The Role of Working Memory

in Statistical Word Learning

by

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ABSTRACT

Statistical word learning (SWL) has been proposed and tested as a powerful mechanism for word learning under referential ambiguity. Learners are adept at resolving word-referent ambiguity by calculating the co-occurrences between words and referents across ambiguous scenes. Despite the generalizability of such capacity, it is less clear which underlying factors may play a role in SWL, such as learners' language experience and individual differences of working memory. The current study therefore asked two questions: 1) How do learners of different language experience (monolinguals and bilinguals) approach SWL of different mapping types–when each referent has one name (1:1 mapping) or two names (2:1 mapping)? and 2) How do working memory capacities (spatial and phonological) play a role in SWL by mapping type? In this pre-registered study (OSF: https://osf.io/mte8s/), 69 English monolinguals and 88 bilinguals completed two SWL tasks (1:1 and 2:1 mapping), a symmetry span task indexing spatial working memory, and a listening span task indexing phonological working memory. Results showed no differences between monolinguals and bilinguals in SWL of both mapping types. However, spatial and phonological working memory positively predicted SWL regardless of language experience, but only in 1:1 mapping. The findings show a dissociation of working memory's role in SWL of different mapping types. The study proposes a novel insight into a theoretical debate underlying statistical learning mechanisms: learners may adopt more explicit processes (i.e. hypothesis-testing) during 1:1 mapping but implicit processes (i.e. associative learning) during 2:1 mapping. Future studies can locate memory-related brain areas during SWL to test out the proposal.

Keywords: statistical word learning, working memory, bilingualism

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The ability to acquire a language is one of the hallmarks of human development. Among aspects of language acquisition, word learning (mapping words with referents) is one of the first steps of vocabulary acquisition and plays a fundamental role for developing grammar (Walker et al., 2020), syntax (Gleitman & Gleitman, 1992), and reading comprehension (Mezynski, 1983). Word-referent mapping can occur explicitly in which the entity of a referent is the only possible candidate of a word, such as in instructional settings (Nurmi & Jaakkola, 2006; Werker et al., 1998). However, word learning often happens under ambiguity, as is often the case in naturalistic learning environments: words are heard in the context of a number of potential referents, with limited cues to track which words refer to which referents (Medina et al., 2011; Quine, 1960; Yu & Smith, 2007). For example, in a living room, a novice learner could hear two novel words in the strings of conversation, such as “shoe” and “sofa”, and see many possible referents including a shoe and a sofa. How can learners resolve such word-referent ambiguity to form a correct word-referent mapping?

1. Statistical Word Learning

Statistical word learning (SWL), one possible learning mechanism, proposes that learners can resolve such word-referent ambiguity by employing a form of statistical calculation and aggregating the co-occurrences between words and referents across multiple learning events (Smith & Yu, 2008; Yu & Smith, 2007). In the first test of SWL, Yu and Smith (2007) instructed adults to map artificial words with novel objects. Within a trial, several auditory words were presented with an equal number of objects without a clear indication as to which word referred to which object. Across trials, however, each word occurred consistently with a single target object, and less consistently with distractor objects. Results showed that adults aggregated the word-referent co-occurrences across trials and learned the correct word-referent mappings. To date, a large literature has replicated this effect in adults, and demonstrated that infants and children also utilize such statistical co-occurrences to identify word-referent mappings from ambiguous naming events (Benitez et al., 2020; Smith & Yu, 2008; Suanda et al., 2014; Yu & Smith, 2007, 2011; Yurovsky & Yu, 2008; Zettersten et al., 2018).

