**Sensorimotor Effects in Surprise Word Memory – a Registered Report**

**Stage 1 Submission**

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**Abstract**

Sensorimotor grounding of semantic information elicits inconsistent effects on word memory, depending on which type of experience is involved, with some aspects of sensorimotor information facilitating memory performance while others inhibit it. In particular, information relating to the body appears to impair word recognition memory by increasing false alarms, which may be due either to an adaptive advantage for survival-relevant information (whereby words pertaining to the body spread activation to other concepts and generate a confusable memory trace) or to a somatic attentional mechanism (whereby words pertaining to the body activate a false sense of touch that renders their representations less distinctive as memory trace and retrieval cue). To date, the existing literature does not distinguish between these two explanations. We set out to adjudicate between them using a surprise memory task, where participants study the words under a guise of a lexical decision task, which allows us to examine how participants form a memory trace for words grounded in bodily experience.

*Keywords*: word memory; sensorimotor information; semantic richness; incidental memory

**Introduction**

Memory for words is facilitated by semantic content of their representations. As proposed by semantic richness theory (Buchanan et al., 2001; Pexman et al., 2008), a richer representation, such as a larger number of features or associates, higher body-object interaction ratings, or higher imageability, makes it easier to process and respond to the word (e.g., Cortese & Fugett, 2004; Dunabeitia et al., 2008; Pexman et al., 2003; Siakaluk et al., 2008). This idea has been extended to memory research, where a richer representation makes the memory trace more distinctive: that is, it increases the amount of conceptual knowledge associated with an item that is not shared with other items in the list (Dobbins & Kroll, 2005). Specifically, a word richer in semantic information elicits stronger semantic activation (Pexman et al, 2013), and therefore produces a stronger memory trace (Hargreaves et al., 2012; Sidhu & Pexman, 2016). Such rich, distinctive representations are more likely to be retained until the test phase (Lau et al., 2018) and correctly recognised as old, because their memory trace will not easily fade or be replaced by interfering information. Indeed, it has been demonstrated that word memory is better for items with higher imageability (Cortese et al., 2010; 2015), body-object interaction (Sidhu & Pexman, 2016), higher animacy and perceived threat (Bonin et al., 2014; Leding, 2020), and stronger sensorimotor grounding involving experience with manipulable objects and food concepts (Dymarska et al., 2023a). Additionally, more distinctive and semantically rich words are also less likely to be mistaken for previously-seen words (see e.g., Glanzer & Adams, 1985; Zechmeister, 1972), leading to lower false alarms for words higher in imageability or arousal (Cortese 2010; 2015; Lau et al., 2018; but cf. Ballot et al., 2021, regarding imageability). Such studies show that semantically-rich, distinctive words tend to facilitate recognition memory in the classic mirror pattern (Glanzer & Adams, 1985) of increasing hit rates and reducing false alarms.

Notably, semantic information facilitates memory above and beyond lexical word characteristics, which can facilitate memory performance in their own right when they make the word more distinctive. Repeatedly encountered-high frequency words, or words with high contextual diversity

(i.e., encountered in multiple contexts) tend to be remembered better (Cortese et al., 2015) as their distinctive trace is less likely to be confused with other items. Similarly, words which have fewer orthographic or phonological neighbours are less confusable and easier to remember (Cortese et al, 2004; 2015; Glanc & Greene, 2007). Nonetheless, word meaning – that is, semantic representation of the word's referent – is activated automatically upon encountering a word, and its effects on memory performance have been found even when lexical characteristics such as word frequency have been taken into account (Dymarska et al., 2023a; Glanzer & Adams, 1985; Sidhu & Pexman, 2016).

However, when it comes to the perception and action experience that underlies representations of word meaning, there is a wide range of sensorimotor dimensions that can provide grounding (Lynott et al., 2020), and these various forms of sensorimotor experience do not all elicit straightforward semantic richness effects on word memory. In Dymarska et al. (2023a), we compressed ratings of sensorimotor strength in 11 dimensions (i.e., measuring the extent to which a concept is experienced with each of 6 perceptual modalities and 5 action effectors: Lynott et al., 2020) into four orthogonal (uncorrelated) principal components and investigated their effect on recognition memory for over 5000 words (data from Cortese et al., 2010; 2015). Although all forms of sensorimotor experience were initially expected to make a word's representation more distinctive and hence facilitate recognition memory performance, as per other semantic richness variables, we instead found that results were mixed. Words that scored highly on Object experience (e.g., *pillow, comb*; involving vision, touch, and hand/arm action) or Food experience (i.e., *pastry, omelette*; involving taste, smell, and mouth action) were indeed remembered better. Consistent with semantic richness effects, higher scores in these sensorimotor components resulted in more hits, fewer false alarms, and overall improved recognition memory performance (i.e., higher HR-FA and *d'*). However, Communication experience (e.g., *chat, rumor*; involving hearing, interoception, head action and mouth action) had no discernible effect on recognition memory, as higher scores in this component made no difference to either hits or false alarms, which Dymarska et al. (2023a) suggest may be due to lack of distinctiveness in Communication-related words. Most strikingly, words that scored strongly on the Body component (e.g., *cuddle, fitness*; involving touch, interoception, and action of the hand/arm,

foot/leg, and torso) *impaired* rather than facilitated memory performance. Instead of producing the mirror pattern predicted by semantic richness theory of increased hits and fewer false alarms, higher Body scores unexpectedly had little effect on hits but led to *more* false alarms, overall worsening recognition memory (i.e., negative HR-FA and *d'*). That is, semantic richness from the Body component actually led participants to mistakenly respond to new words as if they had been previously seen.

