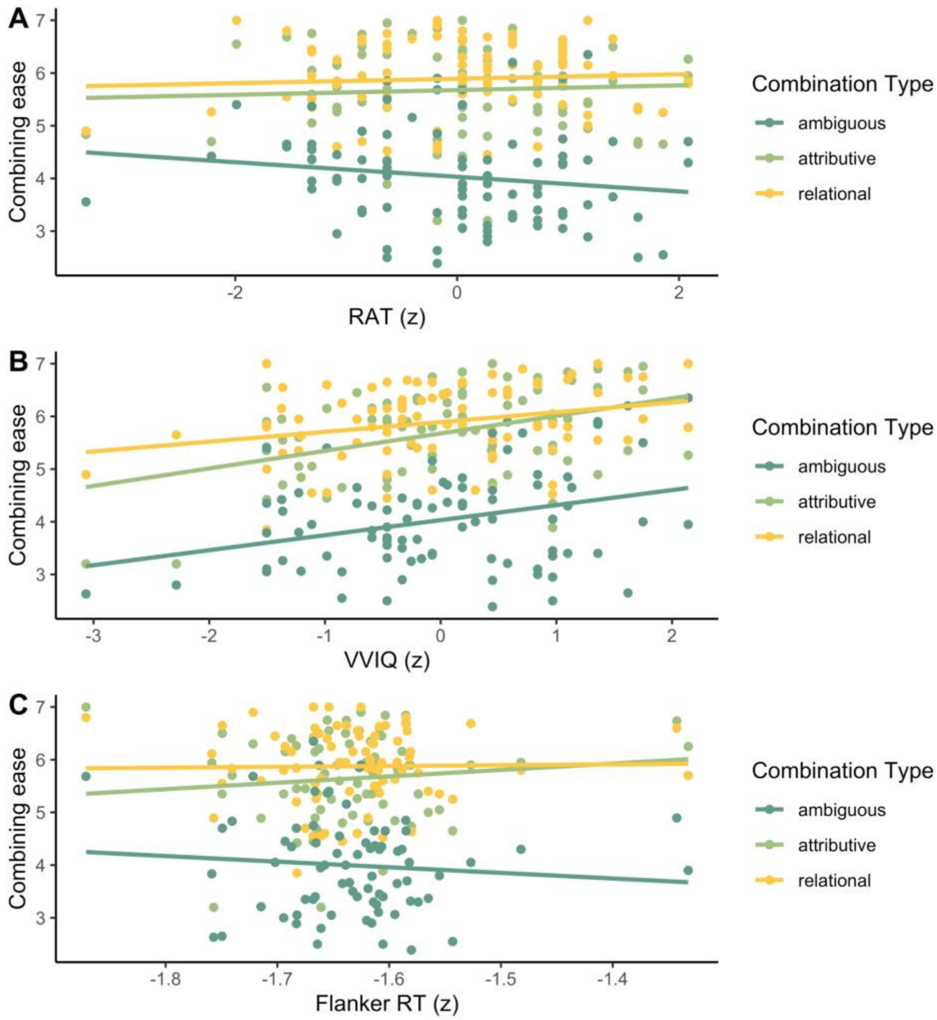

Figure 3. Interaction effects of individual difference measures predictive of ease of combining in older adults.

3.3 Discussion

This study examined how cognitive control, semantic processing, creativity (divergent and convergent thinking), and visual imagery predict ease of combining during conceptual combination in both younger and older adults. Ultimately, cognitive control was an important factor for both age groups. In addition, more individual difference measures appear to be important in predicting ease of combining in older adults. These findings suggest that cognitive control is an important factor throughout the lifespan when conceptually combining, but as one's semantic network becomes less efficiently organized (Dubossarsky, et al. 2017), other individual differences are recruited to compensate.

In both younger and older adults, cognitive control, as measured in the Flanker task, was shown to predict ease of combining. Inhibition has been shown to be an important factor in creative cognition, particularly during conceptual expansion, as it aids in suppressing more salient solutions in order to generate more unusual solutions (Abraham, 2014). However, given the time constraints of the task in this study, it is likely that participants found combinations easier to combine when a solution could be more quickly defined, as opposed to more creatively combined. As such, the benefit of cognitive control in our task may be more analogous to the benefit of inhibition during metaphor comprehension, which has been argued to be driven by conceptual combination (Holyoak & Stamenković, 2018). During metaphor comprehension, competitors are prioritized to the current combination context (Newsome & Glucksberg, 2002). For example, when asked to interpret "My lawyer is a shark," the property that sharks can SWIM is inhibited, allowing for the prioritization of the VICIOUS property. Whereas older adults have trouble inhibiting text-irrelevant information when comprehending literal text (Hasher & Zacks, 1988), they have been shown to maintain this inhibitory ability in metaphor comprehension. During conceptual combination, similar property prioritization may be essential to efficiently select competitors and settle competitions between them, both in younger and older adults. Relatedly, ambiguous stimuli in older adults do not show the same pattern of results in which they benefit from increased cognitive control, as seen with other combining strategies. Although this study cannot directly speak to this possibility, one explanation may be that these combinations, which require less complex analogical thinking, may reflect these changes in processing of literal text, while the more complex ambiguous combinations are spared.

At least for older adults, we found that semantic processing predicts ease of combining on a conceptual combination task. This relationship was expected, as conceptual combination relies on the ability to efficiently navigate one's semantic networks. During conceptual combination, the head and modifier nouns must be decomposed into elements that are compared and integrated to produce coherence (Holyoak & Stamenković, 2018). This requires the searching of semantic neighborhoods of the constituent nouns (Holyoak & Stamenković, 2018). It is unclear why we did not find support for this relationship among young adults. Though there are known changes to the semantic network throughout the lifespan (e.g., younger adults tend to have semantic networks that are more connected, organized, and efficient than those of older adults; Cosgrove, et al. 2021; Dubossarsky, et al. 2017), conceptual combination would still rely on the efficient navigation of one's semantic networks. These findings show the importance of efficient semantic networks for conceptual combination. Whereas young adults reliably have their networks organized in this manner, older adults do not. This may also explain why, along with semantic processing, older adults showed reliance on more cognitive processes than younger adults.

The lack of a relationship between divergent thinking and conceptual combination was initially surprising, as one study found that conceptual combination can actually be used as a divergent creative strategy (Chan & Schunn, 2015). The researchers found that, when combinations are more semantically distant from one another, they tend to be more creatively combined so long as people are given time to iterate ideas (Chan & Schunn, 2015). This emphasis on the importance of time and iteration may explain why divergent thinking did not emerge as a predictor. Iteration is known to be an essential part of the creative process (Dow, Heddleston, & Klemmer, 2009). Given additional time, participants might have been afforded additional flexibility and iterated through several ideas using more divergent thinking. I would expect that this effect would be present for both younger and older adults, as older adults have been shown to think as divergently as younger adults in the verbal domain given sufficient time (Fusi, et al. 2020). I suspect that similar logic may be applied to the finding that convergent thinking was shown to make combining ambiguous word pairs more challenging in older adults. Specifically, I suspect that ambiguous combinations require more flexible processing via divergent thinking. Convergent thinking, which prioritizes finding a single correct solution, is likely a particularly poor strategy for defining these combinations. Older adults, who require more time to engage in divergent thinking (Fusi, et al. 2020), likely needed to rely on convergent thinking to attempt this task, and as a result of using a subpar strategy for ambiguous combinations, performed worse. This hypothesis could be addressed similarly by increasing time for combining. I expect that this increase would show that, instead of a relationship between convergent thinking and ease, there would be a benefit of divergent thinking.

Finally, visualizing predicted combining ease in older adults, but not younger adults. In older adults, this effect interacted with combination type such that attributive combinations were most strongly related to visualizing ability. This finding suggests that attributive combinations, which rely on the manipulation of featural information of concepts, may depend on more perceptual processing pathways than other conceptual combination strategies. This is consistent with past studies of visualizing behavior. When people mentally manipulate the featural components of stimuli, visual perceptual areas of the brain are often more active than other forms of higher-order thinking. Researchers in one study, for instance, found that they could decode voxel patterns in the brain as people were processing complex scenes (Naselaris, et al. 2015). An interesting study to follow-up this finding might involve asking participants who have congenital aphantasia, who have severely reduced abilities to mentally produce visual images, to complete conceptual combination. Our study suggests that this may harm their ability to use attributive strategies of combining but not other strategies. A cross-sectional approach would also indicate whether there is a minimal threshold of visualization needed across the lifespan or if the relevance of this process truly is confined to older adults.

It is important to note that the younger and older adults recruited for this study were recruited from two different sources. While the younger adults were recruited from the University of Pittsburgh's student portal for course credit, the older adults were recruited from Prolific and financially compensated. This may explain the unusual finding that older adults performed as well as or better than younger adults on many of the individual difference and combining tasks. This finding may be further explained by noting that the population of older adults in our sample, who signed up to participate in online research on the Prolific website, may differ from the typical aging population. Studies have found that internet-using older adults tend to be more highly educated, and in some cases, are more likely to have higher cognitive functioning than non-internet-users (Berner, et al. 2015). The population in our sample may therefore have higher cognitive functioning and more education than the typical older adult sample.

4.0 Study 3: Shifts in Mental Models of Constituent Concepts

During conceptual combination, people use their prior knowledge to internally adjust their representations of known entities, changing or forming new connections between concepts. Given the evidence in Studies 1 and 2 that there may be divergence between the processing of relational, attributive, and ambiguous combinations, there is reason to suspect that these combinations may also show different levels of representational change. In fact, one study used network analysis and found that relational combination leads to more restructuring of the semantic network (namely, increased connectivity) than attributive combination (Kenett & Thompson-Schill, 2017). This finding was in line with other studies showing that relational categories are more mutable than entity categories (Asmuth & Gentner, 2017). As the head noun tends to be altered by the modifier noun in the process of creating a new conceptual combination, in this study, I examined whether the head noun experiences cognitive representational changes as a result of conceptual combination.

The distance between cognitive representations of concepts can be measured using the multi-arrangement method. With this method, participants move concepts around a physical space to indicate their similarity. Concepts that are nearer one another are more similarly represented. Importantly, this method has been shown to have high reliability (Kriegeskorte & Mur, 2012). By implementing this method twice in my study, once before an associative pairing task and once after, I can uncover how these representations change as a result of combining. To be sure that the changes measured here are a result of conceptual combination, and not measurement error, half of the participants were asked to complete a different associative pairing task that involves little association between the pairs as a baseline.

I anticipated two areas where we may expect to find representational change. First, I hypothesized that, relative to another task that involves less manipulation of a noun, head nouns would experience more change during conceptual combination, moving nearer to one another after combining. Second, clustering may be determined by the combining strategy used (e.g., attributive head nouns would shift nearer one another post-combining). I hypothesized that head nouns would be organized more in line with the definitions created from the conceptual combination after combining than before. In other words, head nouns that recently experienced similar processing (i.e., attributive, relational, ambiguous) will be nearer one another after having been combined. I expect that this change will either not occur or will occur to a lesser extent in another task requiring less modification of the representational space of the noun of interest. Finally, I anticipated, in line with studies that have shown greater changes to the semantic network following relational conceptual combination than attributive (Kenett & Thompson-Schill, 2017), I would uncover a similar pattern.

