

Manipulability impairs association-memory: Revisiting effects of incidental motor processing on verbal paired-associates



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ABSTRACT

Imageability is known to enhance association-memory for verbal paired-associates. High-imageability words can be further subdivided by manipulability, the ease by which the named object can be functionally interacted with. Prior studies suggest that motor processing enhances item-memory, but impairs association-memory. However, these studies used action verbs and concrete nouns as the high- and low-manipulability words, respectively, confounding manipulability with word class. Recent findings demonstrated that nouns can serve as both high- and low-manipulability words (e.g., CAMERA and TABLE, respectively), allowing us to avoid this confound. Here participants studied pairs of words that consisted of all possible pairings of high- and low-manipulability words and were tested with immediate cued recall. Recall was worse for pairs that contained high-manipulability words. In free recall, participants recalled more high- than low-manipulability words. Our results provide further evidence that manipulability influences memory, likely occurring through automatic motor imagery.

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1. Introduction

Imageability, the ease by which a word evokes a mental image, is known to enhance association-memory for verbal paired-associates (e.g., Madan, Glaholt, & Caplan, 2010; Paivio, 1971). One hypothesis proposed to account for this phenomenon is the dual-coding theory (Paivio, 1971, 1986, 2007), which suggests that low-imageability, i.e., abstract, words are encoded through only a verbal 'code', while high-imageability, i.e., concrete, words can be encoded through both verbal and imaginal 'codes'. Engelkamp and Zimmer (1984) proposed an extension of the dual-coding theory, to include additional motor 'code'. However, in studying the effects of motor processing on memory, researchers had previously compared action verbs with concrete nouns (see Engelkamp & Cohen, 1991, for a review) confounding motor processing with noun versus verb (i.e., word class; see Madan & Singhal, 2012a,b, for detailed discussions).

It is problematic that previous studies confounded word class with motor processing, as it is known that word class also influences memory, including association-memory (e.g., Earles & Kersten, 2000; Earles, Kersten, Turner, & McMullen, 1999; Gupton & Frincke, 1970). Of particular relevance, Dilnika (2002) found that participants were worse at

remembering verb–verb pairs than noun–noun pairs, independent of any motor-related effects. This issue of word class was first identified by Saltz (1988), who suggested that semantically related nouns could be used as the motor-conductive stimuli (e.g., HOP to RABBIT). Further, Helstrup (1989, 1991) directly suggested that verb pairs may be more difficult to integrate than noun pairs (also see Kormi-Nouri, 1995). To partially justify this confound, it is important to note that this body of research on motor processing and memory developed around the enactment effect, where memory is enhanced for phrases that described actions performed by the subject, relative to phrases that were only read, heard, or were performed by the experimenter (e.g., Cohen, 1981; Engelkamp & Cohen, 1991; Madan & Singhal, 2012c). Due to this original focus, it is understandable that researchers focused on using verbs. Additionally, researchers in the 1980s were unaware that other solutions were available, as Engelkamp (1986) specifically states that “concrete nouns, for instance, cannot per se be encoded via motor activity”.

Given recent advances, we are now able to design studies that better match stimuli sets for other item properties. Briefly, neuroimaging evidence indicates that nouns and verbs are processed differently within the brain (e.g., Bedny, Caramazza, Grossman, Pascual-Leone, & Saxe, 2008; Shapiro & Caramazza, 2003). There is also evidence that concrete and abstract nouns (i.e., high- vs. low-imageability) are processed through different brain regions (Binder, Westbury, McKiernan, Possing, & Medler, 2005). Nonetheless, of greatest relevance are findings that

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high-manipulability words, which are a subset of concrete nouns, engage motor regions of the brain more than low-manipulability words (Buxbaum & Saffran, 2002; Just, Cherkassky, Aryal, & Mitchell, 2010; Rueschemeyer, van Rooij, Lindemann, Willems, & Bekkering, 2010). Specifically, both high-manipulability and low-manipulability words (e.g., CAMERA and TABLE, respectively), are concrete nouns that represent objects. However, high-manipulability words refer to objects that can easily be functionally interacted with using one's hands, while low-manipulability words are not. Note that manipulability specifically refers to hand-object interactions, unlike body-object interaction (BOI; e.g., Siakaluk, Pexman, Aguilera, Owen, & Sears, 2008; Wellsby, Siakaluk, Owen, & Pexman, 2011) which encompasses interactions using any body part, though both are based on motor-related processing.