One possible explanation for such divergent sensorimotor effects is that the unexpected effect of the Body component resulted from an adaptive advantage for survival-relevant information. It has been suggested that stimuli pertaining to our survival, such as threatening sounds, wild animals, or bodily sensations (e.g., *movement* or *pain*, which scored highly on the Body component) automatically and preferentially capture attention and spread activation to other, interconnected concepts that may increase the chance of survival, which offers an adaptive advantage in threat detection from an evolutionary perspective (Howe & Derbish, 2010; Nairne et al., 2007; 2008). While this process leads to a strong memory trace for studied words (thereby increasing hit rates), the activation of other, related concepts has the side effect of increasing the probability of false recall and inflating false alarms in recognition memory (Howe & Derbish, 2010; Leding, 2019; 2020; Otgaar & Smeets, 2010). Since bodily function and integrity is, by definition, important to survival, this account offers a potential reason why Dymarska et al. (2023a) found elevated false alarms for Body-related words. That is, even though the semantic representation of a strongly Body-related word might be distinctive by itself, its tendency to activate networks of other survival-relevant concepts lowers its distinctiveness and leads to a more confusable memory trace and less-effective retrieval cue, hence inflating false alarms when new Body-related words in the test phase are mistakenly matched to those granted a memory trace via spreading activation.

However, finding this adaptive effect for Body-related words in a standard recognition memory task, which does not specifically require attending to survival-related information, may be an artefact of the experimental paradigm used. Previous observations of inflated false alarms for survival-related words come from experiments that place particular emphasis on contextual elaboration during the

study phase, such as by asking participants to rate the usefulness of presented words for survival in a grasslands scenario (e.g., Howe & Derbish, 2010; Otgaar & Smeets, 2010), or to generate ideas associated with the presented words (Bonin et al., 2022). Although participants in Dymarska et al (2023a) and in Leding (2020) were not instructed to elaborate on the meaning of the study words, they knew that they were going to be tested later on their memory for the words, and so were likely to employ whatever strategies they could to remember the words better, such as elaborating their meaning and mentally imagining them in a context that would be easy to remember (e.g., a threatening scenario). Hence, when learning words that involve bodily experience in the study phase, such strategies could have led to activation of related concepts in the memory trace and inadvertently reduced participants' ability to correctly discriminate between the survival-relevant words they studied and new (survival-relevant) stimuli presented at the test phase. Body-related words may therefore inflate false alarms and impair memory performance only when learned with contextual elaboration, meaning that this pattern of effects would be unlikely to occur within a memory paradigm where participants were not motivated to elaborate on a word's representation during the study phase.

Alternatively, it is possible that the inflated false alarms in Dymarska et al. (2023a) were due to a somatic attentional mechanism which modulates perception and representation of body-related experiences. Directing attention to the hand (Mirams et al., 2010), to interoceptive sensations (i.e., heartbeat: Mirams et al., 2012), or to locations within peripersonal space (Mirams et al., 2013) all caused people to mistakenly believe they were perceiving tactile sensations (i.e., a micro pulse being delivered to their finger) when none were present. In other words, directing attention towards the body in various ways leads people to false alarm on touch sensations. Several other perceptual phenomena have been found to reappear in semantic processing of word stimuli (e.g., modality switching costs: Pecher et al., 2003; tactile disadvantage in stimulus detection: Connell & Lynott, 2010), and grounded cognition theories hold that that the conceptual system has co-opted the sensorimotor system for the purposes of representation (e.g., Barsalou, 1999; Connell & Lynott, 2014). Hence, the somatic attentional account also offers a potential reason why Dymarska et al. (2023a) found elevated false alarms for Body-related words. That is, if attending to the body (or space

close to the body) in one perceptual modality activates a false sense of touch, then the presence of hand/arm action and interoceptive experience in Body-related words may similarly cause additional, irrelevant tactile activation when presented in a recognition memory task, rendering the overall representation of the word less distinctive and prone to false alarms. Even though the semantic representation of a strongly Body-related word might be distinctive in its own right, its tendency to activate other modalities of body-related experience (particularly touch) lowers its distinctiveness and leads to a more-confusable memory trace and a less-effective retrieval cue. Unlike the adaptive account, the attentional account does not depend on the experimental paradigm used to investigate word recognition memory. If Body-related words inflate false alarms and impair memory performance because they tend to activate other modalities of bodily experience such as touch (i.e., creating a less-distinctive memory trace), then it will occur regardless of how participants are instructed in the study phase.