4.1 Methods

4.1.1 Participants

I collected data from 100 participants online from the Pitt psychology subject pool via a Qualtrics survey. Twenty-three participants were excluded from analyses for not having American English as their most proficient language (see criteria in Exp 1) and one for indicating that they had a learning or attention disorder. I excluded an additional 28 participants after screening responses for task engagement (see Results). My final sample consisted of 48 participants (age *M*

= 18.6 years old, 26 female, 22 male) with 27 participants who completed conceptual combination and 21 who completed the frequency comparison task.

4.1.2 Procedure

This study consisted of five phases: Initial Mental Model, Distractor Phase, Association Trials, Final Mental Model, and Definition Phase.

Participants' mental models were measured using the multi-arrangement method, which has been shown to have good test-retest reliability (Kriegeskorte & Mur, 2012) on Qualtrics using the Qualtrics-spatial arrangement method (Q-SpAM) method (Koch, Speckmann, & Unkelbach, 2020). During both mental model tasks, participants viewed a set of 60 nouns in the middle of their screen and were told that they could drag and drop each word to any location on the screen anytime during the sorting task. These 60 nouns (20 attributive, 20 relational, 20 ambiguous; see Appendix A for norming study and Appendix B for final stimulus list) were the head nouns of the word pairs they would later see during the Association Trials phase. Participants were instructed to make use of the entire screen, sort more similar words closer together, and sort more dissimilar words further apart. Each word had to be moved at least once to complete each sorting task.

During the distractor phase, participants answered progressively challenging math problems for 5 minutes. This phase was implemented to keep participants from rehearsing where they placed each noun during the initial phase and to avoid the explicit recognition of the repetition of nouns from the initial phase in later phases.

During the Association trials, participants either completed a conceptual combination or a frequency-comparison task (Lucas, et al. 2019). Both tasks were automatically paced. Before completing the conceptual combination task, participants were given examples of 3 word pairs and definitions (one attributive and one relational definition for each word pair) and told that their goal for this part of the study was to imagine the definition that they felt fit best for each word combination. For each trial of the conceptual combination task, participants viewed the word pair for 2 seconds, viewed an “I” for 4 seconds when they were instructed to imagine the definition for the word pair, and then were prompted for 4 seconds to indicate how well they could define the word combination on a scale of 1 (very well) to 7 (not well at all). Participants were encouraged to use the full range of the scale and were told to use 7 when they could not come up with any definition at all. For each trial of the frequency task, participants viewed the word pair for 2 seconds, viewed a fixation cross (+) for 4 seconds when they were instructed to imagine which item they encountered more frequently, and then prompted for 4 seconds to indicate which item they encountered more frequently on a scale of 1 (first more) to 7 (second more).

Finally, participants completed a definition phase where they were prompted to give the best definition that they thought applied to each word pair. Participants who completed the conceptual combination task were asked to give the definitions they imagined during the conceptual combination task. Participants who completed the frequency-comparison task were given the examples given prior to the conceptual combination task and asked to think of their definitions in the moment. All participants completed their session by completing brief demographics and language history questionnaires (adapted from Tokowicz, et al. 2004).

4.1.3 Analyses

For each model, the Euclidean distance (i.e., dissimilarity) between the 60 nouns, divided by each subject’s maximum possible distance (i.e., the diagonal of their screen size), was calculated using scripts created by the Q-SpAM package (Koch, et al. 2020). This process left us with a 60 x 60 matrix of dissimilarity. For each noun, I then calculated its average dissimilarity from other nouns of the same combination type (e.g., for a given attributive noun, its average dissimilarity score was the average of its dissimilarity from the other 19 attributive nouns). This produced, for each model, the average distance between each noun and the other nouns of the same combination type, where higher averages indicate more dissimilarity from other nouns of the same type.

To determine whether dissimilarity was lower in model 2 relative to model 1 for participants who completed conceptual combination, a mixed-effects model predicting distance was run. The model contained two within-subjects categorical fixed effects variables: combination type (attributive, relational, ambiguous) and mental model (first, second). It also contained a between-subjects categorical fixed effect of task (combining, frequency). Orthogonal contrasts were created for each categorical variable. All interactions were examined. The regression model contained a random effect for subject and random slopes for combination type and mental model. The bobyqa optimizer was implemented to help the model converge. A model was also run without the random slopes. AIC values were compared to select the model with the best fit.

4.2 Results

4.2.1 Task Performance

Performance was examined to ensure engagement in the tasks. For both the participants who completed the conceptual combination task and those that completed the frequency task, participants who were three standard deviations below the average standard deviation, had a standard deviation of 0, or left more than half of their trials blank, were removed from the sample. In addition, participants were excluded for failing to provide definitions in the definition phase (e.g., re-writing the word pair, typing whether they thought the definitions were associated). As indicated in the Methods, 28 participants were removed from these criteria, resulting in a final sample of 48 participants.

4.2.2 Representational Change

AIC comparisons of models with and without random slopes indicated a better fit for the model containing random slopes (ΔAIC = 80.69, $\chi^2 = 98.691$, $p < .001$), so results reported here reflect that model.

There was a marginal effect of combination type for the contrast of ambiguous relative to unambiguous (i.e., attributive and relational) nouns, $\beta = 0.007$, $SE = 0.004$, $t(48) = 1.84$, $p = .071$. Further examination shows that, across both models and in both tasks, ambiguous nouns were numerically slightly less dissimilar to one another ($M = 0.306$, $SE = 0.007$) relative to unambiguous nouns (Attributive: $M = 0.313$, $SE = 0.006$; Relational: $M = 0.315$, $SE = 0.006$). No other effects approached significance.

4.3 Discussion

This study was aimed at examining cognitive representational changes as a result of conceptual combination. I anticipated less dissimilarity between nouns that had recently been combined compared to those that were compared in a frequency task. In addition, I hypothesized that combinations formed using the same strategy might be more similar to one another than to combinations formed using different strategies after combining. Results of this study do not lend support to these hypotheses. One possibility is simply that the brain does not cognitively alter representations as a result of conceptual combination. Given the overwhelming support for the flexibility of the brain provided a goal, I would argue that this possibility is unlikely (Brouwer & Heeger, 2013; Bugatus, et al. 2017; Dunsmoor, et al. 2013; Kenett & Thompson-Schill, 2017; Malone, et al. 2016; Nastase, et al. 2017; Nosofsky, 1986). Below, I will examine some reasons as to why I did not find the results I anticipated in this study.

This study examined whether there might be high-level clustering as a result of using similar strategies for different word pairs. It is possible that this level of clustering is too broad a scope to be used to examine these changes. Instead of the strategy used during processing, it is instead the content of the representations that constitute how the cognitive representations are altered. One study, for instance, found that relational conceptual combinations cluster together around types of relations (Devereux & Costello, 2005). Instead of a general clustering of all relational combinations, the authors found that the combinations formed three subgroups: head noun ABOUT modifier noun, head noun DERIVED FROM modifier noun, and modifier noun CAUSES head noun. It is possible that this lower-level clustering is where these types of representational changes occur, as opposed to the higher-level strategy-wise changes. Future studies can examine whether this is the case, not only for relational combinations but also for attributive (e.g., similar features) and ambiguous combinations. One important difference to note when comparing this study to the current work is the context in which the combinations are presented. Whereas all combinations in the previous study were of the same type, the combinations in this study required an assortment of strategies. It is possible that the granularity at which these representations change will depend on this context. Whereas strategy may be a relevant feature in a context like the current study, more granular details may be more prominent in a study in which combination strategy is maintained throughout.

In addition to this possible explanation, there may have simply been methodological reasons why the results of this study did not demonstrate the expected changes. First, I suspect that the manipulation in this study was not sufficiently strong to alter the strong and long-standing knowledge representations they were meant to. During the conceptual combination task, participants thought about each word pair for only 10 seconds. In future studies, researchers may wish to use a more powerful manipulation. They may achieve this by simply increasing the number of presentations of each pairing to influence the representations of each concept more effectively. Another strategy may be for the manipulation to require participants to engage in the elaboration phase of conceptual combination for a longer period. By elaborating on the finer details of the combination, participants would more deeply engage in the processing and may induce more substantive changes.

Another reason we may not have seen evidence of a representational change may have been the method delivered to measure participants' mental representations of knowledge. If the method is not reliable, it could have resulted in measuring too much noise to capture the changes, though multiple studies have shown this to be a reliable measure (Kriegeskorte & Mur, 2012). Another issue may be that the model is not sensitive enough to the kinds of changes we were measuring in this study. Participants deliberately and explicitly examine their semantic knowledge during this task (Kriegeskorte & Mur, 2012). It is possible that any goal-related changes that resulted as a function of the conceptual combination task were washed away by the pre-existing connections. Perhaps a more implicit method that could measure more minute, temporary changes, would better measure the types of representational changes created in this kind of processing. Future studies may accomplish this with other implicit methods of measuring dissimilarity structures such as confusions or discrimination times (Kriegeskorte & Mur, 2012). As these methods tend to be effective for specifically measuring perceptual changes and tend to add more time constraints than the multiple arrangement method used here (Kriegeskorte & Mur, 2012), these studies should consider focusing their examination on attributive combinations. Another strategy may be to examine the brain for neural representational change – a strategy we implemented in Study 4.

5.0 Study 4: Neural Underpinnings of Conceptual Combination Strategies

Questions of how conceptual combination occurs and its influence on one's representations may be best addressed using neuroimaging methods, which could provide insight into changes in neural patterns during and after conceptual combination. In Studies 1 and 2, I manipulated semantic activation during combining and measured individual differences to examine how the brain accomplishes conceptual combination. In this study, I more directly examine the neural underpinnings of conceptual combination. Studies have identified numerous candidate regions in the brain that may be responsible for this ability, but there remains debate about which regions are involved under which circumstances.

In particular, it is unclear if neural pathways during conceptual combination diverge depending on the strategy used. Some who support a dual-process theory of conceptual combination (Estes, 2003; Wisniewski, 1997) state that relational and attributive strategies for conceptual combination are dissociable processes and point to evidence of a double dissociation between the ATL, a feature processing region responsible for attributive combinations, and the ANG, a relation processing region responsible for relational combinations. Others argue for relational theories, which argue that attributive combinations are simply a special instance of relational combination specified by a RESEMBLANCE relation (Gagné, 2000). As such, followers of these theories suggest that the neural underpinnings of relational and attributive combinations are shared. Relational theories also suggest that relational processing occurs earlier than attributive processing (Gagné & Shoben, 1997; Gagné & Spalding, 2013).

One recent study explored these theories. The authors found evidence that featural processing in the ATL preceded relational processing (Boylan, 2015; Boylan, et al. 2017). This finding is consistent with accounts holding that relational and attributive combination strategies are processed serially (Gagné & Shoben, 1997; Gagné & Spalding, 2013). However, the order of processing was inconsistent with these theories, which predict that relational processing precedes featural. The authors also found some evidence for divergent pathways, showing that relational combinations activated the ANG more than attributive combinations (Boylan, 2015; Boylan, et al. 2017), more consistent with theories of unique neural underpinnings (Estes, 2003). Overall, there is sufficient evidence to suggest that there may be some degree of divergence in the ANG and ATL depending on combining strategy, where the ATL is responsible for property-based operations and the ANG for relation-based operations (Boylan, 2015; Boylan, et al. 2017; Schwartz, et al. 2011).