Studies have found that motor-related words can interfere with overt motor movements, even when the motor properties are not directly attended to, which we refer to as 'automatic motor processing,' demonstrating the functional importance of motor-related processing on cognition. For instance, Glover, Rosenbaum, Graham, and Dixon (2004) demonstrated that when picking up a wooden blocks and silently reading a word, participants used a larger grip aperture if the word represents a relatively larger object (e.g., APPLE). If the word represents a smaller object (e.g., GRAPE), a smaller grip aperture is used (also see Gentilucci & Gangitano, 1998). Additionally, activation of motor regions through either overt movements (Shebani & Pulvermüller, 2013) or artificially via TMS (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005) impairs the processing of motor-related words that involve the same effector, e.g., arm-related words and arm movements interfere, but leg-related words and leg movements can occur in parallel unhindered. These interactions and impairments demonstrate that motor processing is a relatively sequential process. See Pulvermüller (2005) and Madan and Singhal (2012a) for related reviews.

Demonstrating the validity of manipulability as a word property, several studies have found that words that represent objects that can be functionally interacted with, i.e., high-manipulability words, are processed differently within the brain than words that cannot be functionally interacted with, i.e., low-manipulability words (e.g., CAMERA and TABLE, respectively; Buxbaum & Saffran, 2002; Just et al., 2010; Rueschemeyer et al., 2010). Given this important result, it is plausible that manipulability can affect memory, and the word class confound can be avoided. Madan and Singhal (2012b) tested this hypothesis directly, using a between-subjects design. One group of participants was presented with high- and low-manipulability words, one at a time, and asked to judge if the word represented an object that the participant had seen in the past three days ('personal experience' group). This judgment task was followed by a surprise free recall task, where participants were asked to recall any words they could from the preceding task. Madan and Singhal (2012b) found that participants in the personal experience group recalled more high- than low-manipulability words. Another group of participants was asked to judge the length of the words to be odd or even ('word length' group), but was otherwise given the same task. Here participants also recalled more high- than low-manipulability words. A third group was asked to rate the words on the functionality, i.e., if the object represented by the word can be functionally manipulated ('functionality' group). Unlike the other two groups, participants in the functionality group recalled more low- than high-manipulability words. Madan and Singhal (2012b) suggest that there is a manipulability that automatically enhances memory. However, when manipulability is directly attended to, as in the functionality group, controlled motor-related processes override this automatic bias. Montefinese, Ambrosini, Fairfield, and Mammarella (2013) also tested for effects of manipulability on memory. Specifically, Montefinese et al. (2013) asked participants to intentionally study high- and low-manipulability verbs, followed by an old/new recognition test. Participants were found to demonstrate a bias to endorse high-manipulability verbs as 'old,' despite demonstrating no difference in memory. This bias to endorse high-manipulability words is suggestive of an influence of

motor processing on memory, but perhaps only a weak effect when items are encoded intentionally and tested with recognition.

Here we tested whether manipulability has an effect on association-memory. The presence of such an effect would indicate an automatic influence of motor-related processing on how words are processed, integrated into an association, and remembered. Additionally, any effect of manipulability will provide further evidence for theories of embodied cognition and suggest that manipulability is an important additional item-property to be considered when testing for stimulus properties that influence memory. Engelkamp (1986) was also interested in the effect of motor processes on association-memory, comparing memory for pairs of concrete nouns ('visual imagery') to memory for pairs of action verbs ('motor imagery'); however, this comparison was confounded by differences in word class. Here an impairment of association-memory due to motor imagery was found, with the verb ('motor imagery') pairs being recalled to a lesser degree than the noun ('visual imagery') pairs. (These results are replicated in Engelkamp, Mohr, & Zimmer, 1991, and discussed further in Engelkamp, 1988, 1995) However, Lippman (1974) conducted a similar study using *only* verb-verb pairs. Specifically, Lippman (1974) had participants study pairs consisting of verbs that were either high in enactive imagery (HH; e.g., MOW, WADE), low in enactive imagery (LL; e.g., BEGIN, OBEY), or a mix (HL or LH). Lippman (1974) found that memory was enhanced when either the cued recall probe or target was high in enactive imagery, as well the combination of both the probe and target was high in enactive imagery. Taken together, these results are suggestive of an enhancement of association-memory due to motor processing. Thus, in this case where word class is not a confound, association-memory was enhanced due to motor processing. Supporting this result, Harris, Murray, Hayward, O'Callaghan, and Andrews (2012) presented images of high- and low-manipulability objects in a rapid serial visual presentation task. While repetition blindness was observed for the low-manipulability objects, a repetition advantage was found for high-manipulability objects.