A majority of SWL work has focused on acquiring one-to-one word-referent statistics, where a referent co-occurs consistently with a single word (*1:1 mapping*). However, in everyday scenarios, the cases of lexical overlap are ample, where a referent can be labeled by multiple names. For instance, learners can encounter synonyms of the same category (e.g. "*dog*" and "*puppy*" refer to the referent **dog**) or of different categories (e.g. "*dog*" and "*animal*" can sometimes refer to the same concept **dog**) within a language, and/or translation equivalents across languages for a large population of bilingual speakers (e.g. English "*dog*" and Spanish "*perro*" both refer to the referent **dog**). In all these scenarios, learners need to accommodate multiple-to-one statistics (or *2:1 mapping*), where the word-referent mappings can be overlapped.

How do learners accommodate multiple-to-one statistics? Does learning multiple-to-one statistics and one-to-one statistics go through a similar learning process? A limited set of studies have addressed such questions, and suggest that learning 2:1 statistics is more challenging than learning 1:1 statistics (Benitez et al, 2016; Benitez & Li, 2022; Ichinco et al., 2009; Kachergis et al., 2012; Poepsel & Weiss, 2014, 2016, but see Chan & Monaghan, 2019). One possible reason for a challenge in learning 2:1 statistics is that learners tend to form a mutual exclusivity (ME) assumption in acquiring lexicons. The

ME assumption refers to the bias to expect each object to have only one label by default (Markman, 1990; Merriman et al., 1989). For instance, both children and adults tend to reject mapping a novel word to a known object to achieve fast mapping during explicit naming events (e.g. Carey, 2010; Carey & Bartlett, 1978; Au & Glusman, 1990). In the realm of statistical learning, Ichinco et al. (2009) suggested that word-referent mapping also respects the mutual exclusivity assumption by comparing human data with computational models. Specifically, Ichinoco et al. (2009) designed SWL conditions that violated the ME assumption, where either a referent could have two names (2:1 mappings) or a word could have two referents (1:2 mappings). Results showed that despite the fact that adults occasionally learned multiple mappings (2:1 or 1:2 mappings), this happened far less often than learning 1:1 mappings, demonstrating a strong ME bias. Further, researchers also compared the results of a simple associative account model without the ME assumption and a complex Bayesian model with a strong ME assumption against the observed human data, and found that the model that held a strong ME assumption provided a better fit of the human data. Together, the study argues that the statistical learning mechanism, if partially accounted for by simple associative learning, needs to obey constraints of naturalistic lexical acquisition– mutual exclusivity assumption, so that learners' performance is impaired by a challenge to get rid of ME assumption when labels or referents overlap (see also Goodman et al., 2007). Given the potential different operating mechanisms underlying learning 1:1 and 2:1 mappings, the study further intends to investigate *whether and which* factors may contribute to SWL in different mapping types.

2. Language Experience and SWL

One factor that may play a role in statistical word learning is learners' language experience. Consistent use of a second language or constant exposure to dual language input (i.e. bilingualism) has been documented to facilitate acquiring novel words in general (Kan & Kohnert, 2012; Kaushanskaya & Marian, 2009; Singh et al., 2018) due to an effect of practice (Bialystok, 2007). For instance, in their explicit word learning task, Kaushanskaya and Marian (2009) had bilingual and monolingual adults learn a made-up novel word and its English translation, so that each new word was mapped with a known lexicon unambiguously. Results showed that bilinguals of various language backgrounds outperformed monolinguals in explicit novel word learning. Also, a bilingual effect in explicit word learning is also found among infants (Singh et al., 2016; Singh et al., 2018). In this vein, if bilingual experience *per se* facilitates word learning in general, it shall help with word learning in any types, including statistical word learning.

Limited research has investigated how language experience affects statistical word learning, inviting mixed results (Benitez et al., 2016; Escudero et al., 2016; Poepsel & Weiss, 2016). While some studies suggest a bilingual effect in 1:1 mapping (Escudero et al., 2016), a majority of them do not (Benitez et al., 2016; Poepsel & Weiss, 2016). While some studies point to a strong bilingual advantage in 2:1 statistics (Poepsel & Weiss, 2016), others do not (Chan & Monaghan, 2019) or suggest such an advantage depends on language inputs (Benitez et al., 2016) and/or language familiarity (Li & Benitez, 2022). To conclude, the current literature suggests that language experience may have some impact on SWL, yet needs further investigation on the robustness of such an effect.