Most studies of conceptual combination tend to use stimuli at extremes – combinations that are very likely to produce relation-based or attribution-based operations. As such, they cannot speak to ambiguous combinations, which tend to be more challenging and have fewer strong competitors. In fact, in addition to the ATL and ANG, there is also ongoing debate regarding the role of another brain region, the left inferior frontal gyrus (LIFG), during conceptual combination. Some suggest that this region only shows effects of retrieval during long-distance dependencies (Leiken, et al. 2015; Leiken & Pylkkänen, 2014), but there is fMRI work showing that it may be active for two-word combinations (Schell, et al. 2017; Zaccarella & Friederici, 2015). In addition to conceptual combination, some have suggested that the LIFG may act as a region involved in selection during competition of semantic or memory-related information (Solomon & Thompson-Schill, 2017; Thompson-Schill, et al. 1997), as it has been linked to performance in a language-related Flanker task (Morimoto et al. 2008). One previous fMRI study has examined ambiguous conceptual combinations and found no evidence of activation differences in the ANG, ATL, or LIFG (Boylan, 2015; Boylan, et al. 2017). This finding was surprising, as the RICE model suggests that these combination types should induce more competition than others (Gagné & Spalding, 2013). Given this model's focus on competition, the difficulty in examining null findings in one study, and the evidence for differential processing of ambiguous word pairs in Studies 1 and 2, this question is worth examining with a design more directed at addressing this dissociation. This study re-examines how combining regions differently respond to ambiguous combinations using stimuli intentionally selected for increased competition, where neither strong attributive nor strong relational competitors are present in the modifier noun, to examine how the brain processes ambiguous conceptual combinations.

To understand the role of selection during the earliest steps of conceptual combination, I presented participants with ambiguous, relational, and attributive nominal compounds to conceptually combine. All combination types were defined in a norming study (see Appendices A and B). I expected that in cases where the modifier is not a strong competitor (i.e., ambiguous, showing neither strong relational nor attributive competitors), there would be higher activation in the LIFG, as more selection of semantic information during competition would be required to successfully combine. In addition, I expected to replicate past findings for combinations with stronger competitors (i.e., unambiguous, with strong relational or attributive competitors). In line with past findings (Boylan, et al. 2017; Schwartz, et al. 2011), I expected that combinations containing more competitive relations in the modifier noun will show more activation in the ANG. Finally, I did not anticipate activation differences in the ATL (Boylan, et al. 2017), but I was unsure whether I should expect earlier relational processing (in line with Gagné & Spalding, 2013) or earlier attributive processing (in line with Boylan, et al. 2017).

An additional goal of this dissertation was to understand how conceptual combination influences the semantic network. This goal was first addressed in Study 3, which examined cognitive representational changes as a result of conceptual combination. In this study, I will examine how conceptual combination might alter the *neural* representations of the constituent head noun that is modified. Past research has pointed to several candidate brain regions that may experience neural representational changes during conceptual combination. Because the features of combined concepts change from those of the constituent concepts, it is likely that there will also be shifts in regions responsible for representing these features, such as the lateral occipital cortex (LOC), responsible for processing objects and shape (Grill-Spector, et al. 1999), and V4, responsible for processing color. In addition, prior literature suggests that the anterior temporal lobe (ATL) acts as a hub capable of representing semantic information, with some suggesting that it actually holds concept representations (Lambon Ralph, et al. 2017). Given that attributive combinations tend to shift a prominent feature (i.e., color or shape) of the modifier noun in the head noun, I expect that these feature regions will undergo more change relative to relational combinations, and both will undergo more changes relative to ambiguous combinations.

5.1 Methods

5.1.1 Participants

Data were collected from 25 participants. All participants were screened prior to participation. They were included in the study if they 1) were between the ages of 18 and 35, 2) indicated they were a native speaker of American English, 3) had no learning or attention disorder, 4) were right-handed, and 5) had no MR contraindications. Two participants were removed for excessive head motion, leaving us with a final sample of 23 participants (age M = 22.6; 14 female, 9 male, 1 unspecified). All study procedures were approved by the Institutional Review Boards at the University of Pittsburgh and Carnegie Mellon University and participants provided written informed consent prior to participation.

5.1.2 Procedure

A summary of the procedure can be found in Figure 4. Participants began with an anatomical scan. They then completed a series of tasks during functional runs: Pre, Imagine, and Post. Participants began with 2 Pre runs where they passively viewed the head nouns from the word pairs. Each trial consisted of 4 s of viewing and trials were separated by a jittered ITI, lasting an average of 2 s. Each of the 24 head nouns was repeated 3 times in each run (72 trials). After, during 3 Imagine runs, participants were asked to imagine a new meaning for unfamiliar word combinations. Participants were told that the meanings they were imagining had no right or wrong answer and that they should simply define the combination as they saw best. Participants were told to press their thumb at the moment when they had decided on the meaning of the word pair. Each trial consisted of 1 second where the noun pair appeared followed by 5 s to imagine the definition. Trials were separated by a jittered ITI lasting 2 s on average. Each of the 24 noun pairs was presented once per run. After combining, participants completed 2 Post runs, again passively viewing the same head nouns from Pre runs. The format was consistent with that of the Pre runs, where each trial lasted 4 s to view the head noun followed by a jittered ITI with an average length of 2 s. Head nouns were repeated 3 times each run. Head nouns viewed in Pre and Post runs were the same head nouns used in the Imagine runs. The twenty-four compounds combined by participants (8 attributive, 8 relational, 8 ambiguous) were previously normed with a sample of 60 participants (see Appendices A and B for norming details).

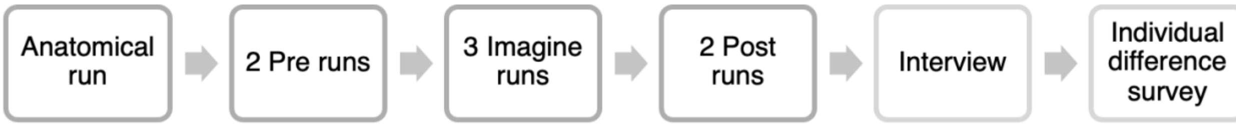

Figure 4. Procedure overview for Study 4.

Darker gray represents neuroimaging data collection, lighter gray, behavioral.

After scanning, participants completed a post-interview in which they discussed with the experimenter what their definitions were and their strategy for defining the word pair. The session ended with a short survey delivered on Qualtrics. In the survey participants indicated how challenging they found combining the word pairs to be (1 = very easy, 7 = very challenging) and how challenging they found it to maintain a single definition for each word pair (using the same Likert scale), and they typed any other definitions they thought of about the word pair aside from the one given during the interview. Participants then completed a Flanker task, VVIQ, and semantic test (see Study 2 Methods for details on these individual difference tasks), before finishing with a brief demographic and language history questionnaire (adapted from Tokowicz, et al. 2004).

5.1.3 Data Acquisition

Participants were scanned using a Siemens 3-T Prisma magnet and standard radio-frequency coil equipped with a mirror device to allow for fMRI stimuli presentation. Whole-brain imaging was conducted. T1-weighted images were acquired at the start of both sessions (TR = 2.3 s, TE = 1.99, voxel size = 1.0 × 1.0 × 1.0 mm). Two runs were collected for pre and post tasks and 3 were collected for imagine tasks (TR = 2.0 s, TE = 30). All functional runs employed voxel sizes of 2.0 × 2.0 × 2.0 mm. A predetermined jitter was used in all functional runs. The optimal sequence was determined using Optseq 2 (http://surfer.nmr.mgh.harvard.edu/optseq/) and an average jitter length equivalent to the run's TR length.

5.1.4 Data Preprocessing

Imaging data were preprocessed using the Analysis of Functional NeuroImages (AFNI) software package (Cox, 1996). Anatomy were skull stripped and deobliqued using AFNI's @SSwarper. Functional data were slice time corrected and motion corrected to register them to the third functional volume. Runs were scaled to 100 for each voxel and a highpass filter was applied to remove low-frequency trends below .008 Hz from all runs. For univariate analyses, data were smoothed using a kernel with full width with a half maximum (FWHM) of 6 mm. For multivariate analyses, betas were calculated, separately for the Pre runs and Post runs, using the Least Squares-Separate (LSS) method based on the onset time of the image appearing on the screen (Mumford et al. 2012).

5.1.5 Regions of Interest

Five regions of interest (ROIs) were created (see Figure 5). Three of the regions (ATL, LOC, V4) were created in MNI space using coordinates from prior literature and warped to each subject's native space. The ATL was defined with a 10 mm-radius sphere in each hemisphere (43 -13 -25; -42 -13 -23; Coutanche & Thompson-Schill, 2015), the LOC with three 6 mm-radius spheres in each hemisphere (39 -73 -3, 36 -69 -18, 34 -46 -22; -41 -78 -2, -37 -71 -21, -41 -50 -25; Grill-Spector et al. 1999), and V4 with one 6 mm-radius sphere in each hemisphere (29 -70 -16; -22 -80 -10; Beauchamp, et al. 1999). The ANG was created in FreeSurfer, as was the IFG, which was formed by combining the pars orbitalis, pars opercularis, triangularis, and the most dorsal region of the IFG (Hirshorn & Thompson-Schill, 2006).

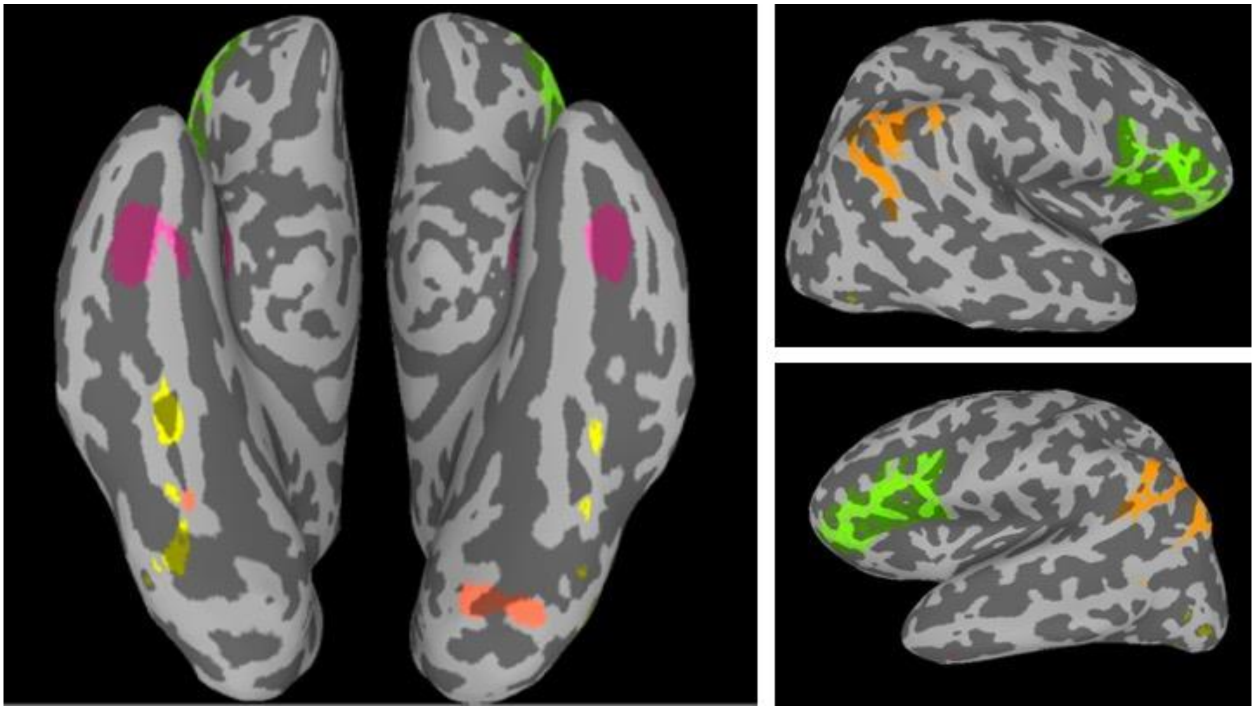

Figure 5. ROIs visualized in standard space (MNI).