Given these contradictory findings, it is unclear whether manipulability will enhance or impair association-memory. If manipulability functions similar to imageability, where motor representations can be used to integrate information, association memory should be enhanced due to manipulability (association-memory enhancement hypothesis). This hypothesis is given credence by the results of Lippman (1974), where participants studied verb-verb pairs that varied in enactive imagery. If this result generalizes to nouns, we would predict that association-memory should be enhanced due to manipulability. In contrast, since hand-related motor actions must occur sequentially, unlike visual imagery, it is possible that motor imagery, and thus manipulability, will impair association-memory (association-memory impairment hypothesis). Engelkamp (1986) compared memory for pairs of concrete nouns and action verbs and found worse association-memory due to motor processing. If these results generalize afterword class is no longer confounding the degree of motor processing, association-memory should also be impaired due to manipulability. In the case of either hypothesis, a caveat must be made: the size of the observed effect will be small in magnitude. As manipulability is nested within imageability, both high- and low-manipulability words are high in imageability. Thus, while imageability has been shown to have a large effect on recall (e.g., Madan et al., 2010), variability in manipulability is serving as inter-item 'noise' in these studies, and both high- and low-manipulability words are being recalled well. The aim of the current study is to determine if manipulability is causing a relative enhancement or impairment of association-memory, above the enhancement known to be produced by imageability.

In the current study, participants intentionally studied pairs of words that were either both high-manipulability, both low-manipulability, or consisted of one word of each type. Participants were then tested using cued recall, where they were given one of the paired words and asked to recall its associate. It is important to note that cued recall is not a direct test of association-memory, it is also influenced by item-memory. For instance, if a word property improved item retrievability, but not

association-memory, it would nonetheless enhance cued recall accuracy. This effect has been demonstrated empirically with word frequency (Madan et al., 2010). By including all possible pair types, Madan et al. (2010) developed a modeling approach to dissociate item- and association-memory effects in cued recall. Here we took advantage of this same modeling approach to directly test for effects of manipulability on association-memory.

To supplement our main finding, we will also test item-memory at the end of the experimental session using a final free recall task. Here we predict more recalls of high- than low-manipulability words, as the motor properties of words will only be processed incidentally/automatically. However, we predict that this bias may be weaker than that found in our previous study (Madan & Singhal, 2012b), as the participants will be intentionally encoding the words in this study, attenuating biases driven by automatic encoding processes. Additionally, the free recall task will occur after the cued recall task, possibly decreasing memory biases due to manipulability.

2. Methods

2.1. Participants

A total of 173 undergraduate students participated for partial credit in an introductory psychology course at the University of Alberta. All participants were required to have learned English before the age of six and to be comfortable typing. Participants gave written informed consent prior to beginning the study, which was approved by a university ethics board.

2.2. Materials

Study sets were constructed from two pools of nouns: high-manipulability and low-manipulability. All words were selected from Madan and Singhal (2012b) based on the manipulability ratings by the participants in the functionality group. Manipulability ratings ranged from 0 (low) to 1 (high). Both pools contained 64 English nouns, ranging from three to nine letters in length (inclusive). Between pools, words were matched on imageability, frequency, familiarity, number of letters and number of syllables as obtained from the MRC Psycholinguistic Database (Wilson, 1988). See Table 1 for the word property statistics.

We also calculated LSA $\cos(\theta)$ as a measure of within-pool word similarity (Landauer & Dumais, 1997). LSA $\cos(\theta)$ for each word pool is as follows (mean \pm sd): high-manipulability (.12 \pm .11) and low-manipulability (.12 \pm .18). Independent-sample t-tests (with *df* based on the effective number of independent comparisons) of the LSA $\cos(\theta)$ values suggest that both pools were similar in their semantic cohesiveness [$t(126) = 0.80, p > .1$].

Table 1

Word pool statistics. IMAG = imageability rating; FREQ = word frequency (per million); FAM = familiarity; NLET = number of letters; NSYL = number of syllables; MANIP = manipulability rating.

		IMAG	FREQ	FAM	NLET	NSYL	MANIP
High	Mean	587	28	533	5.34	1.64	0.87
	St. dev.	35	54	51	1.49	0.74	0.06
	Min	494	1	407	3.00	1.00	0.78
	Max	645	352	643	9.00	3.00	1.00
Low	Mean	584	36	529	5.41	1.53	0.35
	St. dev.	30	47	51	1.33	0.62	0.17
	Min	524	1	411	3.00	1.00	0.04
	Max	639	239	635	9.00	3.00	0.58
<i>t</i>		0.51	0.81	0.45	0.25	0.91	21.13***

*** $p < .001$.

** $p < .01$.

* $p < .05$.