Dymarska et al. (2023a) could not distinguish between these possibilities due to analysing a conventional expected memory task, where participants deliberately learned a list of words during the study phase because they expected to be tested on them later. When participants learn a list of words with the explicit knowledge their memory will later be tested, they are likely to employ strategies to help them remember the words such as semantic and contextual elaboration. Conversely, when participants are *not* aware they will be later tested on their memory for presented words (i.e., a surprise memory task), such elaboration is far less likely, and offers us an opportunity to adjudicate between theoretical accounts and adapt the semantic richness theory to account for this additional mechanism. Table 1 illustrates the mechanisms behind the two theoretical accounts, and their predictions are outlined in detail in the Current Study section.

Table 1. Mechanisms underlying the two proposed accounts of the Body effects given an expected and a surprise memory task.

| Theoretical account | Expected task: study phase = deliberate word learning (Dymarska et al., 2023a) | Surprise task: study phase = lexical decision word/nonword (the present RR) |
|---|---|---|
| Adaptive advantage | Word learning leads to strategic elaboration of word meaning, which | Lexical decision leads to minimal elaboration of meaning, and so |

| | triggers spreading activation for survival-relevant words → Body-related words lose distinctiveness in memory trace and inflate FA | minimal spreading activation for survival-relevant words → Body-related words remain distinctive in memory trace and either do not inflate FA or actively lower FA. |
|---|---|---|
| Somatic attention | Reading words automatically grounds meaning in sensorimotor information, which then activates irrelevant modalities for words concerned with bodily states → Body-related words lose distinctiveness in memory trace and inflate FA | Reading words automatically grounds meaning in sensorimotor information, which then activates irrelevant modalities for words concerned with bodily states → Body-related words lose distinctiveness in memory trace and inflate FA |

**Current Study**

In the current study, we are going to test the effects of multiple aspects of sensorimotor experience on a surprise (or incidental) word recognition memory task, which will allow us to distinguish the adaptive and the attentional accounts of the Body effects on word memory via contrasting predictions. As in Cortese et al. (2010; 2015), we take a megastudy approach (Balota et al., 2012) to word recognition memory by testing an item set of over 5000 words. The advantage of this approach is that it allows for a large-scale analysis using multiple, continuous predictors, without the need to match word samples on each of the characteristics in different factorial conditions. As predictors of word recognition memory, we employ the same lexical and sensorimotor variables analysed in Dymarska et al. (2023a) that were obtained via Principal Components Analysis of a large number of lexical variables with multidimensional sensorimotor dimensions.

To create a surprise memory paradigm, we will use a lexical decision task to present words to participants in the study phase (i.e., without informing them they will later be tested on their memory for these words), and then conduct the test phase using a regular old/new recognition task. Our reason for using a lexical decision task (i.e., decide whether or not a string of letters is a valid word) is that the semantic activation of different aspects of sensorimotor information has recently been established (Dymarska et al., 2023b): sensorimotor components reflecting Body, Communication, Objects and Food experience all facilitate lexical decision to varying extents. Based on these findings, we expect that semantic information from all four sensorimotor components will be activated in the study phase

of our surprise memory task and thereby contribute to the memory trace of each word, but their influence on the recognition memory decision in the test phase will vary by component.

In line with semantic richness theory, we predict that encountering words whose referents involve object- and food-related experience will activate a rich semantic representation, which will support a distinctive memory trace in the study phase and serve as an effective retrieval cue in the test phase. That is, we expect the current surprise memory task to produce the same effects as in Dymarska et al. (2023a)'s expected memory task, where words scoring highly on Object and Food components will be remembered better and will be discriminated easily between old (studied) and new words (i.e., higher hit rates and lower false alarms). However, based on previous findings for word recognition memory in Dymarska et al. (2023a), we expect that – despite its activation during lexical decision (Dymarska et al., 2023b) – words involving communication experience will not produce particularly distinctive representations, meaning such words are neither very memorable nor provide informative cues for correct discrimination between studied and non-studied words. As a result, the Communication component will not elicit any effects on word memory performance.

Critically, when it comes to words relating to body experience, we aim to disentangle the underlying reasons for their inflated false alarms observed in Dymarska et al. (2023a). In an expected memory task, participants are likely to use elaboration as a strategy to make the word memorable, for example by placing a concept in a particular scenario or context. According to the adaptive advantage explanation, this process will trigger survival-relevant words to spread activation to a network of other, related concepts, which will make the memory trace for those words less distinctive and prone to false alarms. However, participants are unlikely to use elaboration as a strategy in a surprise memory task because they do not know that they will be tested on memory for the words. Therefore, without such elaboration, spreading activation to related concepts will not take place for survival-relevant words, and they will no longer be prone to false alarms. It is possible that the pattern of the Body component effects in Dymarska et al.'s (2023a) expected task was due to such an elaboration strategy, but if so, the same pattern will not emerge in the surprise memory task.

