Associative asymmetry of compound words

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Abstract

Early verbal-memory researchers assumed participants represent memory of a pairs of unrelated items with two independent, separately modifiable, directional associations. However, memory for pairs of unrelated words (A–B) exhibits associative symmetry: a near-perfect correlation between accuracy on forward (A→?) and backward (?←B) cued recall. This was viewed arguing against the independent-associations hypothesis, and in favor of the hypothesis that associations are remembered as holistic units. Here we test the Holistic Representation hypothesis further by examining cued recall of compound words. If we suppose pre-existing words are more unitized than novel associations, the Holistic Representation hypothesis predicts compound words (e.g., ROSE BUD) will have a higher forward–backward correlation than novel compounds (e.g., BRIEF TAX). We report the opposite finding: compound words, as well as non-compound words, exhibited less associative symmetry than novel compounds. This challenges the Holistic Representation account of associative symmetry. Moreover, pre-experimental associates (positional family size) influenced associative symmetry— but asymmetrically: increasing family size of the last constituent increasing decoupled forward and backward recall, but family size of the first constituent had no such effect. In short, highly practised, meaningful associations exhibit associative asymmetry, suggesting associative symmetry is not diagnostic of holistic representations, but rather, is a characteristic of ad-hoc associations. With additional learning, symmetric associations may be replaced by directional, independently modifiable associations as verbal associations become embedded within a rich knowledge structure.

Keywords: compound words, association-memory, associative symmetry, cued recall, unitization, hippocampus

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Introduction

A major focus of verbal episodic memory research is memory for associations, pairs of items, A–B. A fundamental, yet still unresolved, question is how participants representation associations between pairs of items, A and B, in memory.

Initially, it was assumed a forward-directed association, from A→B, was learned independently (and was separately modifiable) of the backward-directed association, A←B (e.g., Wolford, 1971). However, Gestalt psychologists proposed that people learn verbal associations (e.g., BRIEF TAX), by transforming the constituent items into a holistic unit. Asch and Ebenholtz (1962) reasoned that, therefore, testing a pair with a forward probe (BRIEF–???) and with a backward probe (???–TAX) should have the same outcome, because there are not two directional associations, but a single compound unit accessed with either probe-direction. As they predicted, forward and backward cued recall are equally accurate on average (e.g., Asch & Ebenholtz, 1962; Horowitz, Norman, & Day, 1966; Kahana, 2002; Murdock, 1966; Rizzuto & Kahana, 2001). However, Kahana (2002) pointed out that independent associations can be equally strong on average, so the classic comparison of recall probabilities is not diagnostic of theories of associative memory. Rather, one must measure the correlation between forward and backward recall, tested on separate occasions, in a “successive-testing” procedure (Table 2). If forward and backward probes of a pair test memory for the same underlying learned information (the “Gestalt”), accuracy on a forward test should be nearly perfectly correlated with accuracy on a backward test of the same pair. This property— the *Different* correlation (forward–backward and backward–forward conditions in Table 2) taking on a value close to 1— has been confirmed (Caplan, Glaholt, & McIntosh, 2006; Kahana, 2002; Madan, Glaholt, & Caplan, 2010; Rehani & Caplan, 2011; Rizzuto & Kahana, 2000, 2001; Sommer, Rose, & Büchel, 2007).

In the current paper, we ask whether the Holistic Representation account can be further supported by considering compound words, such as *rosebud*. On the one hand, compound words are made up of two (or more) words and, as such, could be thought of as verbal associations. On the other hand, compound words (e.g., *rosebud*) are more than just associations between two existing representations (e.g., between ROSE and BUD); compounds have their own representation in the mental lexicon (Libben, 1998), and for this reason, memory for compound words might be even more like holistic units in memory than novel compounds.

To elaborate, we reasoned that words, including compound words, can be viewed as highly practised, verbal associations (residing in semantic memory). Because a compound word is not only an association, but also a unit, the Holistic Representation hypothesis leads to the prediction that the Different correlation in an episodic paired-associate memory task should be greater for compound-word stimuli than for the novel associations that have been the focus of prior studies.[1] Consistent with this prediction, Crepaldi, Rastle, Davis, and Lupker (2012) found influences of constituents on lexical decision of compound words, independent of the position of the constituents. Reversed compounds (e.g., *moonhoney*, which is *honeymoon* with its constituents reversed) took longer to reject (as nonwords) than matched, control nonwords (e.g., *moonbasin*), which is interpreted as evidence of interference from the reverse-ordered word (e.g., *honeymoon*). So, a compound, AB, may be similar to its reverse, BA. However, other findings suggest that access to morphemes is position-dependent. For example, Crepaldi, Rastle, and Davis (2010) found that suffixes influenced lexical-decision times for nonwords, but only when they were placed in the last position (e.g., *gasful* vs. *fulgas*).