ATL = hot pink, ANG = orange, IFG = green, LOC = yellow, V4 = salmon.

5.1.6 Analyses

5.1.6.1 Univariate

I examined brain activation differences between the three combination types in native space using AFNI's afni_proc.py. Orthogonal contrasts were created to compare unambiguous combination types (attributive, relational) with ambiguous and to compare attributive combination types with relational.

Analyses were first conducted in pre-determined ROIs. They were conducted separately in the left and right hemispheres for each ROI: ATL, ANG, and IFG. To determine significance of the contrasts, the average beta coefficient for each contrast was calculated in each subject in each ROI. An independent t-test was used to determine whether the average beta was significantly different from zero. A group-level cluster analysis was also run to determine whether any other regions of the brain showed significant activation differences for my contrasts. To do this, the beta coefficients calculated in native space were warped into standard MNI space. FDR correction thresholds were calculated using AFNI's 3dttest++ with the ClustSim option.

In addition to activation difference analyses, I also conducted a time-to-peak analysis in the ATL. Analyses were conducted using AFNI's TENTzero function to calculate the finite impulse response (FIR) for each condition in each voxel (Boylan, et al. 2017) in the right and left hemispheres of the ATL. The TENT function was implemented with a bin-width equal to the 2 s TR and with 10 knots representing 9 intervals ((6 s trial + 12 s HRF)/ 2 s bin-width) modeled for each trial. Given that the FIR model models each knot and zeros out the first and final knot, it outputs 8 beta coefficients for each voxel for each condition. Latency of each subject's effect peak was determined for each condition, separately for the left and right ROI, as whichever time point had the highest magnitude. Significant time-to-peak differences between attributive and relational conditions were determined by conducting nonparametric Wilcoxon signed rank tests.

5.1.6.2 Multivariate

Betas were calculated separately for each word pre and post combination using LSS. To determine the extent to which these patterns changed as a result of the imagination phase, I correlated my array of betas pre- and post-combining in each ROI. Correlations were Fisher-z corrected and then averaged across words of the same combination type (i.e., ambiguous word correlations were averaged, as were relational and attributive). Separately for each ROI, effects were calculated using a mixed-effects model to predict correlation. Combination type (attributive, relational, or ambiguous) was included as a within-subjects categorical fixed effects variable. Orthogonal contrasts were created (unambiguous vs. ambiguous; attributive vs. relational). In addition, I included a random effect for subject, a random slope for combination type, and, when needed, the bobyqa optimizer. A model was also run without the random slopes. AIC values were compared to select the model with the best fit.

In addition to analyses in my pre-planned ROIs, I also conducted group-level whole-brain cluster analysis using AFNI's 3DMVM (Chen, et al. 2014). Fisher-z corrected correlations were calculated in each searchlight sphere as above. Two general linear tests were specified, one comparing unambiguous combinations to ambiguous and another comparing attributive to relational. Residual error from the model was used to determine cluster thresholds using AFNI's 3dClustSim.

5.2 Results

5.2.1 Activation Changes During Imagination

I examined activation differences between unambiguous and ambiguous stimuli in 3 ROIs: ANG (left and right), ATL (left and right), IFG (left and right); see Figure 6. Higher activation was measured in the right IFG for the unambiguous conditions relative to the ambiguous combinations, $t(22) = 2.40$, $p = .025$. In addition, the left ANG showed marginal significance where unambiguous combinations showed higher activation relative to ambiguous, $t(22) = 2.05$, $p = .052$. No other regions approached significance for this contrast. In addition, I examined the same ROIs for activation differences between attributive and relational combinations. Only the left IFG approached significance, where attributive combinations produced marginally more activation than relational combinations, $t(22) = 1.90$, $p = .071$.

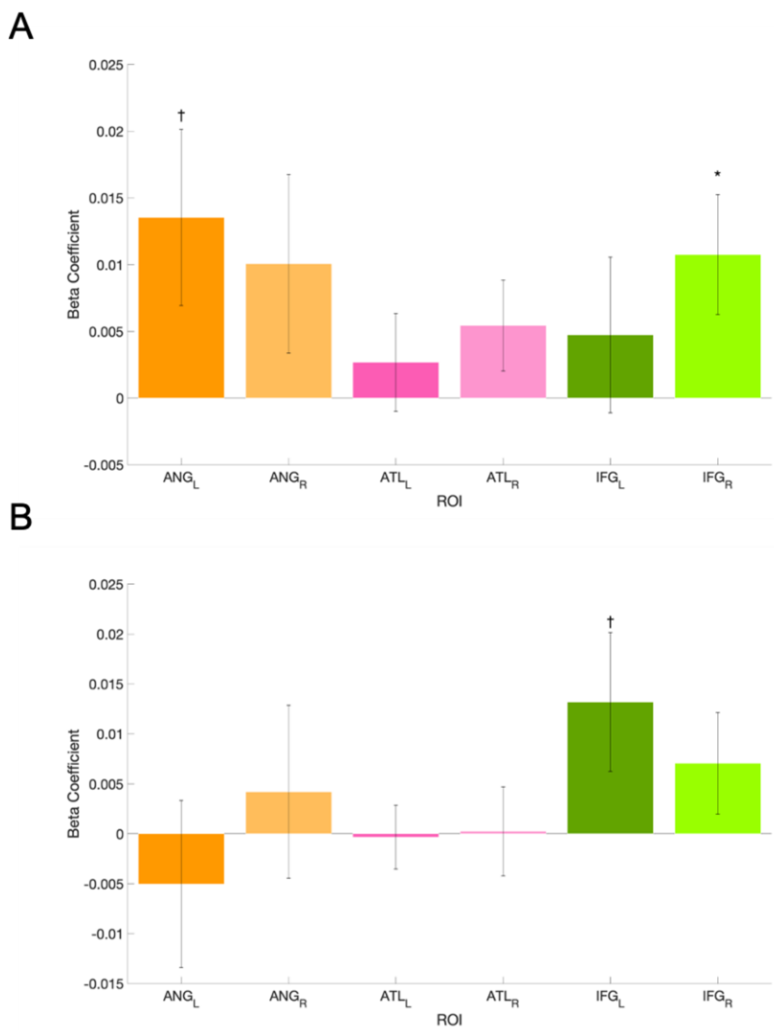

Figure 6. Beta coefficients predicting activation difference in ROIs.

A) unambiguous vs. ambiguous B) attributive vs. relational

In addition to my planned contrasts, I ran a wholebrain cluster analysis of the same contrasts (see all results in Table 4; Figure 7). Three clusters were uncovered where unambiguous combinations showed higher activation than ambiguous. In addition, one cluster was more active during relational conceptual combination processing than attributive.

Table 4. Coordinates of significant clusters from wholebrain cluster analysis.

Unambiguous vs Ambiguous								
Peak			Center of mass					Location of Center of Mass
x	y	z	x	y	z	Size (# Voxels)	*p*	
56.0	69.0	30.0	51.7	59.7	27.1	6778	0.02	Left ANG
0.0	46.0	22.0	1.9	50.9	32.1	5698	0.03	pCC
54.0	5.0	-44.0	55.9	7.2	-26.9	4787	0.04	Left ITG
Attributive vs Relational								
Peak			Center of mass					Location of Center of Mass
x	y	z	x	y	z	Size (# Voxels)	*p*	
32.0	40.0	-12.0	29.3	37.0	-16.2	5605	0.03	Left PHG

Note. Coordinates in MNI.

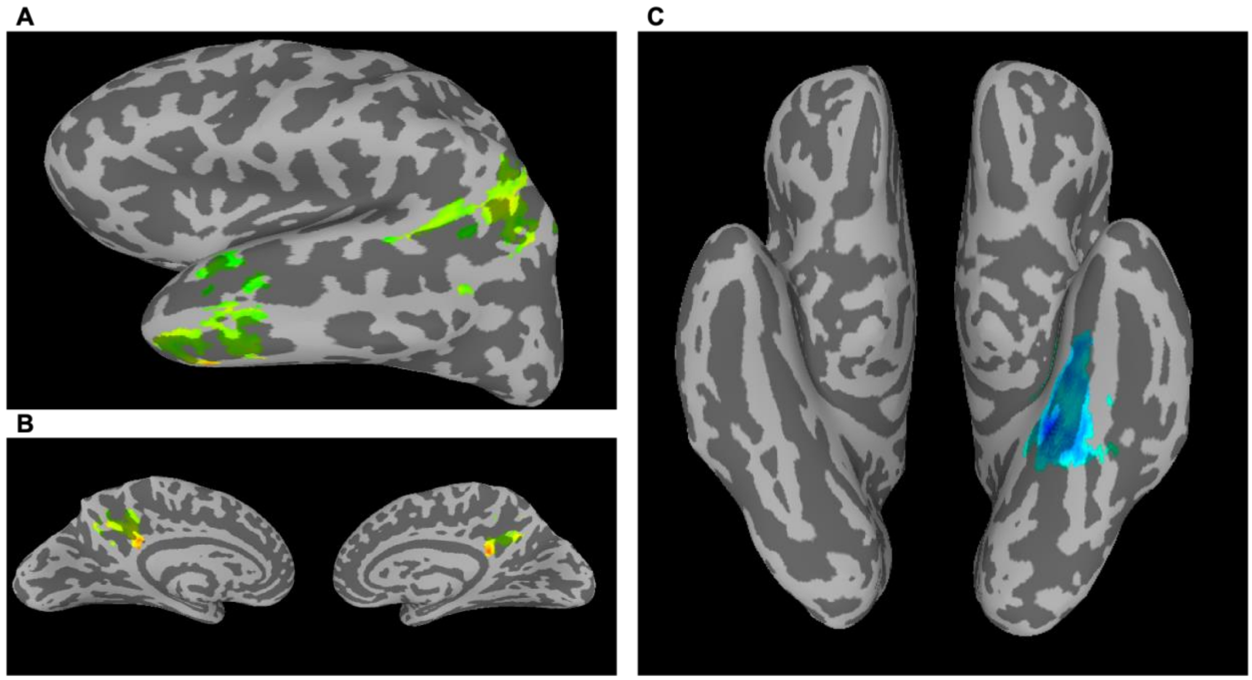

Figure 7. Results of univariate amplitude difference analyses.

Panels A and B show clusters where unambiguous word pairs showed more activation than ambiguous. Panel C shows a cluster where activation for relational combinations was higher than for attributive.

5.2.2 Time-to-Peak Analysis

Finally, I examined the time-to-peak in the right and left ATL to determine whether there are any latency differences between relational and attributive combination strategies (see Figure 8). Neither region showed significant differences in the latencies in each subject's effect peak (*p*s > .322).