3. Working Memory and SWL

Alternatively (and not mutually exclusively), individual differences in working memory can serve as a key factor in statistical word learning for specific reasons. Theoretically, working memory can be particularly crucial for SWL processes where the word-referent associations are ambiguous. Learners need to keep track of multiple visual referents and various auditory words in a single trial, and retain the information of visual display (e.g. shape, pattern, and spatial location of a visual object) and auditory words (e.g. the phonotactic structure and syllable length) across multiple trials. The process requires eye-gazes onto distinctive spatial locations within and across trials while concurrently processing auditory sounds (Yu et al., 2011, 2012). In this vein, learners may tax working memory resources to remember the auditory features of words and hold the visual-spatial information pertaining to objects, possibly to a greater extent than other types of word learning, such as explicit word learning. Empirically, very few studies have addressed the role of working memory in SWL. The most relevant study came from Vlach and Debrock (2019) who investigated how cognitive skills predict SWL in 1:1 mapping among 2- to 4-year olds. Researchers used recognition memory tasks to address working memory, in which learners sought for target objects among foils in different spatial locations. Results suggested that recognition memory served as the strongest predictor to SWL performance than other factors (e.g. age, receptive knowledge, and verbal word-picture association capacity). Despite the investigation of working memory in SWL, Vlack and Debrock (2019) might not have fully explored the types of working memory pertaining to SWL (e.g. phonological and spatial), have not asked how such a role may hold for adults whose working memory capacities reach a relatively mature and stable stage, and have not tapped into different mapping types. Taken together, based on the theoretical soundness and empirical novelty of addressing working memory in SWL, the study investigated how working memory (phonological and spatial) affect SWL in 1:1 and 2:1 mapping.

4. The Current Study

Despite the fact that statistical word learning has been replicated as a robust learning mechanism for infants, children, and adults to resolve real-world word-referent ambiguity, the underlying factors that contribute to such a learning process remain unknown. The current study aimed to explore *whether and how* two possible underlying factors, learners' language experience and working memory, may contribute to statistical word learning. Specifically, we probed monolingual and bilingual adults' statistical word learning abilities in conditions where each object had one name (1:1 mapping condition) and two names (2:1 mapping condition), phonological working memory from a Listening Span Task in English[1], and spatial working memory from a Symmetry Span Task. Additionally, we asked adults' subjective rating on how well they've learned immediately after each condition and at recall to explore the relation between conscious awareness and statistical learning. In this pre-registered study (OSF: https://osf.io/mte8s/), we addressed two research questions and provided corresponding hypotheses.

Q1: How do learners of different language experience (monolinguals and bilinguals) approach SWL when referents have a single name (*1:1 mapping* condition) vs. two names (*2:1 mapping* condition)?

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[1] Bilinguals also completed a Listening Spanish Task launched in their other languages, if the bilingual was Spanish-English bilinguals or Mandarin Chinese-English bilinguals. See Procedure Phonological Working Memory for more details.

H1: We expected that language experience mattered to SWL. Specifically, bilingual adults would have a higher learning accuracy for SWL in 2:1 and/or 1:1 mapping conditions over monolingual adults. The learning accuracy in 1:1 mapping would be higher than that in 2:1 mapping across language groups.

Q2: How does individuals' working memory capacities (spatial and phonological) play a role in SWL abilities in the two conditions?

Q2.1 If language experience affects SWL (or not), how do working memory capacities may mediate the process from language experience to SWL?

H2: We expected that working memory, phonological and spatial, jointly or independently contribute to SWL. Specifically, individuals who are higher in phonological and/or spatial working memory will have a higher SWL in 1:1 and 2:1 mapping conditions. Additionally, based on the results from Q1 and Q2, we hypothesized that working memory, phonological and spatial, jointly or independently may mediate the relation from language experience to SWL.