[1]Note that the Different correlation, although high, is never perfect. This could be because novel associations do not exhibit as high a correlation as is empirically possible, and compound words might in fact produce even higher correlations. Alternatively, this may simply be due to random error, and the Different correlations typically observed with novel compounds might already be effectively at ceiling; if this is the case, the Holistic Representation hypothesis would predict that the Different correlation should be no lower for compound words than for novel associations.

Finally, associative recognition of compound words shows a high rate of endorsements of recombined compounds (e.g., if *horsefly* and *snowshoe* were studied, *horseshoe* would be a recombined probe), and recombined probe stimuli were facilitated in an implicit word-fragment completion task (Reinitz & Demb, 1994), suggesting that compound words may be decomposed in both explicit- and implicit-memory tasks. However, Reinitz and Demb (1994) found evidence against such decomposition in a perceptual-identification task using these same stimuli, which might indicate that, in some sense, compound words are processes as units.

Cued-recall findings are also mixed. Wollen (1968) and Levy and Nevill (1974) found forward-probe accuracy advantages for two-digit numbers, which Kahana (2002) suggested may have a holistic representation, as we are suggesting for compound words. In contrast to novel associations, compound words can be viewed as overlearned; participants have many exposures to them. With many presentations of noun-pairs, forward-probe advantages have been reported for accuracy (Wollen, Fox, & Lowry, 1970) and response-time (Waugh, 1970) measures. However, these findings do not bear on associative symmetry because asymmetry in mean performance does not speak to the correlation between forward and backward cued recall (Kahana, 2002), and Madan et al. (2010) demonstrated that novel word pairs can exhibit asymmetric mean performance without any disruption of the high forward–backward correlation. Kahana (2002) presented word-pairs for 1, 3 or 5 times each, and measured the forward–backward correlation, but failed to find the correlation decreasing with number of presentations, despite accuracy more than doubling over this range. This suggests that for episodic associations, there is no relationship between degree of learning and the forward–backward correlation.

Beyond our main hypothesis, we considered characteristics of specific compound-word stimuli that might affect directionality of memory. Compound words, such as *rosebud*, are contrasted with non-compound multimorphemic words, such as *stapler* (Sandra, 1990; Gagné & Spalding, 2004, 2009). Some monomorphemic words, which we will refer to as semi-compound, have embedded words, with the remaining part being nonwords (e.g., *sandwich*). Compounds vary in terms of semantic transparency: the meaning of a transparent compound is predictable from the meaning of the constituents, such as *rosebud*. In contrast, opaque compounds, such as *hogwash*, have meanings that are not predictable from the meaning of the constituents (Libben, 1998; Zwitserlood, 1994). Semi-compounds have one constituent that is a word, and we classify them by the transparency of that constituent. We included stimuli with these ranges of properties to test whether they influence the Different correlation compared to novel compounds (e.g., brief tax), which are similar to stimuli that have previously exhibited associative symmetry.

Finally, Kahana's (2002) simulations showed how pre-experimental associations could produce asymmetries in mean performance. The more prior associations to one word, the worse that word will function as a cued-recall probe (see Criss, Aue, & Smith, 2011, for a related result). In research on compound words, this property is quantified as *family size*, the number of words that contain a particular constituent, and has been shown to influence lexical-decision times (Bertram, Baayen, & Schreuder, 2000; Baayen, Tweedie, & Schreuder, 2002; de Jong, Schreuder, & Baayen, 2000; Schreuder & Baayen, 1997). Positional family size refers to the number of words that contain a constituent in a particular position— for our purposes, the beginning or end of the word. For example, for the compound word *rosebud*, we consider the positional family size of *rose* in the first position and the positional family size of *bud* in the final position. Our task demands that participants retrieve a specific associate. Therefore, large family sizes should make the task more challenging, because the additional family members may compete with the one correct target.[2] Thus, the greater the family size of the first constituent, the lower the accuracy should be on forward probes, which has been found in word-stem completion

[2] Interestingly, this contrasts with studies showing that family size *facilitates* lexical decision (Bertram et al., 2000; Schreuder & Baayen, 1997). We suggest that in lexical decision, the activated family words provide congruent evidence with respect to the lexical decision— that the stimulus is in fact a word.

("lexical set size"; Nelson, Canas, Bajo, & Keelan, 1987). Similarly, the greater the family size of the second constituent, the lower the accuracy should be on backward probes. We take this argument further. Rehani and Caplan (2011) found that inducing symmetric associative interference in an episodic paired associate task by having participants study pairs with overlapping items reduced associative symmetry, as measured by the Different correlation. They explained this in terms of associative interference introducing uncorrelated sources of competition at time of test, dependent on probe-direction. Thus, even if the underlying association is "holistic" (unitary), it can have a lowered Different correlation when it is susceptible to interference that varies with probe-direction. We predicted that family size would produce asymmetries in mean performance, and increasing family size of both constituents would reduce the Different correlation.