By contrast, the somatic attention account does not rely on elaboration at encoding and so is unaffected by the task manipulation. In both expected and surprise memory tasks, when word meaning is automatically accessed on reading during the study phase, any representations relating to bodily states will extend attention to touch and other irrelevant modalities, which will make the memory trace for those words less distinctive and prone to false alarms. It is possible that the pattern of the Body component effects in Dymarska et al.'s (2023a) expected task was due to such automatic processes, and if so, the same pattern of will emerge in the surprise memory task.

*Hypotheses*

Our specific hypotheses concern the following dependent measures of word recognition memory: hit rate (HR), false alarm rate (FA), overall performance (HR-FA), and sensitivity (d'):

1. Higher scores on the Food and Object components will facilitate memory performance, leading to better recognition of old words (positive effect on HR), better rejection of new words (negative effect on FA), and better discrimination of old versus new items (positive effect on HR-FA and d').

2. Higher scores on the Communication component will not affect performance in any variable.

3. Finally, higher scores on the Body component will produce different predictions by theory. If the somatic attention account applies to word memory, there will be a positive effect on both HR and FA, and a negative effect on discrimination (HR-FA and d'). However, if the adaptative account is correct, then there will be a positive effect on HR only and either no effect (or negative effect, in a mirror pattern) on FA, that will potentially be strong enough to produce a positive effect on discrimination (HR-FA and d').

**Method**

**Participants**

We will determine sample size using sequential hypothesis testing with Bayes Factors (BF: e.g., Schönbrodt et al., 2017), where BF is computed repeatedly during data collection until it exceeds an *a priori* defined threshold of evidence or the maximum feasible sample size is reached. We will begin analysing data at Nmin = 20 participants per list (total Nmin = 2120), which is the sample size

in Cortese and colleagues' dataset (for an expected recognition memory task) that allowed us to detect the key Body effect on FA (Dymarska et al., 2023a). Our maximum sample will be 60 participants per word (6360 participants in total). This sample size, which is three times larger than the Nmin, will allow us to detect effect sizes even if they are smaller in the surprise memory task than in the expected memory task. The critical threshold of evidence is set to BF $\geq$ 6 (or its reciprocal BF$\leq$ 1/6). Sequential sampling will proceed in increments of 100 participants to maintain a balanced design across stimulus lists, and will stop when the BF evidence for or against the inclusion of each sensorimotor component in the model clears the critical threshold for all five DVs, or until we reach the maximum sample. In other words, the stopping rule in our sequential hypothesis testing plan requires all sensorimotor predictors for all DVs to be simultaneously out of the equivocal zone in order to stop testing. In case at any point one predictor drops below the threshold of $BF_{10} = 6$ (and remains above the reciprocal $BF_{01} = 1/6$), even if it previously cleared it at a smaller sample, we will continue testing until we find stable evidence for or against all effects, which will provide a robust estimate of the true effect of each sensorimotor component on memory for words, or until we reach Nmax. In case a particular effect is still not detected at Nmax, we will conclude that it is likely too small to be of interest.

Native speakers of English without a reading impairment (i.e., dyslexia) will be recruited via Prolific.co platform. We will recruit participants with prior approval rate on Prolific of at least 95%. Participants will be excluded from analysis according to criteria outlined in the Data Analysis section. Participants will be paid £1.40 for their time (i.e., approximately £8.50/hour pro-rata).

**Ethics and Consent**

The study has received ethical approval from the Lancaster University Faculty of Science and Technology Research Ethics Committee (reference number FST18088). Before taking part in the study, participants will be asked for their informed consent to participate. They will first read information detailing the purpose and expectations of the study, which describes the task as being about "word judgement" (i.e., without mentioning the surprise memory test). Consent will include agreement that payment is on condition of passing two attention checks (i.e., a screen during the

distractor task and after the last trial of the test phase that asks participants to "press the letter Q/P as quickly as possible"), and following the instructions (i.e., participants would be excluded for pressing the same key throughout a task, e.g., giving all word or all nonword responses in the lexical decision task; all correct or incorrect responses to the equations in the distractor task; all old or all new responses in the recognition memory task), and that all data will be shared publicly in anonymised form. All materials, anonymised data, analysis code and full results will be made available on Open Science Framework upon publication.

**Materials**

We will take a sample of 5300 words for which sensorimotor effects were previously analysed by Dymarska et al., (2023a) in an expected recognition memory task using data from Cortese et al. (2010; 2015). In this way, we can use the same words and the same predictor variables as Dymarska et al. (2023a), so any changes in sensorimotor effects can be accorded to task differences rather than item differences. Dymarska et al. analysed 5305 words in total; we will drop five words with the lowest UK prevalence score (Brysbaert et al., 2019) to produce a final set of 5300 words that can be divided into 106 equal lists of 50 target words each. In order to ensure that similar words are distributed across different lists, we will use a binned sampling method when dividing the stimuli into word lists so that all lists contain items that span from low to high scores on all 6 components. We will sample from bins (set as component score quartiles) of each orthogonal component, such that every list will include 3 words from each quartile of each component (i.e., 3 words x 4 quartiles x 4 components = 48 words), plus 2 words selected at random from different bins to bring the total to 50 words per list.