Methods

1. Participants

The final sample included 157 adult participants (M_{age} = 19.37, *SD* = 2.42, 86 Female, 70 Male, 1 Unknown), including 69 monolinguals (M_{age} = 19.44, *SD* = 2.78) and 88 bilinguals of varied language backgrounds (M_{age} = 19.32, *SD* = 2.12)[2] (See **Table 1**

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[2] The original plan was to collect a total of 162 English monolingual (*N* = 81) and English-Spanish bilingual (*N* = 81) adults. The sample size was gauged assuming a power of 0.8, a small-to-medium *a* path (a=0.26), and a small-to-medium *b* path (b=0.26) in the mediation model by using PRODCLIN test (Fritz & MacKinnon, 2007).
The data for the Master's Defense was collected from November 2021 to March 2022. The data collected after March 2022 has not been included in the Master's Defense dataset due to time constrain. This decision was made prior to the data analysis.

for demographic information). Participants were recruited from the Department of Psychology Introduction to Psychology subject pool at Arizona State University (ASU), and received course credit for their participation. Consent was obtained for all participants according to the ASU Institutional Review Board. An additional 11 participants (9 self-reported monolinguals) were tested but excluded due to missing data (7), experimenter error (2), and technical difficulties (2).

Table 1

Demographic information

	Monolingual Group	**Bilingual Group**
Age		
mean (SD)	19.31 (2.12)	19.45 (2.78)
Range	18-35 (17)	18-35 (17)
Race/Ethnicity		
White	46	25
Hispanic or Latino	4	27
Black or African American	3	3
American Indian or Alaska Native	1	0
Asian	5	16
Native Hawaiian or Pacific Island	0	2
Other	1	1
Two or More Categories	9	14
Self-education		
Current College Student	67	81
Bachelors or Higher	2	7
Permanent Residency		
United States	68	78
Canada	0	1
China (incl. HK, Taiwan)	0	5
Nigeria	0	1
Kuwait	0	1
India	0	2
United Arab Emirates	1	0
Total number	69 (36 F)	88 (50 F, 1 Unknown)

Note. For Race/Ethnicity, Self-education, and Residency, the values in the cells depict the number of participants who are qualified for each category. Residency in the study refers to the country where one is officially allowed to live permanently.

Table 2 depicts the linguistic information for the two language groups, and the differences (and effect sizes) between and within groups. In terms of age of acquisition, bilinguals acquired English (M_{age} = 1.93, SD = 3.26) significantly later than English monolinguals (M_{age} = .28, SD = .55, $p < .001$, d = -.72), while bilinguals acquired English significantly earlier than their other language (M_{age} = 7.06, SD = 6.44, $p < .001$, d = -1.16). Bilinguals' proficiency in English (in listening, speaking, reading, and writing) was comparable to that of monolinguals. Bilinguals' proficiency in the other language was lower than bilinguals' English proficiency. Further, English monolinguals' activities with English (e.g. thinking, talking, and using numbers) and cultural assimilation in English (e.g. life, food, and sports) were consistently more dominant than bilinguals' activities and cultural assimilation in English. Consistently, bilinguals' activities and cultural assimilation in English were significantly more dominant than that in the other language. The majority of bilinguals spoke Spanish as the other language (58), with the following alternative languages: Chinese (9), French (6), Arabic (2), Hindi (2), Italian (2), American Sign Language (2), Indonesian (1) , Konkani (1), Urdu (1), Vietnamese (1), Yoruba (1), and not specifying the other language[3] (2).