† $p < .10$.

For each participant, word pairs were drawn at random with an equal number of pairs in each of the following pair types: high–high (HH), high–low (HL), low–high (LH), and low–low (LL).

2.3. Procedure

The paired-associate task consisted of three phases: study, distractor, and cued recall. The session concluded with a final free recall task.

2.3.1. Paired-associate

All stimuli were presented in a white “Courier New” font, which ensured fixed letter width, on a black background, in the center of the screen. Words were presented sequentially, for 3000 ms each, plus a 50 ms inter-stimulus interval within pairs and a 4000 ms inter-pair interval during which a fixation cross, “+”, was displayed in the center of the screen. During the study phase, participants were presented with eight word pairs, asked to study the pairs, and told that their memory for the pairs would be tested later on. Each study set consisted of two pairs of each of the four pair types: high–high (HH), high–low (HL), low–high (LH), and low–low (LL). HH and LL pairs are considered ‘pure’ pairs; HL and LH pairs are ‘mixed’ pairs. Word pairings, word membership by pair type, order of pairs, and order of pair types were all randomized across participants.

The distractor consisted of four simple arithmetic problems, in the form of $A + B + C = _$, where A, B, and C were randomly selected digits between two and eight. Each problem remained in the center of the screen for 5000 ms. The participant was asked to type the correct answer during this fixed interval, after which the screen was cleared for 200 ms.

During cued recall, a probe word was presented along with a blank line. Participants were asked to recall the word that was paired with the probe word during the study phase, type their responses into the computer, and press the “Enter” key. If the blank line was presented on the right, the target word is the second item of the pair (“forward direction”). If the blank line was presented on the left of the probe word, the target word is the first item of the pair (“backward direction”). Within each study set, half of the pairs of each pair type were tested in the forward direction and half were in the backward direction. Note, as the participant was unable to predict the testing direction for a given pair, this further prevented any potential encoding preferences for one part of the association (e.g., asymmetrically learning the associations in the forward direction). Participants had a maximum of 15,000 ms to respond, after which the screen was cleared for 250 ms. If participants could not recall a target word for the probe word, they were instructed to type “PASS”.

This procedure was repeated for eight study sets, and was preceded by one practice study set (which was not included in the data analysis).

2.3.2. Final free recall

Participants had 5 min to recall as many words as they could remember from the experiment. Participants were instructed to type in a word and press the “Enter” key. Once a participant pressed the “Enter” key, the screen cleared and the participant was allowed to type in another word. Repeated responses were only counted once. The task was implemented with the Python experimental library (pyEPL; Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007).

3. Results & discussion

The ANOVA is reported with Greenhouse–Geisser correction for non-sphericity where appropriate. Effects were considered significant based on an alpha level of 0.05.

3.1. Cued recall accuracy

To determine the effect of manipulability on association-memory, we tested memory using a cued recall task. Based on prior research,

it is plausible that manipulability could either enhance association-memory (by improving information integration; similar to Lippman, 1974) or impair association-memory (as motor encoding may necessitate sequential processing; similar to Engelkamp, 1986). We first tested for association-memory effects using a conventional ANOVA approach, followed by the modeling approach developed specifically for this cued recall procedure in Madan et al. (2010).

We conducted a TARGET TYPE [2: high, low] \times ASSOCIATION TYPE [2: pure, mixed] \times TEST DIRECTION [2: forward, backward] repeated-measures ANOVA, with cued recall target accuracy as the dependent measure. Both HH and LL pairs are described as ‘pure’ pairs, as both the probe and target were of the same item type (either both high or both low). HL and LH pairs are described as ‘mixed’ pairs, as the probe and target are of different item types.

Cued recall accuracy is plotted in Fig. 1 (a). We found a significant main effect of TARGET TYPE, where low-manipulability words were recalled with greater accuracy than high-manipulability words

[$F(1,172) = 8.51, p < .01, \eta_p^2 = .047$]. Though the interaction of TARGET TYPE and ASSOCIATION TYPE was not statistically significant [$F(1,172) = 3.07, p = .08, \eta_p^2 = .018$], simple effect analyses found that pure-pair low-manipulability words were recalled better than all other conditions [$t(172) = 3.47, p < .001, d = .26$]. ASSOCIATION TYPE was not a significant main effect [$p > .1$]. TEST DIRECTION was neither a significant main effect [$p > .1$] nor involved in any significant interactions [all p 's $> .1$]. The symmetry is a replication of numerous prior findings of equivalent forward and backward recall in pure pairs (e.g., Kahana, 2002; Madan, Caplan, Lau, & Fujiwara, 2012; Madan et al., 2010).