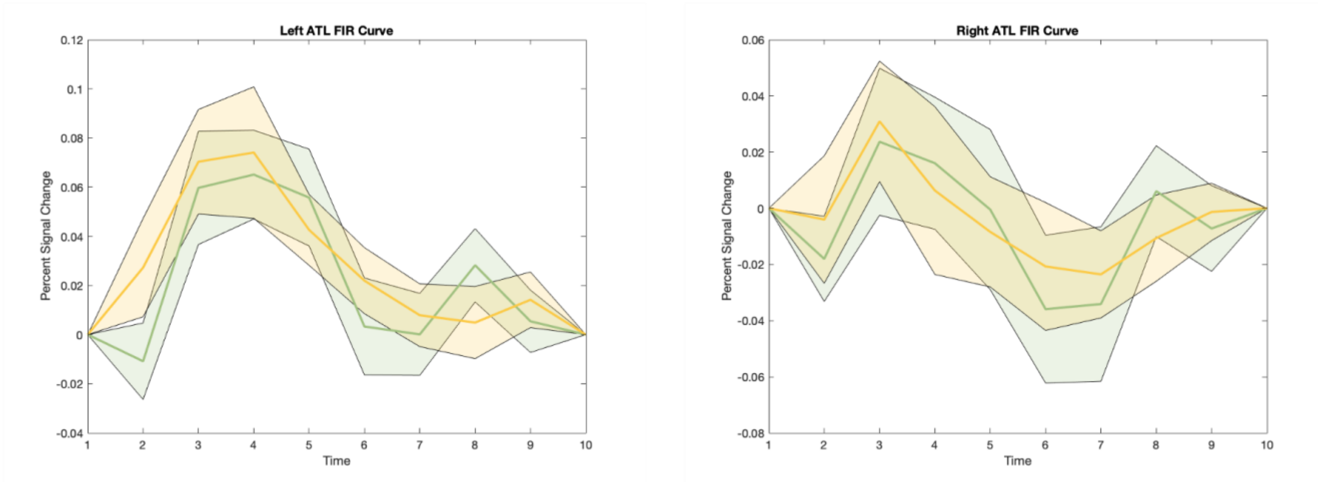

Figure 8. FIR curves of left and right ATL.

Curves for attributive (green) and relational (yellow) activation in each left (left panel) and right (right panel) ATL. Error bars indicate +/- 1 SE. Time presented as knots (1 = stimulus onset, 2 = 2 s post-stimulus, 3 = 4 s post-stimulus, etc.)

5.2.3 Representational Change as a Result of Combination

Representational changes were examined in 3 ROIs: LOC, V4, ATL (left and right). Analyses did not uncover significant differences between the combination types in any of the ROIs, $p > 0.078$ (see Figure 9).

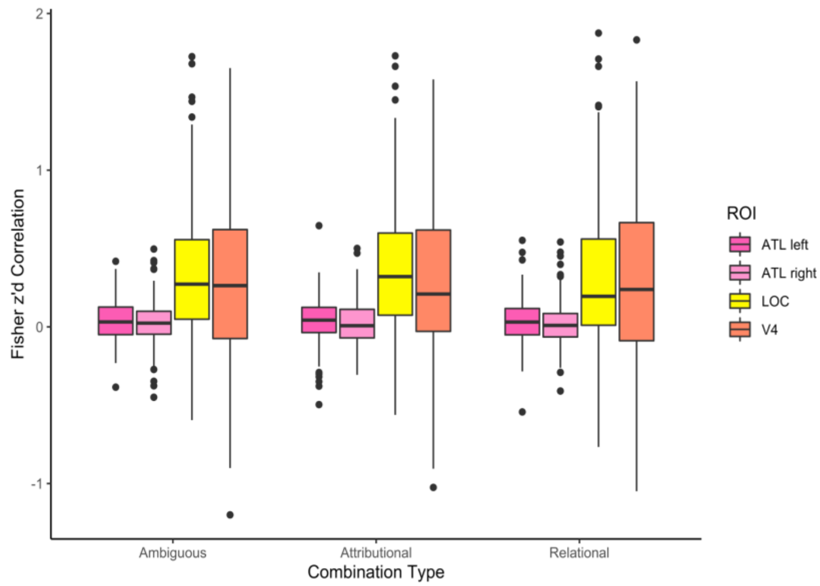

Figure 9. Results of multivariate analysis examining representational changes in feature-processing ROIs.

In addition to the planned ROI analyses, I also conducted an exploratory searchlight analysis to examine whether any region of the brain showed different levels of representational change between the three combination types. One region showed significant differences between combination strategies (see Table 5, Figure 10). Word pairs with ambiguous strategies showed more representational change in a cluster in the left early visual cortex (EVC).

Table 5. Coordinates of significant cluster from multivariate searchlight.

Peak			Center of Mass			
x	y	z	x	y	z	Size (# Voxels)
+17.0	+90	-8.0	+18.4	+91.4	-4.0	5578

Note. MNI space.

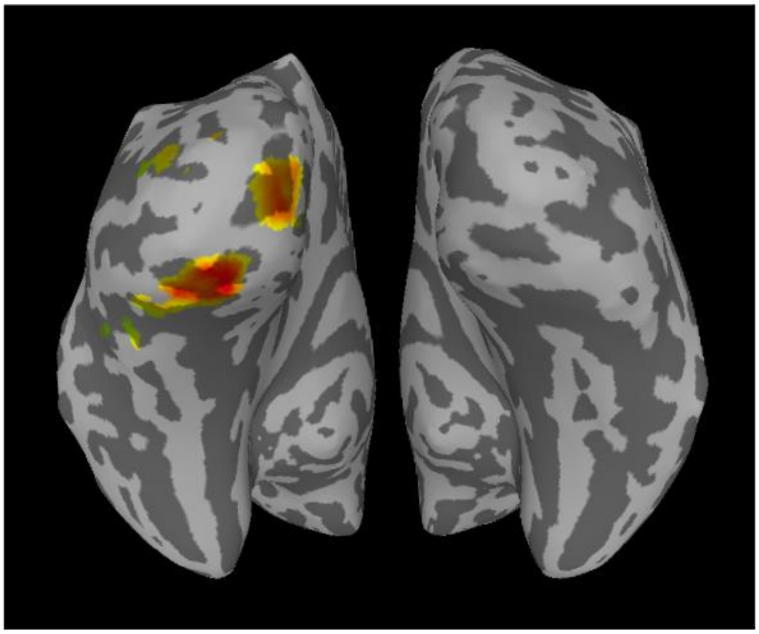

Figure 10. Visualization of cluster with neural representational change.

Cluster in early visual cortex showing more representational change (a lower average correlation between the word pairs of the same strategy) for ambiguous than unambiguous word pairs.

5.3 Discussion

This study was aimed at examining the neural underpinnings of conceptual combination and the neural representational changes that occur as a result of conceptual combination. With both questions, we had a particular focus on how these processes differ depending on the strategy being used to combine. I anticipated that, in accordance with past findings, the ANG would show higher activation for relational stimuli and serial processing in the ATL for attributive stimuli. In addition, I anticipated that the LIFG, whose role has been largely debated in the literature over time, might be most important for combining ambiguous combinations. In addition, as a result of attributive combination, I expected to see representational changes in feature-processing regions, V4, LOC, and ATL. This study found an interesting pattern of results, which, in many ways, demonstrate the importance of incorporating lesser studied ambiguous word pairs in studies of conceptual combination.

5.3.1 Processing of Conceptual Combinations

Instead of the left IFG, our study found activation in the right IFG during conceptual combination, more so for unambiguous combinations than ambiguous. This result was unexpected, as the semantic network is known to be strongly left-lateralized (Alam, et al. 2019; Gao, et al. 2021). The left IFG is thought to contribute to this network by aiding in semantic selection and control (Solomon & Thompson-Schill, 2017; Thompson-Schill et al. 1997) and thought to aid in retrieval of weak associations (Badre & Wagner, 2007). One past study has shown activation of the left IFG during the processing of conceptual combination. The study showed higher left IFG activation during the processing of unfamiliar (e.g., *house lake*) relative to familiar (e.g., *lake house*) combinations (Graves, et al. 2010). It is difficult to parse exactly why this region did not show significant differences between ambiguous and unambiguous combinations, but perhaps similar levels of feature selection need to occur when processing all kinds of unfamiliar combinations. This question may be fruitful for future research to explore by including a condition of familiar combinations for comparison. Though our findings may lend support to theories that long-range processing is needed to activate the LIFG (Leiken, et al. 2015; Leiken & Pylkkänen, 2014), they may simply suggest that any level of novel combination will require LIFG activation. The right IFG, alternatively, tends to be associated with response inhibition (Aron et al, 2003; Hampshire, et al. 2009). Though the right IFG is not typically associated with conceptual combination, it is possible that it was active in this study as a result of the constraints of the task design. Perhaps, with the limited amount of time allowed for combining, participants recruited inhibitory regions to aid in the inhibition of irrelevant competitors. See the General Discussion for more on how this finding relates to the finding that cognitive control (as measured by performance on a Flanker task) was found to aid conceptual combination, for all but ambiguous word pairs, in Study 2.

Both marginal *a priori* and significant exploratory results support the left ANG preferring unambiguous stimuli over ambiguous. Although we anticipated the preference would be for relational over attributive combinations (Boylan et al. 2017; Coutanche, et al. 2019), this finding is consistent with a previous study that showed increased activation for meaningful relative to meaningless (e.g., *plaid jacket* vs. *moss pony*) word pairs in both hemispheres of the ANG (Price, et al. 2015). Similarly, a neurostimulation study found that the left ANG modulates meaningful, but not meaningless, adjective-noun pairs (Price, et al. 2016). It is interesting to note that our effect was left-lateralized. Though the ANG has been well-documented as a region of semantic integration (Geschwind, 1972; Price, et al. 2015), and language is known to be left-lateralized in right-handed individuals (Baciu, et al. 2005; Knecht, et al, 2000), some findings have suggested that the right ANG is more active during relational nominal combination, which requires more implicit relational processing than more explicit combination like with verb-noun pairs (Boylan, et al. 2017). These studies have suggested that the left ANG may be responsible for more explicit combining and right ANG for more implicit combining. It may follow that our left-lateralized effect demonstrates that unambiguous combinations contain more explicit combinations than ambiguous combinations. Given this pattern where studies containing ambiguous stimuli show evidence for left-lateralization (unambiguous > ambiguous) in the ANG and those containing solely relational and attributive show evidence for right-lateralization (relational > attributive), future studies should examine how global context interacts with the lateralization of the ANG during conceptual combination.

Finally, we did not find evidence for increased activation between any conditions or earlier activation in the ATL between attributive and relational combinations. The role of the ATL in semantic integration during conceptual combination is well-documented (Bemis & Pylkkanen, 2011; Lambon Ralph, et al. 2017; Patterson, et al. 2007), but how it processes different types of conceptual combinations has been long debated. Our findings were consistent with a prior study that found similar magnitudes for both combinations (Boylan, et al. 2017), but we did not find evidence for earlier processing in either relational (Boylan, et al. 2017) or attributive (Gagné & Shoben, 1997; Gagné & Spalding, 2013) combinations. Overall, the lack of activation and time-to-peak differences in the ATL do not quite align with either single- or dual-processing models, with the former suggesting we would see activation differences and the latter suggesting we would see serial processing. Because the ATL is known to be prone to signal drop-out (Devlin, et al. 2000; Ojemann, et al. 1997), a temporal signal-to-noise (TSNR) analysis was run to determine whether the null findings were due to poor signal in the ROI. Fairly reasonable and consistent TSNR was found in both hemispheres (left ATL: range = 153 – 298, M = 239, SE = 8, 3 subjects below 200; right ATL: range = 125 – 287, M = 225, SE = 9, 7 subjects below 200), suggesting that the null findings reflect actual signal. It should be noted, though, that the ATL is a highly heteromodal region and that our measurements may reflect multiple subregions. Future studies wishing to understand the mixed findings regarding the role of the ATL in relational and attributive processing may wish to segment these subregions further to see whether different roles emerge in different brain regions, which may explain these inconsistent findings.