Table 2

Language Information

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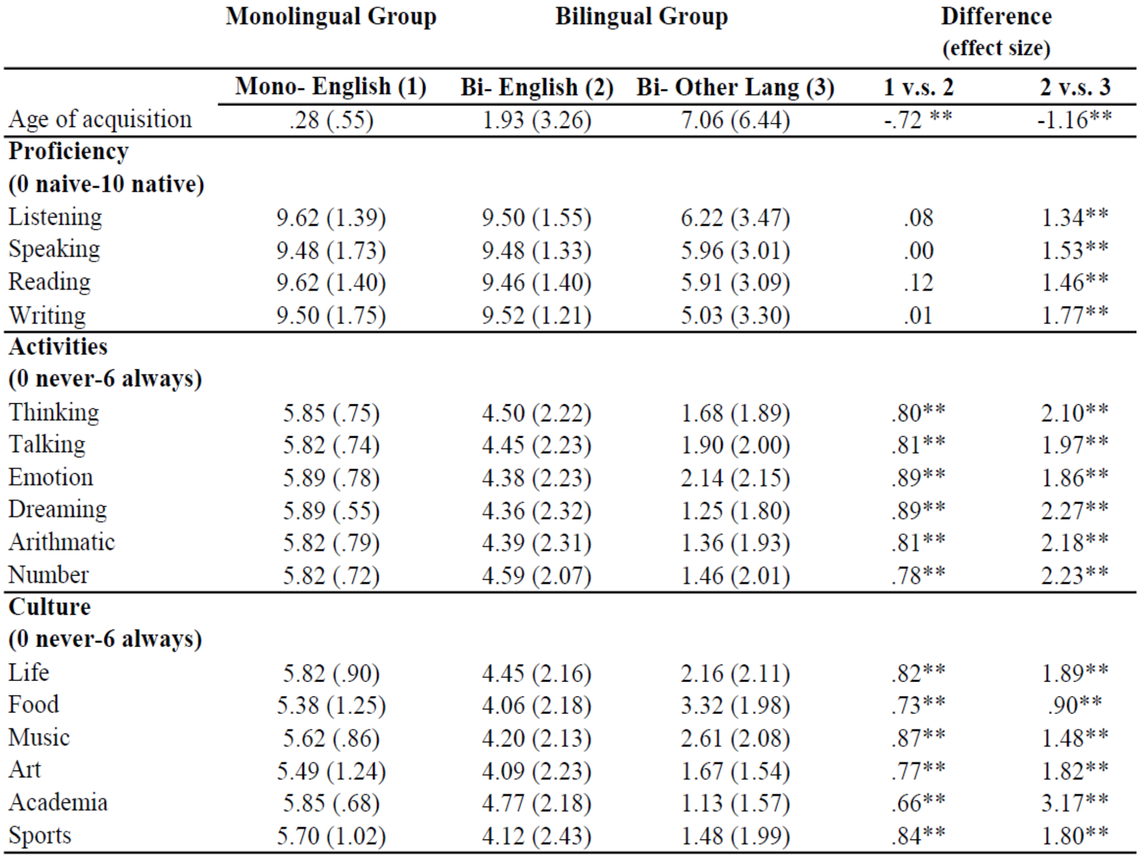
[3] The two participants with the unspecified other language may have missed the box for filling out the specific other language, but filled out the full information of the other language (e.g. age of acquisition or proficiency). Therefore, the two participants were included in the final data analysis.