3.2. Model-based estimation of the manipulability effects on item- and association-memory

To quantify the relative effects of manipulability on item- vs. association-memory we fit a probabilistic “item-relationship” model (Madan et al., 2010, 2012) to the mean accuracy data. This model

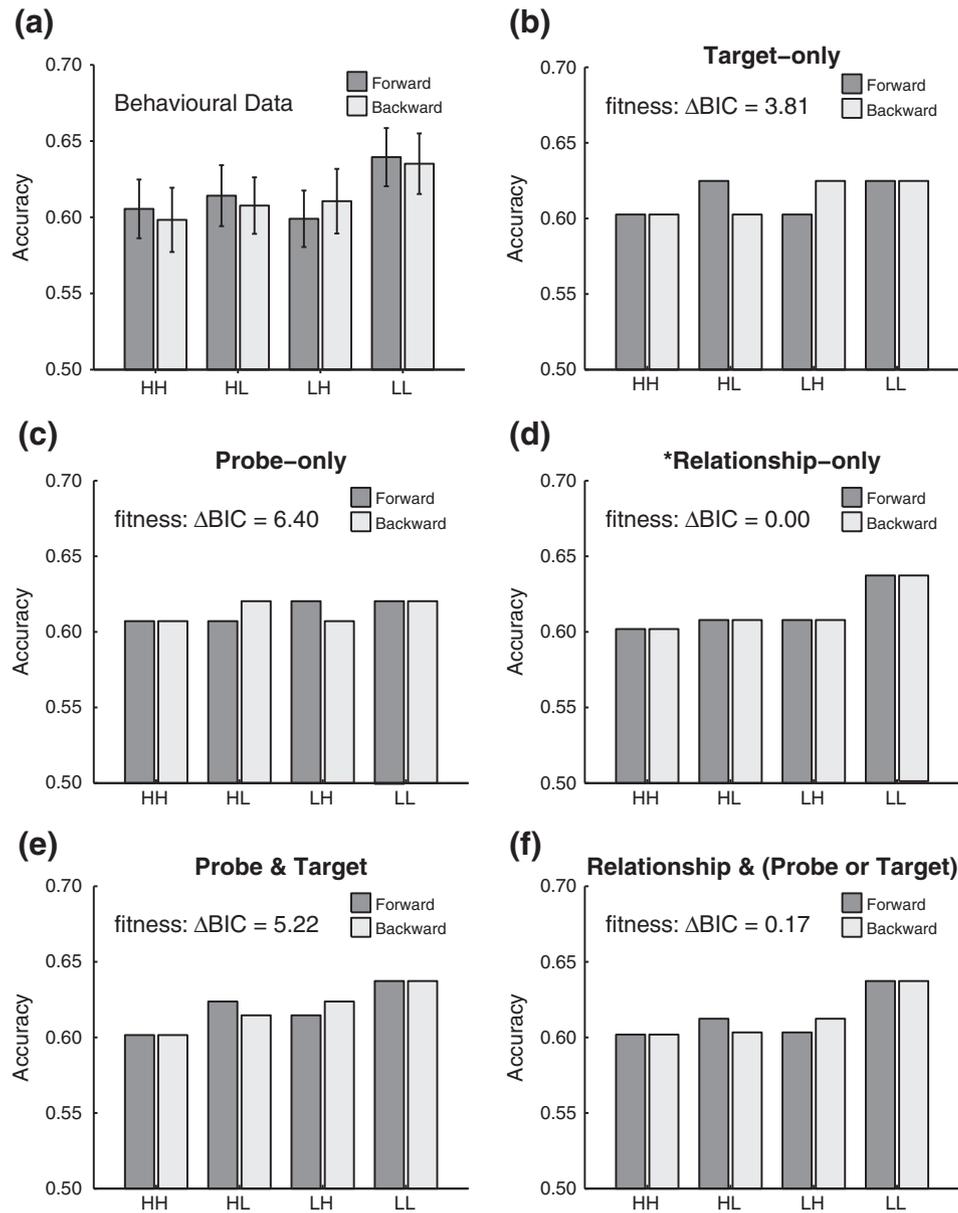


Fig. 1. Cued recall accuracy. high-high (HH), high-low (HL), low-high (LH), and low-low (LL). * denotes the best-fitting models according to our model-fitness measure (ΔBIC) and additional converging evidence. (a) Behavioral data. Error bars represent 95% confidence intervals, corrected for inter-individual differences (Loftus & Masson, 1994). (b) ‘Target-only’ model ($t = [0.94, 0.99]$). (c) ‘Probe-only’ model ($p = [0.96, 1.00]$). (d) ‘Relationship-only’ model ($r_1[0.96, 1.02], r_2 = [0.93, 0.98]$). (e) ‘Probe & Target’ model ($p = [0.96, 1.00], t = [0.94, 0.99]$). (f) Relationship & (Probe or Target) models: ‘Relationship & Target’ model ($r_1[0.96, 1.03], r_2 = [0.93, 0.99], t = [0.95, 1.02]$) and ‘Relationship & Probe’ model ($p = [0.98, 1.05], r_1 = [0.95, 1.02], r_2 = [0.92, 0.98]$).