Experiment

In the current experiment, we included eight stimulus types (Table 1) which we refer to with an uppercase letter denoting the lexicality of the stimulus (N or W), followed by two lowercase letters in parentheses, denoting the status of the first and second constituent, respectively (t— transparent, o— opaque or n— nonword). Our main interest was the comparison between novel compounds, N(ww), and the other word stimuli, which included true compounds, W(oo) and W(tt), semi-compounds, W(on), W(no), W(tn) and W(nt), and multimorphemic words W(nn). Our chief goal was to test whether all forms of word-stimuli (compounds and non-compounds) would exhibit a greater (Holistic Representation hypothesis) Different correlation than novel compounds.

Methods

Participants. Forty-nine undergraduate students with English as their first language participated for partial course credit in an introductory psychology course.

Materials. Study sets of 32 associations were constructed from stimuli chosen from those used in Taft and Forster's (1976) study, with additions obtained from the CELEX lexical database (Baayen, Piepenbrock, & Gulikers, 1995). A final pool of 128 words was constructed based on transparency and constituent types. The first and second word constituents were matched within each word type with respect to Kucera and Francis' measure of word frequency obtained from the MRC Psycholinguistic Database (Wilson, 1988). Sixteen stimuli of each the following eight types were included (Table 1): true compounds that were either opaque [HOG WASH, denoted $\mathsf{W(oo)}$] or transparent [ROSE BUD, $\mathsf{W(tt)}$]; semi-compounds, with either the first or second constituent being a non-word, divided into semi-compound/opaque [SAND WICH, $\mathsf{W(on)}$; and HUS BAND, $\mathsf{W(no)}$] or semi-compound/transparent [BLOCK ADE, $\mathsf{W(tn)}$; and CRAN BERRY, $\mathsf{W(nt)}$]; words that have non-word constituents which have a proper morphemic structure [STAP LER, $\mathsf{W(nn)}$] and novel compounds [BRIEF TAX, $\mathsf{N(ww)}$]. The novel compounds have the same structure as the transparent compounds, because they include a modifier followed by a head noun and are in quite comparable to stimuli used in prior findings of associative symmetry for novel compounds. Study sets were sampled randomly without replacement from the stimulus pool. Positional family sizes were computed by tallying the words from the MRC Psycholinguistic Database (Wilson, 1988) that matched each word-constituent at the start or the end, respectively.

Procedure. The experiment was created with PyEPL (Python Experiment-Programming Language; Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007). Each association was presented visually in the centre of the screen, with constituents separated by a blank space, for 2000 ms with a 250-ms blank-screen inter-stimulus interval. Stimulus types were presented in random order on each study set.

The distractor consisted of five equations of the form $\mathsf{A} + \mathsf{B} + \mathsf{C} = ?$, where A, B and C were randomly selected digits from 2 to 8, with the restriction that the identical distractor could not be used twice in succession. Each equation remained on the screen for 5000 ms and then was erased for 200 ms. The participant was asked to type the answer answer to the equation within the presentation interval.

Cued recall consisted of a constituent with a blank underlined field either to the right (forward probes, e.g., ROSE _______) or left (backward probes, e.g., _______ BUD). The participant was instructed to type the constituent that was paired with the probe constituent. To measure the correlation between forward and backward cued recall, we used successive testing (Table 2); thus, all the stimuli were probed once in a random order (Test 1) and then, followed by the distractor, all stimuli were probed once again in a new random order (Test 2). Probe order was constrained such that the first probe on Test 2 could not be on the same stimulus as the last probe on Test 1. Typed responses (terminated by the "Enter" key) to the distractor and cued recall probes were recorded and assessed for accuracy (misspellings were considered incorrect) and response times. Response times for initiation of response (first key press) and submission of response ("Enter") were measured. Both response-time measures yielded qualitatively similar results, so here we report only analyses of submission-times.

Participants viewed each study set sequentially (see Figure 1). Next, they performed the distractor task and then answered two sets (Test 1 and Test 2) of cued recall questions based on the list, separated by another block of distractor-task questions. A session consisted of 4 study sets composed of 32 stimuli. The first study set was practice, excluded from analyses, composed of similar word types as those used in the experiment and including self-paced instructions preceding each phase of the task.

Analyses. Our chief measure was our measure of associative symmetry: the correlation between forward and backward cued recall (Different correlation), quantified with Yule's $\mathcal{Q}$, the correlation for discrete, two-level variables (Kahana, 2002), which is equivalent to Γ for a discrete correlation based on a 2×2 contingency table. $\mathcal{Q}$ values were calculated for each stimulus across participants, and transformed to log-odds ratios to satisfy the assumption of normality (Bishop, Fienberg, & Holland, 1975).