In addition to the *a priori* ROI analyses, there were also significant differences in group-level exploratory cluster analyses. One cluster, in the posterior cingulate cortex (pCC), which showed greater activation for unambiguous word combinations than ambiguous, is thought to be a central hub of the default mode network and tends to deactivate during complex tasks (Krieger-Redwood, et al. 2016; Leech, Braga, & Sharp, 2012). This is consistent with our finding that ambiguous stimuli, which tend to be more complex to combine, show this deactivation. Future studies may wish to examine whether this relationship between pCC activation and combining strategy is modulated by the ease with which word pairs are combined. Interestingly, recent evidence shows that the pCC might increase functional coupling with prefrontal regions during demanding semantic tasks (Krieger-Redwood, et al. 2016). This coupling occurs during creative tasks requiring divergent thinking. With this in mind, future investigators may consider conducting connectivity analyses to uncover whether ambiguous combination engages the coupling of the pCC with the prefrontal control network.

The left inferior temporal gyrus (ITG) was also more active during the combining of unambiguous word pairs than ambiguous. This finding is consistent with a past study that examined a contrast of meaningful (e.g., *winter clothes*) versus reversed (e.g., *clothes winter*) combinations. Although the contrast is not precisely in line with the ambiguity contrast conducted in this study, it is similar in that one condition (i.e., meaningful, unambiguous) is relatively straightforward to interpret while the other (i.e., reversed, ambiguous) is less so. Together, these studies suggest that the left ITG may be an important region for interpreting conceptual combinations when the strategy at hand is relatively straightforward. Given the role of the left ITG in verbal working memory during conceptual combination (Fiebach, et al. 2007), perhaps more meaningful word pairs activate this region more because the simpler strategies for combining mean that the combined representations can be more easily held in working memory.

Finally, the left parahippocampal gyrus (PHG) was found to be more active for relational than attributive combinations. The left PHG is thought to be part of a largely left-lateralized network of brain regions responsible for the storage and retrieval of semantic information (Binder, et al. 2009). It has also been shown to be involved in contextual associative processing (Aminoff, Kveraga, & Bar, 2013). This is consistent with past studies where authors suggested that relational combinations might be particularly reliant on context generation, a process of generating contexts in which the individual constituents might be compatible and combined (Kenett & Thompson-Schill, 2017). One previous study has shown recruitment of the left PHG to process nominal compounds (Baron & Osherson, 2011). In this study, researchers found that the left PHG additively processes combinations of concepts, likely through the co-activation of the constituent concepts. In other words, instead of processing the semantic integration of constituent concepts like *child* and *male* to multiplicatively combine *boy (child* x *male* = *boy)*, the left PHG more simply processed *child* and *male* as separate concepts (*child* + *male* = *boy)*. These findings are consistent with other findings that the left PHG is responsible for simpler lexical-level, as opposed to phrase-level, processing (Graves, et al. 2010). Though future studies will need to directly address this possibility, perhaps the left PHG generates contexts separately for each constituent concept, aiding combining by detecting (or communicating with another brain region that can detect) when the contexts are compatible.

5.3.2 Neural Representational Change Due to Conceptual Combination

Inconsistent with my hypothesis, there was no evidence of more representational change in the feature-processing regions (V4, LOC, ATL) for attributive compounds. Instead, other feature-processing regions which process early visual information, showed greater representational change for ambiguous word pairs than unambiguous. It is possible that the level at which I measured representational change in this analysis was reflective of change in these clusters, but another level of analysis might be more appropriate to uncover change in my hypothesized regions. For instance, it might be more appropriate to measure representational change in V4, a region known to represent color information, at an item-level, defining clusters by which attribute (e.g., color, shape) was selected to define the compound's meaning (or perhaps, at an even more narrow level of granularity, compounds for which the same color was used to define the pair). Early visual processing regions, on the other hand, would likely be sensitive to change at any level of representation, as they reflect the most low-level visual features of a concept (Lamme & Roelfsema, 2000). Therefore, we can expect that, regardless of which change occurred during the conceptual combination, some low-level visual representational shift likely occurred. The larger representational shifts measured for ambiguous word pairs may reflect the more effortful processing that had to occur to combine these pairs. These findings support current theories that the semantic memory system is dynamically sensitive to context (Yee & Thompson-Schill, 2016).

Finally, these findings speak to the role of the early visual cortex in perception. In this study, participants viewed only the written words for the concepts. In other words, the perceptual features of the visual stimulus presented do not reflect the representational change measured. Instead, it is the perceptual semantic information associated with the concept, information that is only mentally represented, that is shifted. This is in line with evidence that the early visual cortex can code other forms of perceptual semantic information, such as implied size (e.g., that an elephant is larger than a dog), even when only written words for the concepts are being viewed (Borghesani, et al. 2016). These findings may lend additional support that early visual cortex does not reflect purely perceptual information, *per se*, but may be involved in more mental, meaning-related, concept-level perceptual processing.

5.3.3 Conclusions

The neuroimaging methods used in this study allowed for the parsing of an important delineation between unambiguous and ambiguous stimuli. Higher activation in the left ANG, right IFG, and pCC may underlie processing differences between strategies, suggesting that unambiguous combinations are more plausible, better manage competitors, and can be combined while the DMN is active. In addition, higher activation in the left ITG and greater representational shifts in the left early visual cortex demonstrate the increased success, ease, and speed with which unambiguous combinations can be combined. In particular, these findings suggest that unambiguous combinations may be better held in verbal working memory, more effectively shift neural representations, and lead to more elaboration. Alternatively, only one region, the left PHG showed activation differences between unambiguous combinations. This finding may reflect an increased need for context generation for relational combinations. Whereas most studies of conceptual combination will investigate the divergence between attributive and relational combination strategies, this study demonstrates the marked differences between these commonly studied strategies and ambiguous strategies.

6.0 General Discussion

These studies were aimed at examining two main questions about conceptual combination. First, they were aimed at understanding how processing of conceptual combination occurs. Findings suggest that cognitive control may be important for predicting ease of combining unambiguous compounds and that the cognitive processes supporting conceptual combination likely change throughout the lifespan. In addition, we find support for divergence in processing relational and attributive combinations, as well as ambiguous and unambiguous (relational and attributive) combinations. Second, given the flexibility of concept representations in goal-related contexts, these studies aimed at uncovering to what extent these cognitive and neural representations might be altered as a result of conceptual combination. Ultimately, the results showed early evidence of neural representational change as a result of conceptual combination. These findings speak to theories of memory and higher-order cognition and leave open some questions to be explored in future studies.

6.1 Cognitive Control Aids Processing of Unambiguous Nominal Compounds

An emerging theme from Studies 2 and 4 was that cognitive control is important for predicting how easily unambiguous compounds can be combined. This was supported by performance on the Flanker task in Study 2 and by activation in the right IFG in Study 4. Though the right IFG is typically associated with response inhibition and Flanker with response competition (Chambers, et al. 2007), both studies suggest that some instantiation of cognitive control is positively associated with ease of combining unambiguous compounds. These findings are consistent with theories that inhibition, and not facilitation, drives competition during relation selection. This is demonstrated in one study in which a relation prime was delivered using a nominal compound with a modifier noun matching that of the target nominal compound (Spalding & Gagné, 2011). The prime relation could either be consistent with that of the target (e.g., the prime of *snowfort*, a fort MADE OF snow for target of snowball, a ball MADE OF snow), inconsistent (e.g., *snowshovel*, a shovel FOR snow), or baseline (e.g., *snow*). The study showed that inconsistent primes slowed the processing of targets but consistent primes did not affect target processing, suggesting that the presentation of inconsistent primes inhibited the other possible relations but the consistent primes did not facilitate the primed relation. The findings here lend additional support for the finding that cognitive control is important for the combination of unambiguous compounds.

Less expected was our finding, again supported both by Studies 2 and 4, that cognitive control makes combining easier for unambiguous compounds than ambiguous. I anticipated compounds requiring more competition (i.e., ambiguous compounds) would also require more inhibition of the possible relations. At least under the constraints of these studies, it appears that the ease with which one is able to conceptually combine unambiguous compounds is dependent on the extent to which one is able to inhibit competing attributes and relations. Future studies may wish to examine whether this is true in other contexts where speed of processing is less constrained and how time constraints interact with different measures of success of combining. In these studies, participants had 4 seconds to decide the meaning of their compounds and success was measured by ease. Here, creativity was sparked in a prompted, time-constrained, goal-directed manner (Benedek & Fink, 2019). Although in typical language processing (e.g., during a conversation), the ability to quickly interpret meaning is important, in other contexts that allow for more time (e.g., during brainstorming sessions), other factors, such as thinking of creative interpretations, may wish to be prioritized. Instead of measuring success in combination as ease, a variable to consider is how creative responses are. On the one hand, it is possible that increased inhibition could harm the creativity of their responses, limiting competitors too well to be able to explore other possibilities. Alternatively, inhibition could be redirected to inhibit automatic interpretations (i.e., strong competitors). This could be akin to studies of cognitive expansion wherein cognitive control is deployed to inhibit salient responses that are commonly co-activated with a cue in the semantic network (Abraham, 2014). Instead of activating these stronger, nearer nodes, it is prudent to prioritize the activation of further, weaker connections during semantic expansion, leading to more creative responses.

Finally, an argument could be made that Study 1 also reflects a lack of a relationship between cognitive control and ease of ambiguous combination. In the study, I hypothesized that ambiguous combination would be more challenging once participants were engaged in a highly active semantic network, as more competitions would need to be resolved. Contrary to my hypothesis, no differences were uncovered for these combinations as a result of the elaboration task. One possible reason for these results is that this increased activation did not induce a need for more cognitive control to resolve because, as seen in Studies 2 and 4, these types of combinations are not impacted by cognitive control.

6.2 Visualization and Memory in Conceptual Combination

Studies have shown that people will often use perceptual simulation during conceptual combination. For instance, when asked to list features of concepts, the features will change after they have been conceptually combined to reflect the ocular occlusion present in the novel combination (Wu & Barsalou, 2009). For example, the features generated when prompted with *lawn* tend to be words like *blades, dirt, green, played on.* However, when prompted with *rolled-up lawn,* the features generated reflect the features consistent with those generated in an imagery task – words that reflect the image of a *rolled-up lawn*, like *dirt*. Though this *lawn* undoubtedly still has the features of *green* and *blades* internally, those features are no longer visually present when imagined. Similarly, another study found that the imageability of the constituent concepts predicted the ease of conceptual combination (Lucas, et al. 2017). Importantly, this study also showed that the imageability of the constituent compounds mediated the relationship between ease of combining and subsequent memory. Though the studies presented here cannot directly speak to this relationship, these findings do align with findings from Study 1 where attributive combinations were better remembered than relational and from Study 2 where attributive combination, but not relational, was supported by visualization in older adults. It is possible that these findings reflect this relationship between ease, visualization, and subsequent memory. They suggest that visualization, which supports attributive combination, may be one factor explaining why these combinations are best remembered.