assumes that successful cued recall relies on three separable and independent processes: probe effectiveness, association strength, and target retrievability. Each of these processes has a probability of being completed successfully:

$$\text{Acc}(\text{Pair Type}, \text{Test Direction}) = P(\text{Probe}_i) \times P(\text{Relat}_j) \times P(\text{Target}_k) \quad (1)$$

where $P(\text{Probe}_i)$ and $P(\text{Target}_k)$ denote the probabilities of effectively handling the probe item and effectively retrieving the target item, respectively, where $i = \text{H,L}$ and $k = \text{H,L}$. $P(\text{Relat}_j)$ denotes the probability of retrieving the pair depending on the relationship between the two items, where $j = \text{HH,HL,LH,LL}$. By this logic, the probability that all three processes will be successful is the result of multiplying the probabilities from the three processes together. This general equation can thus be expanded into a system of equations:

$$\begin{aligned} \text{Acc}(\text{HH}, \text{Forward}) &= P(\text{Probe}_\text{H}) \times P(\text{Relat}_\text{HH}) \times P(\text{Target}_\text{H}) \\ \text{Acc}(\text{HH}, \text{Backward}) &= P(\text{Probe}_\text{H}) \times P(\text{Relat}_\text{HH}) \times P(\text{Target}_\text{H}) \\ \text{Acc}(\text{HL}, \text{Forward}) &= P(\text{Probe}_\text{H}) \times P(\text{Relat}_\text{HL}) \times P(\text{Target}_\text{L}) \\ \text{Acc}(\text{HL}, \text{Backward}) &= P(\text{Probe}_\text{L}) \times P(\text{Relat}_\text{HL}) \times P(\text{Target}_\text{H}) \\ \text{Acc}(\text{LH}, \text{Forward}) &= P(\text{Probe}_\text{L}) \times P(\text{Relat}_\text{LH}) \times P(\text{Target}_\text{H}) \\ \text{Acc}(\text{LH}, \text{Backward}) &= P(\text{Probe}_\text{H}) \times P(\text{Relat}_\text{LH}) \times P(\text{Target}_\text{L}) \\ \text{Acc}(\text{LL}, \text{Forward}) &= P(\text{Probe}_\text{L}) \times P(\text{Relat}_\text{LL}) \times P(\text{Target}_\text{L}) \\ \text{Acc}(\text{LL}, \text{Backward}) &= P(\text{Probe}_\text{L}) \times P(\text{Relat}_\text{LL}) \times P(\text{Target}_\text{L}). \end{aligned}$$

By testing all eight possible combinations of pair type and test direction, we are able to determine the relative effect of manipulability on each process. This relative effect is implemented as a ratio, where each process is assigned a parameter to represent the relative effect of manipulability on that particular process: probe effectiveness (p), association strength (r_1, r_2), and target retrievability (t). A ratio value greater than 1 represents an enhancement of that process due to manipulability (e.g., $t > 1$ suggests greater target retrievability for high- than low-manipulability words), a value less than 1 represents an impairment, and a value equal to 1 represents a null effect. The relationship strength process comprises of two parameters, r_1 and r_2 , for the ratios between (a) 'pure' high-manipulability pairs relative to mixed pairs, and (b) mixed pairs relative to 'pure' low-manipulability pairs, respectively. In other words, we do not assume that these two ratios are identical, and instead fit them independently. An additional scaling parameter (c) is also fit to scale the ratios to the behavioral data. For example, accuracy on a low-manipulability pair would be equivalent to simply c ; however, accuracy on a high-manipulability pair would be equivalent to $c \times p \times r_1 \times r_2 \times t$. Accuracy for a mixed pair with the target word being high-manipulability would be equivalent to $c \times r_2 \times t$.