Results

Different correlation. Our measure of interest was the relationship between forward and backward cued recall, quantified by the Different correlation (filled bars in Figure 2). Consistent with prior studies (Caplan et al., 2006; Kahana, 2002; Madan et al., 2010; Rehani & Caplan, 2011; Rizzuto & Kahana, 2001), the Different correlation was very close to 1 for novel associations. The control for test–retest reliability, the Same correlation (both probes forward or both probes backward; Table 2), was extremely high and significantly greater than the Different correlation for all stimulus types (unfilled bars in Figure 2).

We analyzed the (log-odds-transformed) Different correlation value with hierarchical multiple regression, with four models (summarized in Table 3). Model 1 was a test of our chief hypothesis, with a single predictor: lexicality (1 for all word stimuli and 0 for N(ww), novel compounds). This model explained 15% of the variance, with the Different correlation greater for novel compounds than pre-existing word stimuli. This is in the opposite direction than the Holistic Representation hypothesis.

We noted that mean accuracy was far lower, and response time was far longer for novel compounds than word stimuli (Figure 3). To test whether these differences in overall memory quality might account for the Different correlation differing between words and novel compounds, we next added mean accuracy (log-odds transformed) and response time (log-transformed) as predictors to Model 2. However, Model 2 did not explain significantly more variance than Model 1, and the lexicality effect remained significant even with these variables in the model.

We next asked whether the effect of lexicality on the Different correlation could be explained by characteristics relevant to the word stimuli. As laid out in the Introduction (Rehani & Caplan, 2011), we predicted that family size of both the first and second constituent should reduce the forward-backward correlation by introducing unrelated sources of interference that depend on recall direction. We also speculated that frequency of the whole word might be related to reduced Different correlation, because the more a compound or association is experienced, the more chance it may have to become unitized (Holistic Representation hypothesis). Model 3, with the three frequencies (log-transformed) added as predictors (Table 3), explained additional variance. Whole-word frequency (Kucera-Francis lemma frequency) was inversely related to the Different correlation, suggesting that the total amount of exposure to a stimulus is related to the associative *asymmetry*. Positional family size of the second constituent was also inversely related to the Different correlation, as predicted. Unexpectedly, positional family size of the first constituent was not significantly related to the Different correlation.

Finally, we asked whether semantic transparency of the first and second constituents might explain further variance in the Different correlation. However, adding dummy-coded semantic transparency variables in Model 4 did not explain significantly more variance than Model 3. The added variables were not significant predictors of the Different correlation, and their inclusion did not render the lexicality, whole-word frequency or family size of the second constituent non-significant as predictors.

Asymmetries in mean accuracy and response time. Next, we conducted specific analyses using mean accuracy and response time as measures. Given that family size of constituent 2, but not constituent 1, reduced the Different correlation, we wondered whether the effects of family size on mean accuracy and response time were also confined to constituent 2. We conducted four regression analyses, predicting accuracy (log-odds transformed) and response time (log-transformed) in the forward and backward directions, each using first constituent family size and second constituent family size (log-transformed) as predictors (Table 4). In contrast to the effect of these predictors on the Different correlation, findings were not specific to family size of the second constituent, and were more in line with the pattern we predicted in the introduction (Criss et al., 2011; Kahana, 2002): family size of the cue-constituent weakened mean performance by increasing competition from other possible completions. Thus, increased family size of the first constituent reduced accuracy and lengthened response times in the forward direction but not in the backward direction, and conversely for family size of the second constituent. Interestingly, family size of the target constituent had a facilitatory effect on accuracy.

Discussion

Our chief finding was that, whereas for novel compounds we replicated associative symmetry, for all types of words, associative symmetry did not hold: the correlation between forward and backward cued recall accuracy was reduced for words compared to novel compounds. Although slight reductions in the Different correlation have been reported before and traced to differential sources of interference depending on-probe direction (Caplan, 2005; Caplan et al., 2006; Rehani & Caplan, 2011), this is the first report of such large-magnitude decouplings of forward and backward cued recall, ($\mathcal{Q} < 0.5$ for many words; Figure 2). The finding of associative asymmetry in words challenges the Holistic Representation hypothesis. Perhaps this means words are less holistically represented than novel compounds. However, there is evidence that for compound words, the whole word has its own representation in the lexicon (Libben, 1998), and monomorphemic words ($\mathsf{W(nn)}$) have no obvious decomposition, so it would be challenging to argue that novel associations are somehow remembered *more* holistically than well known words. This suggests that the Different correlation should not be interpreted as a measure of holistic association-memory. Just as Kahana (2002) argued that symmetry of mean accuracy is not diagnostic of holistic associations (Caplan, 2005; Caplan et al., 2006; Madan et al., 2010), we argue that the Different correlation is also not diagnostic of holistic encoding. Rather, whether holistic or not, the way in which the constituent functions as a cue to retrieve the association is a critical determinant of the Different correlation.