For the lexical decision task in the study phase, we will also generate 5300 corresponding pseudowords using Wuggy (Keuleers & Brysbaert, 2010). Wuggy produces pronounceable nonwords that follow the phonotactic constraints of English and match the length and number of syllables of the target words. The pseudowords are produced by changing one or more phonemes in real target words (e.g., "church" → "chulks"). We will divide these pseudowords into 106 lists of 50 pseudowords each, where each pseudoword list corresponds to (i.e., is derived from) one of the 106 target word

lists. In order to ensure a given target word is presented separately from its derived pseudoword, and is different from the subsequent distractor list (see below) each target word list will be paired with a non-corresponding pseudoword list. For example, target word list 1 will be paired with pseudoword list 3, target word list 2 will be paired with pseudoword list 4, target word list 3 will be paired with pseudoword list 5, and so on. This process will produce 106 list pairs (each containing 50 words and 50 pseudowords) for presentation in the lexical decision task, where each participant will see a single list pair.

For the surprise memory task in the test phase, each target word list will be paired with another target word list which will serve as distractors (i.e., "new" words not seen in the study phase), and vice versa. That is, target word list 1 will be presented with word list 2 as distractor list, and will serve as distractor list for target list 2. Target word list 3 will be presented with word list 4 as distractors, and will serve as distractor list for target list 4, and so on. This will produce 106 list pairs (each containing 50 "old" target words and 50 "new" distractor words) for presentation in the recognition memory task.

For a distractor phase (i.e., in between the study and test phases), we will create a list of simple mathematical problems, as per Cortese et al., (2010; 2015). These problems will comprise 18 simple addition and subtraction equations for verification (e.g., "2 + 3 = 6?"), all using single digit numbers, where half of the equations will be correct and half will be incorrect.

Finally, for the statistical analysis, we will use the same six predictor variables used by Dymarska et al. (2023a) to analyse sensorimotor effects on word recognition memory. These variables comprised component scores derived from a principal components analysis (PCA) to consolidate a large set of intercorrelated lexical and sensorimotor variables into orthogonal (i.e., uncorrelated) predictors. The components were originally obtained in a previous study (Dymarska et al., 2023b); full details can be found there, here we summarise the method of extracting the components. The item set for the PCA was based on 9796 words used in the analysis of imageability on visual word recognition by Dymarska et al. (2023b). Variables included in the PCA can be seen in Table 2, and covered a wide range of lexical and semantic characteristics of the words. Critically, they

incorporated 11 dimensions of sensorimotor strength from the Lancaster Sensorimotor Norms (Lynott et al., 2020), where each dimension comprised a rating of the extent to which the word's referent was experienced with the specified perceptual modality or by performing an action with the specified action effector. In addition, they also included Lynott et al.'s composite measure of all 11 dimensions, Minkowski-3 sensorimotor strength, which was weighted towards the dominant dimension(s) for a given word. PCA (parallel analysis at 95th percentile, correlation matrix, varimax rotation) reduced the original 24 dimensions to an optimal 6 orthogonal components that captured 77.4% of the original variance. Each component was labelled according to the variables that loaded upon it, producing two components that represented lexical characteristics of the word (Frequency and Length) and four components that represented sensorimotor experience with the referent concept (Body, Object, Food, Communication). Table 2 summarises how each component relates to the original variables which were entered into the PCA. These six components cleanly distinguished between lexical and semantic information, with the exception of the Object component, which included the noun (part of speech) variable in addition to sensorimotor variables; this contribution was not unexpected since object concepts are typically labelled with nouns (e.g., *apple*, *dog*) and tend to be strongly experienced with visual, haptic, and hand/arm action. Table 3 shows examples of words scoring highest and lowest on each component.

Table 2: Variables used by Dymarska et al. (2023b) in Principal Components Analysis and the rotated

components (used here as predictors) to which they most strongly contributed with positive or negative

weighting ($r > .3$ or $< -.3$).