$$p = \frac{P(\text{Probe}_\text{H})}{P(\text{Probe}_\text{L})} \quad (2)$$

$$r_1 = \frac{P(\text{Relat}_\text{HH})}{P(\text{Relat}_\text{HL,LH})} \quad (3)$$

$$r_2 = \frac{P(\text{Relat}_\text{HL,LH})}{P(\text{Relat}_\text{LL})} \quad (4)$$

$$t = \frac{P(\text{Target}_\text{H})}{P(\text{Target}_\text{L})} \quad (5)$$

Importantly, our item-relationship model is underdetermined, i.e., there are multiple ways to explain the data using various combinations of parameters. For this reason, we only used further-constrained

model variants wherein a subset of the parameters p, r_1, r_2 , and t was fixed to 1 and the remaining parameters were free to vary. After constraining the model, the model can be fit to each participant and parameter values and model fits be summarized across participants. To compare the relative fits of the model variants, we used BIC (Bayesian Information Criterion), which takes into account the number of free parameters. By convention, if the difference between two model fits, $\Delta BIC < 2$, neither of the models' fit to the data is significantly better – thus we report all scores as ΔBIC relative to the best-fitting model.

For further details about the modeling approach, please refer to Madan et al. (2010) and Madan et al. (2012).

3.2.1. Model fits

Model fitness and best-fitting parameters for all of the model variants are listed in Table 2 and the resulting behavioral patterns are illustrated in Fig. 1. Three models were found to have $\Delta BIC < 2$: Relationship-only, Relationship & Target, and Relationship & Probe. In the case of both models that include an item-memory parameter, the item-memory parameter did not significantly differ from 1; in all three models, r_1 did not differ from 1. However, in all three cases, r_2 was significantly below 1. Thus, the common feature leading to the low BIC s for these models is $r_2 < 1$. As the additional parameters in the models that included an item-memory parameter did not differ from 1, they did not sufficiently explain additional features of the data. Thus, the Relationship-only model was considered to be the best-fitting model. $r_2 < 1$ suggests that manipulability items impair association learning, but $r_1 = 1$ suggests that this impairment is not an incremental or step-wise impairment, instead, the inclusion of any high-manipulability words leads to the impairment. In other words, it does not matter if there is one or two high-manipulability words in the pair, association formation is equivalently impaired in either case. $t = 1$ and $p = 1$ suggest that manipulability does not influence the item processes involved in association learning.

3.3. Final free recall

We additionally tested whether manipulability led to difference in item-memory, by examining probability of final free recall. To directly compare these recall rates, we calculated a normalized difference measure, $(\text{High} - \text{Low}) / [1.5(\text{High} + \text{Low})]$, for each participant. This measure thus compares the difference in recall rates for high- and low-manipulability words, relative to the averaged recall rate; positive values indicate a bias to recall high-manipulability words, whereas negative values indicate a bias towards low-manipulability words (also see Madan & Singhal, 2012b). This normalized difference measure was significantly positive, indicating that high-manipulability words were easier to recall [$t(172) = 2.85, p < .01$]. This result is plotted in Fig. 2, along with the normalized difference measures obtained in Madan and Singhal (2012b).

It is important to acknowledge that this free recall test was likely influenced by the earlier cued recall test. Thus, it is possible that the effect

Table 2

Model fits for cued recall accuracy. All model variants are shown, with the exception of the full model (as it is underdetermined by the data). All free parameter fits are presented as 95% confidence intervals. Note that the 'Relationship & Target' and the 'Relationship & Probe' models algebraically produce identical fits due to model mimicry, although their best-fitting parameters are not equivalent. * denotes the best-fitting models according to our model-fitness measure (ΔBIC) and additional converging evidence.

	ΔBIC	p	r_1	r_2	t
Target-only	3.82	1	1	1	[0.94, 0.99]
Probe-only	6.40	[0.96, 1.00]	1	1	1
Relationship-only*	0	1	[0.96, 1.02]	[0.93, 0.98]	1
Probe & Target	5.22	[0.96, 1.00]	1	1	[0.94, 0.99]
Relationship & Target	0.17	1	[0.96, 1.03]	[0.93, 0.99]	[0.95, 1.02]
Relationship & Probe	0.17	[0.98, 1.05]	[0.95, 1.02]	[0.92, 0.98]	1