These findings are, however, consistent with an emerging pattern of dependence of association-memory on the hippocampus. Unitization (e.g., of words) has been suggested to enable hippocampal amnesic patients to exhibit preserved association-memory for stimuli such as compound words (Giovanello, Keane, & Verfaellie, 2006; Mayes, Montaldi, & Migo, 2007; Quamme, Yonelinas, & Norman, 2007). Convergent evidence has also been found with intact hippocampal activity in neuroimaging studies (Ford, Verfaellie, & Giovanello, 2010; Haskins, Yonelinas, Quamme, & Ranganath, 2008; Staresina & Davachi, 2010). Also consider that the hippocampus can support various kinds of generalization. For example, Bunsey and Eichenbaum (1996) found that to generalize from stimulus→response associations to response→stimulus associations, rats required an intact hippocampus. Extending this result to verbal association-memory in humans, Rizzuto and Kahana (2001) proposed that the hippocampus is responsible for associative symmetry. This would be consistent with associative *asymmetry* for associations that are no longer hippocampal dependent; namely, compound words, as well as monomorphemic words.

We propose that directionality of an association (order of constituent items within an association) is provided by neocortical brain regions. For hippocampal-independent associations, such as words, the Different correlation is greatly reduced, due to the highly directional nature of (presumably) neocortical associations. Unlike compound words, which have a pre-existing representation, cued recall of novel compounds is hippocampal-dependent (e.g., Giovanello et al., 2006; Mayes et al., 2007), and for this reason, the Different correlation is high. We propose that hippocampal-dependence of memory may not be all-or-none. Rather, some word stimuli may require more contribution from the hippocampus than other word stimuli. This leads to a testable prediction: memory for words with high Different correlations should be more hippocampal-dependent, showing more of a difference in hippocampal activity depending on later memory outcome than for words with lower Different correlations.

The reduced Different correlation did not straight-forwardly depend on semantic transparency, nor whether or not the association was decomposable, but our design included a modest number (16) of items of each type, so it simply may not have been sensitive enough to detect such effects and is left to future studies.

As explained in the Introduction, we expected that associative competition due to pre-experimental associates (quantified by positional family size) would induce asymmetries (Criss et al., 2011; Kahana, 2002), which we confirmed, and would decouple forward and backward cued recall (Rehani & Caplan, 2011), which we partially confirmed. Only family size of the second constituent was associated with reduced Different correlation. Thus, associative competition may be relevant for highly practised word stimuli, but the asymmetry of the family-size effect points to a new type of directionality effect in memory for verbal associations.

An important consideration is that words and novel compounds were treated the same; there were no cues for either words or novel compounds that were not presented on the current list. For most cues, the participant would, by necessity, have to refer to the specific study phase (i.e., a specific temporal context) to screen candidate responses and find the correct target, making the task clearly episodic. The exception is for cues with a family size of 1, which could be argued test semantic memory only, as there is only one completion of family-size-1 cues, regardless of what was on the most recent list. However, the potentially serious concern, that could complicate the interpretation of the results, is whether participants were doing a different task with words than with novel compounds, and in turn, whether this produced the difference in the relationship between forward and backward cued recall that we observed. We reason as follows. The smaller the family size of a cue, the more participants could rely on semantic memory to excel at the task. However, family size of the first constituent was not reliably related to the forward–backward correlation, and higher family size of the second constituent was related to a lower, not higher forward–backward correlation. Therefore, it is not obvious that this line of reasoning weakens our conclusion that forward and backward cued recall is reduced in correlation for words than for novel compounds.

Another potential concern is that, to equate novel associations and word stimuli, we presented all stimuli with a space. However, most words are usually experienced without an intervening space. That said, words are always decomposed into their constituents (e.g., Libben, 1994; Libben, Derwing, & de Almeida, 1999). Furthermore, intra-word spaces do affect processing; they facilitates reading speed, even when spaces are inserted at orthographically "illegal" locations (Inhoff, Radach, & Heller, 2000). The one disadvantage of inserting spaces that Inhoff et al. (2000) found was that the space increased susceptibility to competing completions of the first constituent. This, if anything, is in the opposite direction of our finding that increased whole-word frequency predicted increased associative *asymmetry*.

A further concern is that our novel compounds were recalled with much lower accuracy than the word-stimuli (Figure 3a). However, we consider it unlikely that this difference in accuracy could explain the difference in Different correlation between novel compounds and words for two reasons. First, Yule's $\mathcal{Q}$ is mathematically distinct from mean accuracy, as the marginal accuracies are controlled for (similarly to Pearson correlations correcting for mean levels), and Madan et al. (2010) demonstrated that even asymmetries in mean accuracy do not determine Yule's $\mathcal{Q}$. Second, Kahana (2002) found little change in the different correlation for novel compounds across three accuracy levels ranging from around 35% to around 75%, which suggests that if the mean accuracy of the novel compounds had been raised, the critical comparison would not have been very different (novel compounds having greater Different correlation than words). Consistent with this, in the regression analyses of the compound words, mean accuracy was not a significant predictor of the Different correlation.