| Original variable | Source | Definition | PCA component |
|---|---|---|---|
| LgSUBTLWF | ELP | Log word frequency (US English) | +Frequency |
| LgSUBTLCD | ELP | Log contextual diversity (how many contexts a word appears in; US English) | +Frequency |
| Zipf Frequency | Van Heuven et al. (2014) | Word frequency on Zipf scale (UK English) | +Frequency |
| Prevalence | Brysbaert et al. (2018) | How many people know the word (probit value) | +Frequency |
| Familiarity | Stadthagen-Gonzales & Davis (2006); Scott et al. (2018); Wilson (1988) | How subjectively familiar a word seems (ratings) | +Frequency |
| Age of Acquisition | Kuperman et al. (2012)[a] | Approximate age that the word was learned | –Frequency |
| Linguistic distributional distance (LDD20) | Dymarska et al., 2023b | Distributional neighbourhood (mean cosine distance to closest 20 neighbours, based on vectors of log co-occurrence frequency) | –Frequency |
| Word length | ELP | Word length in letters | +Length |
| Number of syllables | ELP | Word length in syllables | +Length |
| Orthographic Levenshtein Distance (OLD20) | ELP | Orthographic neighbourhood (mean letter Levenshtein distance to closest 20 neighbours) | +Length |
| Phonological Levenshtein Distance (PLD20) | ELP | Phonological neighbourhood (mean phoneme Levenshtein distance to closest 20 neighbours) | +Length |
| Torso action strength | LSN | Motor strength in torso effector | +Body |
| Foot/leg action strength | LSN | Motor strength in foot/leg effector | +Body |
| Hand/arm action strength | LSN | Motor strength in hand/arm effector | +Body, +Object |
| Composite sensorimotor strength | LSN | Aggregated sensorimotor strength in all dimensions (Minkowski-3 distance of 11-dimension vector from the origin) | +Body, +Object, +Communication, +Food |
| Head action strength | LSN | Motor strength in head effector | +Communication |
| Auditory strength | LSN | Perceptual strength in hearing modality | +Communication |
| Mouth action strength | LSN | Motor strength in mouth effector | +Communication, +Food |
| Gustatory strength | LSN | Perceptual strength in taste modality | +Food |
| Olfactory strength | LSN | Perceptual strength in smell modality | +Food |
| Visual strength | LSN | Perceptual strength in sight modality | +Object |
| Noun (part of speech) | ELP | Whether or not word is a noun (binary coded: noun=1, non-noun=0) | +Object |
| Haptic strength | LSN | Perceptual strength in touch modality | +Object, +Body, –Communication |
| Interoceptive strength | LSN | Perceptual strength in interoceptive (sensations inside the body) modality | –Object, +Body, +Communication |

[a] With extended norms from http://crr.ugent.be/archives/806

Note: ELP = English Lexicon project (Balota et al., 2007); LSN = Lancaster Sensorimotor Norms (Lynott et al., 2020).

Table 3: Top five (highest scoring) and bottom five (lowest scoring) words for each component.

| Component | High scoring | Lowest scoring |
|---|---|---|
| Frequency | the, that, and, what, about | slat, adage, welt, jeer, vise |
| Length | friendship, transplant, somewhere, privilege, threshold | rap, sang, pun, gab, hum |
| Body | move, movement, bathe, strength, pain | because, about, but, than the |
| Food | meal, pizza, pastry, omelette, pasta | waltz, listen, chase, polka, ballet |
| Object | nail, dog, pillow, pistol, cat | quench, queasy, hungry, nauseous, digest |
| Communication | song, concert, joke, word, chat | dorsal, fertile, which, than, enzyme |

**Procedure**

The experiment will be created and hosted through the online experiment builder Gorilla (http://www.gorilla.sc/; Anwyl-Irvine et al., 2019). Following informed consent and demographic questions about first language, age, sex and handedness, it will consist of three stages: a study phase, a distractor task, and a test phase.

In the study phase, participants will be asked to perform a lexical decision task, where they have to decide whether a presented string of letters is a real word in English (e.g., "coat") or not (e.g., "soat") by pressing the "Z" key (not a real word) or "M" key (real word) on their keyboard. Each trial will begin with a blank screen for 200 ms, followed by a fixation cross for 300 ms, and then the word (or pseudoword) presented individually in lowercase in the centre of the screen, 14 pixels in size, using black text on a white background, in Open Sans font (see Figure 1). The (pseudo)word will stay onscreen until the participant responds, or until a timeout limit of 3000 ms is reached. A short practice task with 4 items will be presented before the main task, where participants will receive feedback for accuracy and speed; if they do not respond within 3000 ms, the message "Too slow" will be displayed for 1000 ms and the next trial will commence. If they respond on time, a green tick (for correct responses) or a red cross (for incorrect responses) will be displayed for 1000 ms before the next trial starts. There will be no feedback during the main lexical decision task. The order of (pseudo)words will be randomised for each participant.

Once the study phase (lexical decision task) is over, participants will be presented with a distractor task and asked to verify 18 mathematical equations, as per Cortese et al., (2010; 2015). Participants will proceed through questions by pressing the "Z" key (incorrect) or "M" key (correct) to respond at their own pace, without feedback. The entire distractor task should take approximately 30 seconds.