	Monolingual Group	Bilingual Group		Difference (effect size)	
	Mono- English (1)	**Bi- English (2)**	**Bi- Other Lang (3)**	**1 v.s. 2**	**2 v.s. 3**
Age of acquisition	.28 (.55)	1.93 (3.26)	7.06 (6.44)	-.72 **	-1.16**
Proficiency (0 naive-10 native)					
Listening	9.62 (1.39)	9.50 (1.55)	6.22 (3.47)	.08	1.34**
Speaking	9.48 (1.73)	9.48 (1.33)	5.96 (3.01)	.00	1.53**
Reading	9.62 (1.40)	9.46 (1.40)	5.91 (3.09)	.12	1.46**
Writing	9.50 (1.75)	9.52 (1.21)	5.03 (3.30)	.01	1.77**
Activities (0 never-6 always)					
Thinking	5.85 (.75)	4.50 (2.22)	1.68 (1.89)	.80**	2.10**
Talking	5.82 (.74)	4.45 (2.23)	1.90 (2.00)	.81**	1.97**
Emotion	5.89 (.78)	4.38 (2.23)	2.14 (2.15)	.89**	1.86**
Dreaming	5.89 (.55)	4.36 (2.32)	1.25 (1.80)	.89**	2.27**
Arithmatic	5.82 (.79)	4.39 (2.31)	1.36 (1.93)	.81**	2.18**
Number	5.82 (.72)	4.59 (2.07)	1.46 (2.01)	.78**	2.23**
Culture (0 never-6 always)					
Life	5.82 (.90)	4.45 (2.16)	2.16 (2.11)	.82**	1.89**
Food	5.38 (1.25)	4.06 (2.18)	3.32 (1.98)	.73**	.90**
Music	5.62 (.86)	4.20 (2.13)	2.61 (2.08)	.87**	1.48**
Art	5.49 (1.24)	4.09 (2.23)	1.67 (1.54)	.77**	1.82**
Academia	5.85 (.68)	4.77 (2.18)	1.13 (1.57)	.66**	3.17**
Sports	5.70 (1.02)	4.12 (2.43)	1.48 (1.99)	.84**	1.80**

Note. The Monolingual Group has only the information of English, while the Bilingual Group has the information of English and the Other Language. *Proficiency* refers to the self-rated scores in aspects of listening, speaking, reading, and writing (0-naive and 10-native). *Activities* refers to the self-rated scores in the frequency of using the language for various activities, e.g. thinking, talking, and using numbers (0-never, and 6-always). *Culture* refers to the self-rated scores regarding feeling assimilated in the culture of the language in various aspects, e.g. life, food, and sports (0-never, and 6-always).

2. Materials

Statistical Word Learning Paradigm (SWL). Statistical word learning was measured using a modified task from Yu and Smith (2007) in two conditions. In the *1:1 mapping* condition, participants were trained to learn 8 novel objects each mapped with a unique novel word (8 pairs of 1:1 word-object mappings). In the *2:1 mapping* condition, participants were trained to learn 4 objects each mapped with 2 words (4 pairs of 2:1 word-object mappings). There were four different word-object sets for the two conditions so that no pairings were the same across conditions (e.g., one participant learned Set 1 for 1:1 mapping and Set 3 for 2:1 mapping) (see **Appendix A** for the novel word-object sets). All novel words were disyllabic and followed the word structure of consonant-vowel-consonant-vowel (CVCV) (e.g. "*dabu*" and "*bita*"). The consonant inventory constituted [d], [b], [m], [g], [k], and [t] (Wang & Saffran, 2014); the vowel inventory was made up of [i] (close front vowel), [u] (close back vowel), and [a] (open back vowel). The consonant-vowel combinations (e.g. "*bu*") appeared approximately the same number of times in word initial position as in "*bu*__" or word final position as in "__*bu*" in each word set, varying between zero to three times of repetition (see **Appendix B** for novel word decomposition). All novel words were pronounced in a flat tone and amended to last 0.99s per word via Praat software, with a mean pitch of 153.14 Hz and a mean intensity of 66.39 dB. The novel objects were drawn from the NOUN database (Horst & Hout, 2016).

During the training phase (in both conditions), *within a single trial*, participants were presented with two novel words (presented auditorily) and two novel objects on the computer screen (see **Figure 1**). The two objects appeared simultaneously, while the auditory words were played one after the other with a 1.5-second interval. The onset of the object display was 2 seconds prior to the onset of the 1st word presentation within a trial. The two objects were located at the left and the right of the computer screen symmetrically to the central vertical line, both centered at the central horizontal line. The order of the word presentation (1st and 2nd) did not necessarily match with the objects' spatial location (left and right), so that word-object pairings were ambiguous within each trial. There was a 0.05s blank between trials. *Across multiple trials*, the word-object co-occurrences signaled the correct word-referent associations. In the 1:1 mapping condition, each word co-occurred consistently with one object 6 times, and less frequently with other words 0 to 2 times (see **Figure 1** 1:1 mapping). In the 2:1 mapping condition, each object occurred consistently with two words, 6 times each (see **Figure 1** 2:1 mapping). The two words of the same object never appeared within the same trial, and were intermixed across trials. In each condition, participants were presented with 32 trials during the training, with a total training duration of 2 minutes.