Our findings extend evidence of asymmetries in word processing to the domain of episodic memory (see Gagné, 2009, for a review). For example, lexical decision times are sometimes influenced by the frequency of the first constituent (Taft & Forster, 1976; van Jaarsveld & Rattink, 1988), sometimes the second (Juhasz, Starr, Inhoff, & Placke, 2003), and sometimes both (Zwitserlood, 1994). Eye-movement data has distinguished early and late stages of word viewing. When participants read compounds embedded in sentences, Andrews, Miller, and Rayner (2004) found that first-fixation times were influenced by the first-constituent's frequency, but both constituents' frequencies influenced gaze duration and total looking time (see also Juhasz et al., 2003). In our episodic-memory procedure, we measure a much later process: memory retrieval via cued recall. Thus, this complicated pattern of initial processing of a compound may be partly responsible for the asymmetric effects of family size on mean accuracy and response time in our cued-recall findings.

Associative symmetry (both symmetric mean-accuracy and a near-perfect Different correlation) is an inherent property of a major class of distributed memory models: namely, those based on convolution, such as the Theory Of Distributed Associative Memory (TODAM; Murdock, 1982). TODAM has been successfully fit to an extremely broad range of empirical memory data. In TODAM, the association A–B is indistinguishable from B–A. Our findings suggest that, although consistent with our novel-compound findings, TODAM would have difficulty accounting for our findings if compound words were treated as associations. Compound words, therefore, might be best modeled in TODAM simply as items, wherein the first and second constituents would be combined (perhaps concatenated) to form a single item vector. This would suggest that participants treat our novel compounds quite differently than words, or that pre-existing linguistic associations (e.g., in the mental lexicon) influence the formation of new associations for use in the episodic memory task. TODAM would still need an additional assumption to explain our asymmetric family-size result. The other chief mathematical operation used in distributed memory models is matrix outer product. Although inherently asymmetric, such matrix models can be straight-forwardly constrained to mimic associative symmetry (Pike, 1984; Rizzuto & Kahana, 2001), but these models would also need to explain the asymmetric family-size effect, wherein the number of pre-existing associations of the second, but not first, constituent influenced the Different correlation.

In sum, although associative symmetry appears ubiquitous in memory for novel associations, it did not hold for episodic memory for previously learned associations— compound words— nor for non-compound words, that may function more like units. Thus, the Different correlation might not at all speak whether or not an association is holistic. The Different correlation does, however, reveal whether associations in episodic memory are directional in one specific way, namely, whether the first and second constituent of an access the association in the same way. Our findings are consistent with the hypothesis that associations formed by the hippocampus embody associative symmetry, and directionality within associations is instead provided primarily by neocortical regions.

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Type	**Example**	**Compound Type**	**Whole**	**Constituent1**	**Constituent 2**
W(oo)	HOG WASH	True Compound	Word	Word(Opaque)	Word(Opaque)
W(tt)	ROSE BUD	True Compound	Word	Word(Transparent)	Word(Transparent)
W(on)	SAND WICH	Semi-compound	Word	Word(Opaque)	Non-word
W(no)	BLOCK ADE	Semi-compound	Word	Word(Transparent)	Non-word
W(tn)	HUS BAND	Semi-compound	Word	Non-word	Word(Opaque)
W(nt)	CRAN BERRY	Semi-compound	Word	Non-word	Word(Transparent)
W(nn)	STAP LER	Multimorphemic	Word	Non-word	Non-word
N(ww)	BRIEF TAX	Novel Compound	Non-Word	Word	Word

Table 1

Stimulus design. Constituents 1 and 2 denote whether the first and second constituents, respectively, are words or non-words, and for true compounds and semi-compounds, whether semantically transparent or opaque relative to the meaning of the whole word.

Correlation Condition	**Test 1**	**Test 2**
Same	ROSE–?	ROSE–?
Same	?–BUD	?–BUD
Different	ROSE–?	?–BUD
Different	?–BUD	ROSE–?

Table 2

Successive testing design for an example stimulus, ROSE BUD. Each stimulus was tested twice, once in Test 1 and once again in Test 2. The direction of test could remain the same for both tests, in which case the stimulus would enter into calculation of the Same correlation, a control for the test–retest effect. The direction of test could instead vary between tests, in which case the stimulus would enter into calculation of the Different correlation, which is the measure that speaks directly to the holistic property of associations.