Finally, in the test phase following the distractor task, participants will perform a surprise recognition memory task. Participants will be asked to decide whether or not they saw each displayed word earlier in the study (i.e., in the lexical decision task) by pressing the "Z" key (new word) or "M" key (old word) on their keyboard. Words will be displayed in randomised order as per the lexical decision task (see Figure 1) and will stay onscreen until the participant responds or until a timeout limit of 3000 ms is reached. There will be no feedback during the recognition memory task. We will measure accuracy of responses and response times from the onset of each word until participant presses a response key; accuracy per word will be used to calculate the dependent measures of memory performance (see Data Analysis Plan) and RT will be used for data exclusions. At the end of the test phase, participants will see a short debriefing screen that thanks them for taking part and they will be redirected to the recruitment platform. We expect the entire procedure from consent to debrief to take up to 10 minutes.
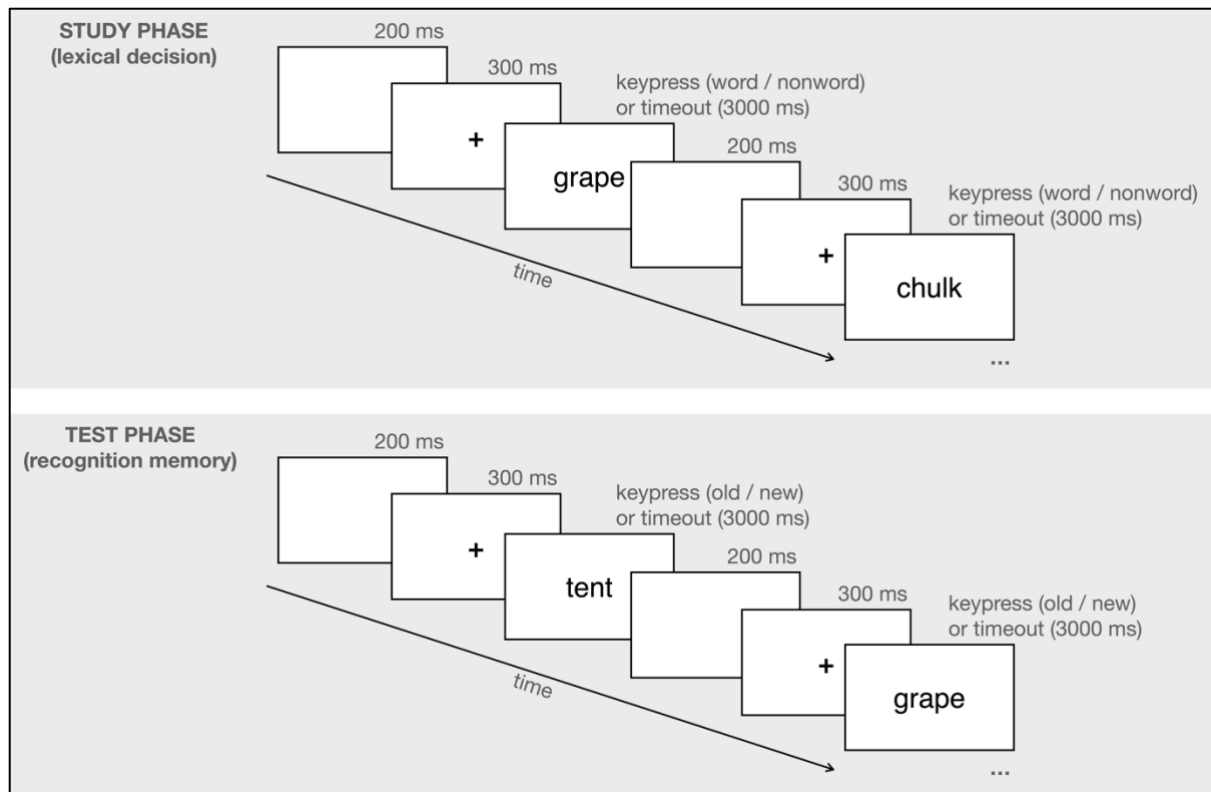
Figure 1: Trial sequence diagrams for the lexical decision task in the study phase (upper panel) and the recognition memory task in the test phase (lower panel).

**Data Analysis Plan**

*Data Exclusions*

We will replace any participants who were rejected without payment (see Ethics and Consent section) and participants who time out on more than 30% of trials in the study or test phases. We will also replace participants who do not reach 60% overall accuracy (i.e., across hit rates and correct rejections) on the recognition memory task, in line with Cortese et al. (2010; 2015). This accuracy threshold takes into account both old words where participants correctly respond "old" (i.e., hit rates to targets) *and* new words where participants correctly respond "new" (i.e., correct rejections of distractors = 1 – false alarms), and thus subsumes a threshold based on $d'$. We expect that any participants who do not perform well on the lexical decision task, for example due to inattention, will also not perform well on the memory task, and therefore we do not plan to use separate exclusion criteria based on lexical decision task accuracy.

Trials with RT below 300ms will be classified as motor errors and removed. Trials which do not register a response within 3000ms will time out and will be removed from the analysis. No other data will be excluded as outliers, and no outlier correction method will be performed.

***Dependent Variables***

We will calculate the following memory performance measures per item, as in Cortese et al. (2010; 2015): hit rate (HR: proportion of times studied word was correctly classified as "old"), false alarms (FA: proportion of times new word was incorrectly classified as "old"), hit rate minus false alarms (HR-FA: overall performance per word), and sensitivity ($d'$: sensitivity per word). The signal detection variable $d'$ measures the sensitivity in discriminating a given word as old versus new, and (unlike HR-FA) is unaffected by underlying response bias; it will be calculated using a log-linear approach (Stanislaw & Todorov, 1999) to compensate for floor/ceiling performance (i.e., HR or FA at 0% or 100%).