6.3 Conceptual Combination Recruits More Areas of Cognition throughout the Lifespan

Our findings show that, as people age, more cognitive substrates predict their ability to easily combine concepts. Throughout the lifespan, semantic networks become less connected, less organized, and less efficient (Cosgrove, et al. 2021; Dubossarsky, De Deyne, & Hills, 2017). These findings suggest that conceptual combination likely relies on having highly connected, organized, and efficient semantic networks, and, as these variables decrease, other cognitive processes are recruited to compensate. How these individual differences appear throughout the lifespan is not yet fully understood, though some have suggested that cumulative experience may explain individual differences among older adults (Wulff, et al. 2021). As aging occurs, different individuals engage with different books, hobbies, and wide assortments of experiences that may influence the size and structures of their semantic networks. Overall, these findings join others in demonstrating that conceptual combination shows aging-related changes (Lucas, et al. 2019; Taler, et al. 2005; Taler, et al. 2011) and suggest that it may be a fruitful area of study for those looking to study the aging lexicon.

6.4 Attributional and Relational Combinations

Different accounts of conceptual combination provide differing accounts as to whether relational and attributive combinations diverge. Whereas dual-process theories state that relational and attributional combinations require unique processing pathways (Estes, 2003; Wisniewski & Love, 1998), relational theories state that all conceptual combinations are relational and that attributional combinations are combined using the RESEMBLES relation (Gagné, 2000). More recently, a study has argued for an intermediary option where the processing pathways for all conceptual combinations are consistent with one another, but the extent of processing at each step may diverge (Boylan, et al. 2017). This more flexible explanation may be supported by our findings, where all combinations are processed similarly.

These findings demonstrate that some areas of cognition differ for processing relational and attributive combinations. Behaviorally, attributive combinations were shown to be more easily recalled than relational combinations and that deeper processing of more challenging relational combinations made remembering those combinations less likely. Additionally, Study 2 showed that older adults benefit from visualizing more for attributive than relational combination. Finally, we see additional activation of the left PHG during relational combinations. Overall, these findings show some divergence in processing between the two combination types, suggesting that there may be more feature-processing during attributive combination and more context generation during relational combination.

6.5 Ambiguous and Unambiguous Combinations

These studies contain a series of findings that ambiguous combinations, which require more competition before combining is possible, are distinctly processed from unambiguous combinations. This lends support for the RICE and CARIN models of conceptual combination, which rely on the assumption that the competition between relations is the main factor driving conceptual combination. We found differences in how ambiguous compounds are processed in Studies 1, 2, and 4. For ambiguous stimuli, there is less ease, less engagement of inhibitory control (as evidenced by Flanker task performance and right IFG activation), less convergent thinking (as evidenced by RAT performance), more explicit relations (as evidenced by left ATL activation), more complexity in processing (as evidenced by pCC/DMN activation), less verbal working memory (as evidenced by left ITG activation), and more neural representational change in early visual processing regions, relative to unambiguous stimuli. These results suggest that the additional competitive processing that takes place as a result of conceptual combination does indeed require unique processing from more straightforward, unambiguous combinations. Given the surprising number of cognitive processes that seem to be disengaged during ambiguous combining relative to unambiguous, future studies will want to examine exactly which processes are engaged to a greater degree during ambiguous combining. One possible route for future research is whether one such factor is coupling of the pCC with the prefrontal control network. Though we have begun to pare down the ways in which ambiguous compounds are differently processed, the collection of findings that this divergence does exist is notable on its own. Ambiguous stimuli have been largely used as methodological tools for conceptual combination studies in the past (e.g., Estes, 2003) but rarely directly examined. These findings suggest that studies working to understand how conceptual combination takes place will do well to include ambiguous compounds.

An important question to explore is how ambiguous combinations are defined in future work. In these studies, we use a fairly wide brush to define what is considered “ambiguous”. Our study creates three categories of stimuli, chosen to exaggerate the differences between conditions. In particular, our ambiguous stimuli were chosen for being unlikely to be combined as attributive or relational. These were combinations that were about 50-50 relational-attributive at the group level and those where multiple features of both the modifier and head nouns were present in the final combination. Future studies may wish to conduct continuous analyses of these stimuli (as seen in Boylan, et al. 2017), using an intentionally expansive collection of stimuli across the attributive-relational spectrum. In addition, although this study examined ambiguous conceptual combinations, there are other areas of ambiguity that we do not address. For instance, for a single attributive combination, multiple attributive definitions may come to mind. Future studies may wish to address whether this form of ambiguity functions similarly to the relational-attributive ambiguity I have focused on here.

What actually makes ambiguous combinations different from the relational and attributive combinations that they are mostly ultimately destined to become? One explanation for why these combinations may differ from traditional unambiguous combinations may come from examining the associative theory of creativity (Mednick, 1962), which theorizes about how the semantic network relates to creativity. According to this theory, creativity relies on the structure of the semantic memory system. By combining weakly-related, remote concepts, one can form creative thoughts, ones that are novel and relevant. When concepts are located further away from another in semantic space, the combinations they form are more creative (Mednick, 1962). This theory relies on the assumption that the organization of the semantic network directly influences how well people can navigate that space. When individuals have more connected and flexible networks, they can span greater gaps of semantic space and form more creative representations (Kenett, Anaki, & Faust, 2014; Kenett & Faust, 2019). Unambiguous combinations may require less creativity for meaning to be derived (i.e., they may require activation of few, common associations). Alternatively, ambiguous combinations may require more unique activation of the semantic network, requiring activation of broader associations. If, with the broader activation, ambiguous combinations are also situated in the semantic network such that the associated features and relations are nearly equidistant from the concept, competition between two alternative meanings may ensue, creating more conflict than in an unambiguous context. This may explain why these combinations were consistently shown to be more challenging to combine relative to unambiguous combinations. It may also explain why convergent thinking is less useful in creating ambiguous conceptual combinations (as seen in Study 2) because there is no strong, nearby competitor to converge on. Finally, this additional conflict that arises from intersecting multiple concepts may explain why processing ambiguous concepts is more complex, shutting down the default mode network (as implied by activation of pCC in Study 4).

Researchers may wish to examine these data using different analytical methods from the ones used here to approach our questions from different angles. For example, to explore how attributional and relational combinations diverge, another strategy could be to use the interview responses to code the conditions. Although this approach loses the inclusion of an ambiguous condition (which is defined at the group level), it does allow for more precise categorization of attributive and relational combinations for each subject than used here. Despite our norming study to ensure our compounds were very likely to fit in the condition, the most accurate approach would still be to define the conditions based on each subject's meanings. In addition, this would allow for the inclusion of attributional and relational combinations with a wider range of competition (i.e., an attributional compound that was likely to be attributional vs. that was likely to be ambiguous). In addition, researchers may examine individual differences further by using the participants' interview responses. In particular, there may be a relationship between an individual difference measure and one's tendency to interpret an ambiguous combination as relational or attributive. For example, there may be a relationship between visualizing and bias toward attributive combining.

Is the conflict we see between ambiguous and relational combination unique from other types of conflict? In our analyses, we compare two groups – ambiguous combinations (which, ultimately, do typically become relational or attributive combinations, but are inconsistently combined between people) and unambiguous combinations (which are relational and attributive combinations that are more consistently combined across people). According to the RICE model, both unambiguous and ambiguous combinations experience competition. Because we did not examine ambiguity within a combination type (i.e., multiple attributes that could be applied to a head noun) in norming or in responses, it is fair to say that, at least for some attributive and relational combinations, there was a fair deal of competition present. So, what constitutes such an increase in difficulty and complexity in processing ambiguous combinations? Perhaps this is driven by conflict between ambiguous and relational combinations. In other words, intra-strategy conflict (e.g., which attribute to choose) may not be as challenging to overcome as inter-strategy conflict (i.e., attributive or relational).

6.6 Conceptual Combination Can Alter Neural Conceptual Representations

Studies 3 and 4 were aimed at uncovering the extent to which the semantic network can be shifted as a result of conceptual combination. Theories of the semantic network suggest that it is rather flexible, allowing for complex, creative, goal-oriented high-order cognition (Yee & Thompson-Schill, 2016). I approached this question by examining how cognitive representations of concepts shift (as measured through mental models) and how neural representations shift (as measured through correlations of multivariate patterns of BOLD signal). Though conceptual combination did not appear to impact cognitive representations, it is likely that this is due to a methodological downfall, such as lack of robustness in measurement of the mental models. Instead, we turned to a more reliable measure of cognitive representations – the multivariate neural patterns produced prior to and after conceptually combining. This study showed that the early visual cortex underwent more representational change for unambiguous combination than ambiguous. This suggests that this area may contain perceptual information for novel imagined concepts.

The finding that neural representations could be shifted in relation to context supports theories of memory that state that the semantic network is flexible and can be altered by context (Yee & Thompson-Schill, 2016). These findings join a number of neuroimaging (Brouwer & Heeger, 2013; Bugatus, et al. 2017; Nastase, et al. 2017), network (Kenett & Faust, 2019), and behavioral studies (Kruschke, 1992; Nosofsky, 1986) demonstrating this dynamic feature of the semantic system. The study is the first to demonstrate this in neural representations during conceptual combination, supporting network studies that have similar findings (Kenett & Faust, 2019). Interestingly, the shift measured occurred in the absence of instructional differences. Past studies showing task-related representational change have done so in contexts where participants were asked to approach the task differently (e.g., combine the following pairs attributively/relationally). Here, representations shift despite no direction to the combiner. These findings suggest that strategy-specific representational change is possible, even when participants independently select their own self-initiated strategy.

In future studies, researchers may wish to examine the extent to which conceptual combination shifts neural and cognitive representations of concepts at different levels of granularity. The approach used here was in line with past studies examining how the task goal (in this case, combinatory strategy) shifts representations. However, it is true that concepts exist at multiple levels of representation. Any given concept may exist at multiple granularities of representation (e.g., *mammal*, *4-legged*, *brown, dog*, *Gracie*) and these levels of representation have cognitive implications. Though we may remember that a friend has a dog, we might not remember its name, for example. An avenue for future researchers of conceptual combination to explore whether these levels of granularity also show representational change. It is possible that the representational shifts occur at one or many levels of granularity. In this study, we examined one dimension of change – the relational/attributional/ambiguous approach taken in combining. In addition, representational change may take place at other levels of abstraction, such as shifting representations according to color, shape, or type of relation. If we take the example of color, we might imagine that constituent nouns combined similarly along this dimension (e.g., if lemon flamingo, sunshine hair, etc. were all interpreted as a head noun that is yellow), may show representational shifts aligned with this dimension.

Some have suggested that, similar to how concepts are represented at multiple levels of granularity, their relations similarly exist at multiple levels of abstraction (Gagné & Spalding, 2013). For example, a HAS relation may be a level of granularity above HAS-PART and HAS-POSSESSION. As such, conceptual combinations may have preferred levels of abstraction or, as one elaborates the combination more, may refine the level more. This question of how relations are represented might be answered using measures like those implemented here to measure cognitive or neural representations, though given the null findings in measuring cognitive representational change, there may be more success in using neural measures.