Model	Predictor	β	t	Adj. R^2	df1,df2	ΔF
1	Lexicality	–0.394	–4.81‡	0.149	1,126	—
2	Lexicality	–0.397	–3.883‡	0.140	1,124	0.35, n.s.
	Accuracy^{a}	–0.007	–0.07, n.s.			
	Response Time^{b}	0.069	0.84, n.s.			
3	Lexicality	–0.257	–2.39†	0.258	3,121	7.63‡
	Accuracy^{a}	–0.017	–0.16, n.s.			
	Response Time^{b}	0.116	1.33, n.s.			
	Whole-Word Frequency^{b}	–0.241	–2.56*			
	First Constituent Family Size^{b}	0.081	0.89, n.s.			
	Second Constituent Family Size^{b}	–0.227	–2.38*			
4	Lexicality	–0.295	–2.16*	0.245	4,117	0.44, n.s.
	Accuracy^{a}	–0.012	–0.10, n.s.			
	Response Time^{b}	0.128	1.38, n.s.			
	Whole-Word Frequency^{b}	–0.228	–2.22*			
	First Constituent Family Size^{b}	0.104	1.07, n.s.			
	Second Constituent Family Size^{b}	–0.248	–2.39*			
	Opacity 1	0.063	0.66, n.s.			
	Transparency 1	–0.003	–0.028, n.s.			
	Opacity 2	0.78	0.81, n.s.			
	Transparency 2	0.010	0.100, n.s.			

Table 3

Regression models for (log-odds) Different correlation. Opacity 1/2, Transparency 1/2: dummy-coded (opaque/transparent/other) by constituent. ^{a}*log-odds transformed.* ^{b}*log-transformed.* ΔF*: relative to previous model.* $^{*}p < 0.05$ $^{\dagger}p < 0.01$ $^{\ddagger}p < 0.001$

Measure	First Constituent Family Size^b	Second Constituent Family Size^b	Adj. R^2	$F(2, 125)$
Accuracy^a (Forward)	$\beta = -0.33,\ t = -3.90^{\ddagger}$	$\beta = 0.20, t = 2.40^{*}$	0.155	$12.7^{\ddagger}$
Accuracy^a (Backward)	$\beta = 0.189,\ t = 2.32^{*}$	$\beta = -.370, t = -4.54^{\ddagger}$	0.185	$15.5^{\ddagger}$
Response Time^b (Forward)	$\beta = 0.089,\ t = 1.00$, n.s.	$\beta = -0.145, t = -1.62$, n.s.	0.018	2.2, n.s.
Response Time^b (Backward)	$\beta = -0.092,\ t = -1.055$, n.s.	$\beta = 0.260, t = 2.99^{\dagger}$	0.070	$5.8^{\dagger}$

Table 4

Summary of regression models for accuracy and response time in the forward and backward directions. ^{a}*log-odds transformed.* ^{b}*log-transformed.* $^{*}p < 0.05$, $^{\dagger}p < 0.01$, $^{\ddagger}p < 0.001$, *n.s. non-significant*

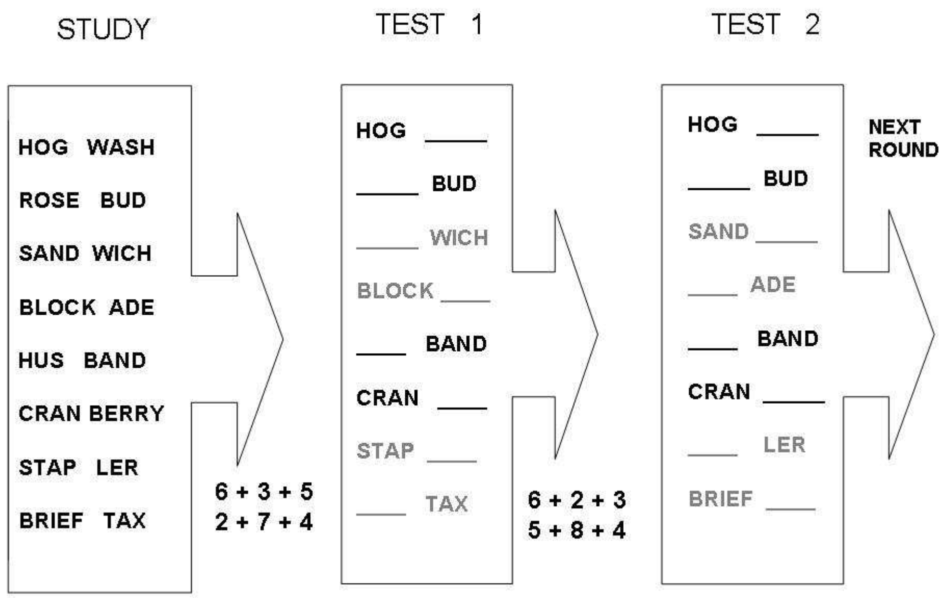

Figure 1. Procedure for a single study set. Stimuli are examples only; stimuli were randomized across participants. In the Study phase, participants would sequentially view a set of verbal association stimuli. In each Test phase, each association was probed exactly once, with either a forward or backward probe. The direction of probe varied between Test 1 and Test 2 for half the associations within a given study set. For illustrative purposes, associations that switched probe-direction are denoted in grey. A brief arithmetic distractor task separated the Study, Test 1 and Test 2 phases.