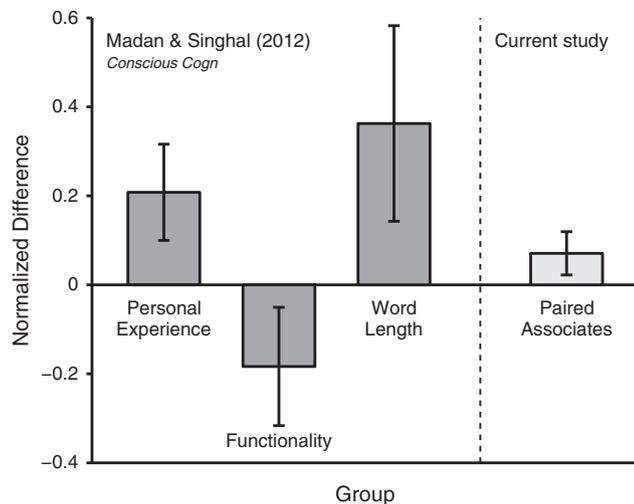


Fig. 2. Normalized difference for recall of high- and low-manipulability words in the final free recall task, compared with the same measure for the free recall task used in Madan and Singhal (2012b). Error bars represent 95% confidence intervals, corrected for inter-individual differences (Loftus & Masson, 1994).

on manipulability on free recall may be underestimated in the current study.

4. General discussion

We found that manipulability impairs association-memory, even after removing word class as a confound. We additionally found that when words are studied intentionally, manipulability still biases free recall, though this effect is attenuated relative to incidental study. Taken together, these results indicate that automatic motor imagery influences not only memory for items, but also memory for associations. Additionally, the results of the model comparisons allow us to rule out item-process hypotheses. Specifically, if high-manipulability words influenced cued recall due to a distinctiveness (e.g., pop-out) effect, this would have manifested as an influence on probe effectiveness and/or target retrievability, as has been found with taboo words (Madan et al., 2012).

The finding that manipulability impairs association-memory indicates a limitation of human memory. Motor-related processes are known to be particularly suited for processing information sequentially, i.e., motor sequence learning. After all, it is difficult to engage in multiple motor actions in parallel, particularly if the actions rely on the same type of motor effector, e.g., both hands. Perhaps this is a drawback of embodied cognition (see Barsalou, 2008; Wilson, 2002, for reviews); even though high-manipulability words provide richer representations than low-manipulability words due to their additional motor properties, these same motor properties appear to limit our ability to simultaneously process the items relative to items that are imageable but not motoric.

To better understand the cause of this impairment of association-memory due to manipulability, it is important to again consider the basis of manipulability as a word property. High-manipulability words are more elaborative than low-manipulability and abstract words, as they inherently contain verbal, imaginal, and motor codes — and the motor processing only occurred automatically. This multi-faceted nature of high-manipulability words makes them individually easier to remember, however, while imagery can be used to enhance association formation (e.g., Madan et al., 2010), motor processing in this case is sequential in nature. Demonstrating this sequentiality, many studies have found that motoric words and motor movements can interfere with each other (e.g., Gentilucci & Gangitano, 1998; Glover et al., 2004; Shebani & Pulvermüller, 2013). Thus, as a result of this sequentiality, motoric properties of to-be-associated words

interfere with the association formation process, though only slightly, impairing subsequent association-memory. This is a different sort of effect on association-memory as have been observed with imageability (Madan et al., 2010) and emotional arousal (Madan et al., 2012), which both were found to incrementally affect association-memory. In other words, as more imageable items were added to the pair (0, 1, or 2), association-memory was incrementally enhanced (both r_1 and $r_2 > 1$); a step-wise impairment was observed with emotional arousal (r_1 and $r_2 < 1$). Here we observed a more subtle effect, where association-memory was impaired equivalently regardless of the number of high-manipulability words present. We suggest that this difference is driven by the sequential nature of motor processing, whereas the impairment of association-memory due to emotional arousal instead was driven by an item- vs. association-memory trade-off.

By investigating how relatively elaborative item properties such as manipulability affect our ability to remember items and associations, we can gain a better understanding of how language and motor movements are intrinsically related and on how these item-specific properties interplay in our ability to recall experiences from our daily lives. To be more precise, manipulability is a measure of how easy it is to interact with the object that is represented by a given word. Until recently, the effects of manipulability on memory were unknown. Though some studies have broached on the topic, such as the work of Engelkamp and others, the focus of these studies was on the enactment effect. If the property of manipulability is not deliberately attended to, it would not be surprising if it does not influence memory. However, even when words are processed at a fairly superficial level, as in the word length group of Madan and Singhal (2012b), also see Fig. 2), manipulability still has a strong effect. In the current study, we found that manipulability can impair our ability to form associations, even when that is the instructed task, and motor properties of the words are not deliberately attended to. These results demonstrate the depth that stimuli are incidentally processed, and provide additional support to the notion that manipulability is a semantic property (e.g., Campanella & Shallice, 2011). Further investigations into the effect of manipulability on memory to test the breadth and boundaries of its influence are proving to be a fruitful avenue of research.

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