6.7 Conclusions

The first aim of these studies was to explore how conceptual combinations are processed and to explore processing differences between unambiguous and ambiguous and between relational and attributive conceptual combinations. The studies demonstrate the importance of cognitive control in conceptual combination and show numerous processing differences between all three types of conceptual combination. Although these may reflect completely divergent pathways, they more likely reflect a more flexible route of processing wherein similar pathways are engaged, but to different extents at different stages for each combination type. Findings that attributive combinations are supported by visualization and tend to be better-remembered speak to memory theories visualization can aid memory. In addition, the studies provide evidence for recruitment of additional cognitive processes to support conceptual combination throughout the lifespan, lending further support for the reliance of conceptual combination on efficiently organized semantic networks, which deteriorate with age. Finally, early visual cortex showed more representational change due to ambiguous combination than unambiguous, lending early evidence that conceptual combination can alter concept representations in a flexible, goal-sensitive semantic network.

Appendix A Norming Study

Word pairs used in the norming study were selected from past studies investigating conceptual combination for specific combination types. Attributional word pairs (*n* = 48) were selected from Estes, 2003; relational pairs (*n* = 58) from Estes, 2003 and Wisniewski & Love, 1998; and ambiguous pairs (*n* = 82) from Gagné & Shoben, 1997 and Kenett & Thompson-Schill, 2017. From these full lists, eight pairs were removed for containing compound words (e.g., sleeping-pill personality) and fourteen were removed for having matching taxonomic categories between W1 and W2. After, all word pairs containing words with concreteness levels below a 4 according to the Brysbaert Concreteness Ratings (*n* = 43) were removed as well as any remaining duplicate word pairs (*n* = 4). Ultimately, this left 34 attributive, 41 relational, and 48 ambiguous pairs to be used in the norming study.

In the norming study, I collected data from 60 participants through Prolific (https://prolific.co/). Participants were told asked to provide a definition of what each word pair would most likely mean and given three examples (e.g., "Again, given the word combination 'robin hawk,' one can think of multiple definitions. One might define this as a robin with a red chest or as a hawk that preys on robins.") Each participant then viewed a random selection of 30 of these total 123 pairs selected (see paragraph above for selection process). For each pair, they were asked to provide their preferred definition for the combination, indicate their ease for providing the definition using a 1 to 7 Likert scale to indicate their agreement with two statements (i.e., "I had trouble thinking of a definition for this word combination."; "I feel that multiple definitions could apply to this word combination equally well."), and finally to indicate if they were unfamiliar with either word in the pair by typing it in a text box. Finally, all norming participants completed a basic demographics questionnaire. To match my norming study sample with those included in the main study, participants who indicated that they had a neurological disability, intellectual or learning disability, and/or attentional disorder, as well as participants who did not meet my language requirements (see Study 1 Methods). Ultimately, 55 participants were included in the final norming study sample.

Three independent raters categorized the definitions. All definitions were given the distinction of attributional, relational, neither, impossible to determine, or unsure. Raters were trained on identifying relational and attributional combinations in advance. They categorized definitions as "attributional" if they identified a strategy of applying one dominant attribute or feature from the modifier noun to the head noun and "relational" if they identified the strategy of forming a relationship between the nouns. "Neither" was used to categorize valid definitions where words were combined without attributional or relational techniques. For example, if a definition morphed the nouns (e.g., describing an elephant ant as a medium-sized creature with antennae and a tail) or used the second noun to modify the first (e.g., describing an elephant ant as a small elephant), it was classified as "neither." Definitions were categorized as "impossible to determine" if they did not have enough detail to give it another classification (e.g., participant only wrote one word, wrote nonsense, etc.). Definitions categorized as "unsure" if the raters were unsure of how to categorize the definition; all pairs marked "unsure" were re-categorized to one of the other definitions by an independent final judge. After ratings, final categorizations were determined in a winner-takes-all manner, meaning that definitions that were given the same rating by at least 2 of the independent raters were categorized according to their judgment.

After categorizations were made, word pairs were ranked twice – once according to the percentage of attributional definitions and percentage of relational definitions. The top eight attributional word pairs were chosen to be “attributional” and the top eight relational were chosen to be “relational.” Finally, the words that were most balanced as being equally likely to be identified as relational and attributional were identified as “ambiguous.”

For the fMRI study, a total of 24 nouns were selected (8 attributional, 8 relational, 8 ambiguous). All attributional and relational nouns had at least 80% of definitions categorized as attributional or relational, respectively (see Table 6). Ambiguous nouns were selected if they were categorized as below 60% attributional and relational. For the behavioral studies, stimuli included both the noun pairs from the fMRI study as well as additional noun pairs for a total of 60 noun pairs (20 attributional, 20 relational, and 20 ambiguous). All attributional and relational nouns had at least 75% of definitions categorized as attributional or relational, respectively. Again, ambiguous nouns were selected if they were categorized as below 60% attributional and relational.

Table 6. Average categorization as attributional or relational combinations.

	fMRI		Behavioral	
	Attributional	Relational	Attributional	Relational
Attributional	88.9%	5.6%	90.1%	5.0%
Relational	2.0%	94.8%	2.3%	95.3%
Ambiguous	31.8%	44.8%	36.4%	43.1%

Note. Ratings from independent raters for each stimulus condition. Separated for stimuli used in the fMRI (Study 4) and behavioral studies (Studies 1-3).

Appendix B Final Stimuli List

Table 7. Final list of stimuli and their categorization.

air lakes	Ambiguous	
alligator mouth	Ambiguous	
attic leg	Ambiguous	fMRI
cake confetti	Ambiguous	fMRI
cardboard lotion	Ambiguous	
centipede table	Ambiguous	
copper horse	Ambiguous	fMRI
cracker wall	Ambiguous	
grease fish	Ambiguous	fMRI
iron fist	Ambiguous	
liquor keyboard	Ambiguous	
melon planet	Ambiguous	
olive signals	Ambiguous	fMRI
onion bus	Ambiguous	fMRI
picture soup	Ambiguous	fMRI
pudding lamp	Ambiguous	
sap toy	Ambiguous	
sink tub	Ambiguous	
trash house	Ambiguous	fMRI
wreath nerves	Ambiguous	
balloon pregnancy	Attributional	
bullet train	Attributional	
butter grip	Attributional	
canary crayon	Attributional	
chocolate clay	Attributional	
finger tree	Attributional	
fire coffee	Attributional	
leech boyfriend	Attributional	fMRI
lemon paint	Attributional	
molasses traffic	Attributional	fMRI
octopus chair	Attributional	fMRI
pillow lips	Attributional	
piranha lawyer	Attributional	fMRI

rock bagel	Attributional	
rocket sprinter	Attributional	fMRI
sedative voice	Attributional	fMRI
silk hair	Attributional	
strawberry ink	Attributional	fMRI
thunder applause	Attributional	fMRI
vampire insect	Attributional	
book string	Relational	fMRI
bowling sweater	Relational	fMRI
boxing bruise	Relational	
burrito stain	Relational	
car photographer	Relational	
concrete fountain	Relational	fMRI
floor television	Relational	fMRI
grill steak	Relational	
microwave sandwich	Relational	fMRI
mountain snake	Relational	
pancake spatula	Relational	
patio cigarette	Relational	fMRI
prisoner graffiti	Relational	fMRI
rodeo magazine	Relational	
rugby shoes	Relational	
scalpel incision	Relational	
song court	Relational	
student artwork	Relational	
tissue alcohol	Relational	
yarn truck	Relational	

Note. List of all nominal pairs used in behavioral studies (Studies 1 – 3). Stimuli used in fMRI study (Study 4), indicated in column 3.

Appendix C Individual Difference Full Statistical Model, Younger Adults

Table 8. Full statistical model of individual differences in younger adults.

	Estimate	***SE***	**statistic**	***df***	***p***
(Intercept)	-75.53	78.17	-0.97	116	0.336
VVIQ	-0.10	0.11	-0.95	116	0.345
Semantic	0.10	0.15	0.71	116	0.478
AUT	-3.10	3.07	-1.01	116	0.315
RAT	-0.03	0.13	-0.21	116	0.832
Flanker RT	-2.52	0.78	-3.24	116	0.002
Flanker Error Rate	-0.91	0.33	-2.76	116	0.007
Ambiguity (Unambiguous vs. Ambiguous)	23.48	66.02	0.36	116	0.723
Unambiguous (Attributive vs. Relational)	56.10	76.23	0.74	116	0.463
VVIQ x Ambiguity	-0.07	0.09	-0.75	116	0.456
VVIQ x Unambiguous	-0.17	0.10	-1.59	116	0.114
Semantic x Ambiguity	-0.02	0.12	-0.19	116	0.850
Semantic x Unambiguous	0.24	0.14	1.66	116	0.099
AUT x Ambiguity	0.89	2.60	0.34	116	0.732
AUT x Unambiguous	2.23	3.00	0.74	116	0.458
RAT x Ambiguity	0.05	0.11	0.45	116	0.652
RAT x Unambiguous	-0.09	0.13	-0.72	116	0.475
Flanker RT x Ambiguity	-0.77	0.66	-1.18	116	0.241

Flanker RT x Unambiguous	-0.14	0.76	-0.18	116	0.857
Flanker Error Rate x Ambiguity	-0.56	0.28	-2.03	116	0.044
Flanker Error Rate x Unambiguous	-0.13	0.32	-0.42	116	0.676

Results of multiple imputation model of individual differences predicting ease of conceptual combination in younger adults. Model: with (imp, lmer(ease ~ 1 + vviq_z + semantic_z + aut_z + rat_z + flanker_rt_z + flanker_err_z + comboType + vviq_z:comboType + semantic_z:comboType + aut_z:comboType + rat_z:comboType + flanker_rt_z:comboType + flanker_err_z:comboType + (1|id),data = indivDiff_data))

Appendix D Individual Difference Full Statistical Model, Older Adults

Table 9. Full statistical model of indivual differences in older adults.

	Estimate	*SE*	*df*	*t*	*p*
(Intercept)	-7.69	30.50	69	-0.25	0.802
VVIQ	0.26	0.08	69	3.15	0.002
Semantic	0.25	0.09	69	2.94	0.005
AUT	-0.63	1.68	69	-0.38	0.706
RAT	-0.10	0.09	69	-1.17	0.245
Flanker RT	-0.92	1.11	69	-0.83	0.409
Flanker Error Rate	0.58	0.39	69	1.48	0.143
Ambiguity	42.30	25.07	138	1.69	0.094
Unambiguous	23.59	28.95	138	0.82	0.417
VVIQ x Ambiguity	-0.02	0.07	138	-0.25	0.806
VVIQ x Unambiguous	0.16	0.08	138	1.99	0.048
Semantic x Ambiguity	-0.02	0.07	138	-0.25	0.802
Semantic x Unambiguous	-0.02	0.08	138	-0.20	0.846
AUT x Ambiguity	2.06	1.38	138	1.50	0.137
AUT x Unambiguous	1.23	1.59	138	0.78	0.440
RAT x Ambiguity	0.22	0.07	138	3.03	0.003
RAT x Unambiguous	0.01	0.08	138	0.13	0.895
Flanker RT x Ambiguity	1.88	0.91	138	2.07	0.041
Flanker RT x Unambiguous	0.76	1.05	138	0.73	0.469

Flanker Error Rate x Ambiguity	-0.31	0.32	138	-0.97	0.334
Flanker Error Rate x Unambiguous	0.32	0.37	138	0.85	0.398

Results of regression model of individual differences predicting ease of conceptual combination in older adults. Model: lmer(ease ~ 1 + vviq_z + semantic_z + aut_z + rat_z + flanker_rt_z + flanker_err_z + comboType + vviq_z:comboType + semantic_z:comboType + aut_z:comboType + rat_z:comboType + flanker_rt_z:comboType + flanker_err_z:comboType + (1|id),data = indivDiff_data)

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