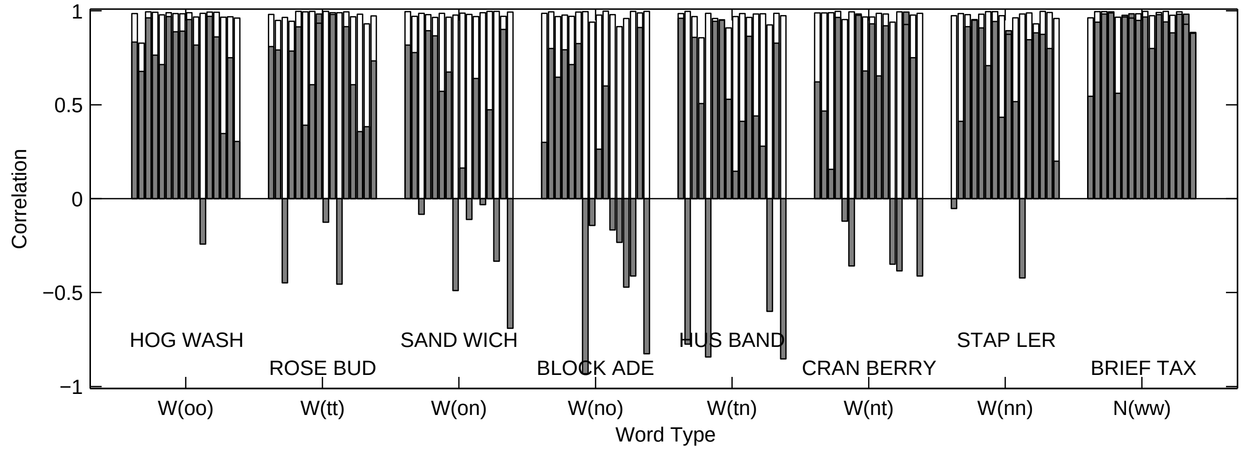

Figure 2. Correlations as a function of stimulus. The Same correlations are plotted in the unfilled outline and the Different correlations are plotted in grey-filled bars. Bars are grouped by word type (but note that in the results, the effect of lexicality was significant, but other word properties were not significant). Within each group, stimuli are sorted in ascending order of positional family size of the second constituent, which was a significant predictor of the Different correlation in the analyses.

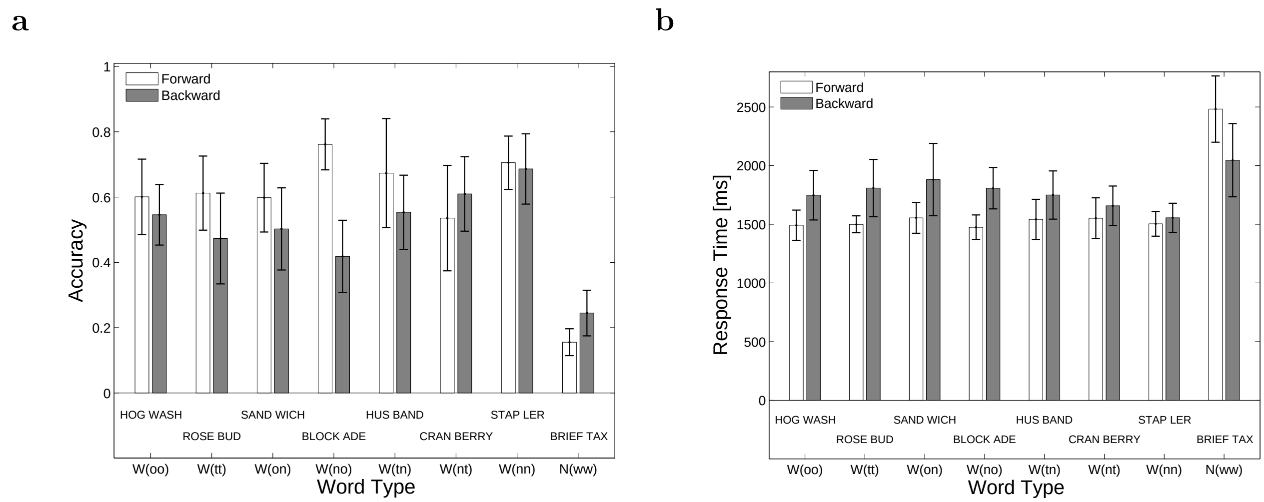

Figure 3. Mean accuracy (a) and correct response time (b) as a function of word type. Error bars are 95% confidence intervals based on standard error of the mean across words.