***Statistical Analysis***

We will analyse memory performance per item by running hierarchical linear regressions on each dependent variable. The hierarchical model structure will allow us to compare our results with previously-found effects of sensorimotor components on expected word memory performance (Dymarska et al. 2023a). In Step 1, we will enter Frequency and Length components as baseline predictors. In Step 2 we will add the four sensorimotor components (Body, Communication, Food, Object). There will be four regressions in total, one for each measure of memory performance (HR, FA, HR-FA, $d'$).

Bayesian linear regressions will be conducted in JASP (*version 0.16.4*: JASP Team, 2022), with default JZS priors ($r = .354$) and a Bernoulli distribution ($p = 0.5$), from which we will report BFs for model comparisons between hierarchical steps and inclusion BFs of coefficients (i.e., relative likelihood of models including a particular predictor compared to models excluding it). The threshold for inference will be $BF_{inclusion} \geq 6$ for evidence *in favour* of a particular component's effect, or its reciprocal $BF_{inclusion} \leq 1/6$ for evidence *against* its effect. Where evidence is in favour, the direction of

the relevant coefficient will determine whether a given sensorimotor component elicits a facilitatory (or inhibitory) effect on word memory performance.

In order to perform an exploratory comparison of the effect sizes per component in the current study with the results of Dymarska et al. (2023a), we will conduct frequentist linear regressions in JASP with the same model structure as above and extract part correlations per component per dependent variable. We will report these part correlations to illustrate the unique contribution each predictor makes to the dependent measure in question.

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| Question | Hypothesis | Sampling Plan | Analysis Plan | Rationale for deciding the sensitivity of the test for confirming or disconfirming the hypothesis | Interpretation given different outcomes | Theory that could be shown wrong by the outcomes |
|---|---|---|---|---|---|---|
| What are the effects of multiple aspects of sensorimotor experience on a surprise word recognition task? | 1. We hypothesise that sensorimotor experience of food and objects will facilitate memory performance in a surprise memory task. Higher scores on the Food and Object components will lead to higher hit rates, lower false alarms, and better discrimination between old and new items. | We will use sequential hypothesis testing with BF to determine optimal sample size. Nmin is 2120 participants (20 per word list), and we will continue in increments of 100 participants until the evidence for or against the inclusion of all predictors in analyses of all dependent variables clears the BF=6 threshold, or until we reach Nmax of 6360 participants (60 per list).

The Nmin sample of 20 participants per word list was sufficient to detect component effects in an expected memory task (see Dymarska et al., preprint).
The Nmax represents the largest sample size our resources allow, in case a surprise task requires a larger sample size to detect effects than the expected memory task. | We will conduct item-level hierarchical Bayesian linear regressions on four dependent variables (hit rate, false alarms rate, and two measures of discrimination: HR-FA and d'). We will examine the effects of sensorimotor information on word memory performance, above and beyond any effects of lexical information, using six orthogonal components as predictors. Step 1 enters lexical controls of Frequency and Length, and Step 2 enters the critical predictors that represent different types of experience: Body, Communication, Food, and Object. | Hypotheses will be confirmed or disconfirmed according to the inclusion BFs of sensorimotor parameters in the Step 2 model. The BF inferencing threshold of 6 is the required level of evidence allowing to conclude the presence or absence of effects in a registered report submission. | Bayes Factor of 6 or above will indicate that the component elicits an effect on memory performance. Bayes factor below 1/6 will indicate that the component does not influence memory performance (i.e., evidence against the effect). Bayes Factor between these values will indicate equivocal evidence regarding whether or not the component influences memory performance.

The direction of the regression coefficient will indicate whether the component enhances memory (positive effect on HR and discrimination measures, negative effect on FA) or impairs memory (negative effects on HR and discrimination measures, positive effects on FA).

null Body effect on FA accompanied by null effects of Food and Object components indicates RTM | 1.If the Food and Objects components elicit null effects (i.e., do not facilitate memory performance), it could suggest that semantic richness effects of food- and object-related experience do not extend to a surprise memory task. In other words, it would suggest that incidental memory and expected memory do not rely on sensorimotor information in the same way. ==Alternatively, if null Food and Object effects are accompanied by null Body effects, it would suggest regression to the mean relative to the previous expected memory task.== |
| | 2. We hypothesise that sensorimotor experience of communication will not affect memory performance, that is, high scores on Communication component will not have any effects on hit rate, false alarms or discrimination measures. | | | | | 2. Any positive evidence for Communication effects would indicate that incidental memory and expected memory do not rely on sensorimotor information the same way. If high scores on the Communication component unexpectedly enhance memory performance, it would counter Dymarska et al.'s (2023a) suggestion that words related to communication experience lack distinctiveness. |
| | 3. We hypothesise that higher Body scores will lead to higher hit rates, but the effects that emerge on false alarms and discrimination measures will vary by theory, and will allow us to determine the underlying mechanism. | | | | | 3. If the Body component increases false alarms and decreases HR-FA and d', then the somatic attention explanation is correct and the adaptive advantage explanation is not. Conversely, if the Body component elicits no effect on false alarms or decreases false alarms, and increases HR-FA and d', then the adaptive account applies and the somatic attention explanation is incorrect. |