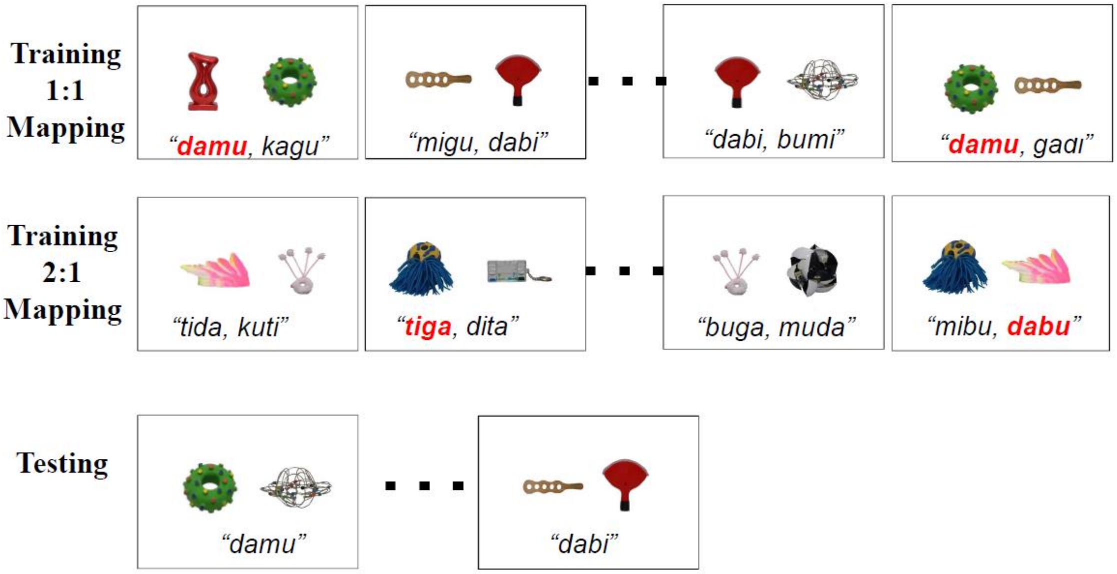
The testing phase immediately followed the training phase in each condition. During the test phase (in each condition), participants heard one word and saw two objects (a target object and a distractor object) on the computer screen. They were instructed to click on the correct object of the heard word using the mouse (see **Figure 1** Testing). Each novel word was tested once in each condition (8 test trials per condition). Test trials were scored as correct (1) or incorrect (0). Participants' word accuracy was calculated by averaging accuracy scores over the test trials by condition.

Participants also rated their confidence in learning words (rating phase), immediately after the testing phase of each condition, and again at the end of the entire study (see the below LBQ section). Participants were instructed to rate their learning during the SWL task by choosing a number from a scale of 0 (not learning at all) to 9 (learning a great deal). Thus, each participant had three scores for subjective rating of learning (SRL): SRL for 1:1 mapping, SRL for 2:1 mapping, and SRL in post-test.

Participants completed one condition (training phase + testing phase + rating phase) before moving on to the second condition, with condition counterbalanced across participants. After completing the first condition, participants could choose to start the second condition with or without a break. The instructions were the same before each condition: participants were asked to figure out which words went with which objects, at the same time being noted that each object could have one or more names in each condition. Participants were also instructed not to use pen and paper to assist learning.

Figure 1

SWL Paradigm in 1:1 and 2:1 Mapping Conditions

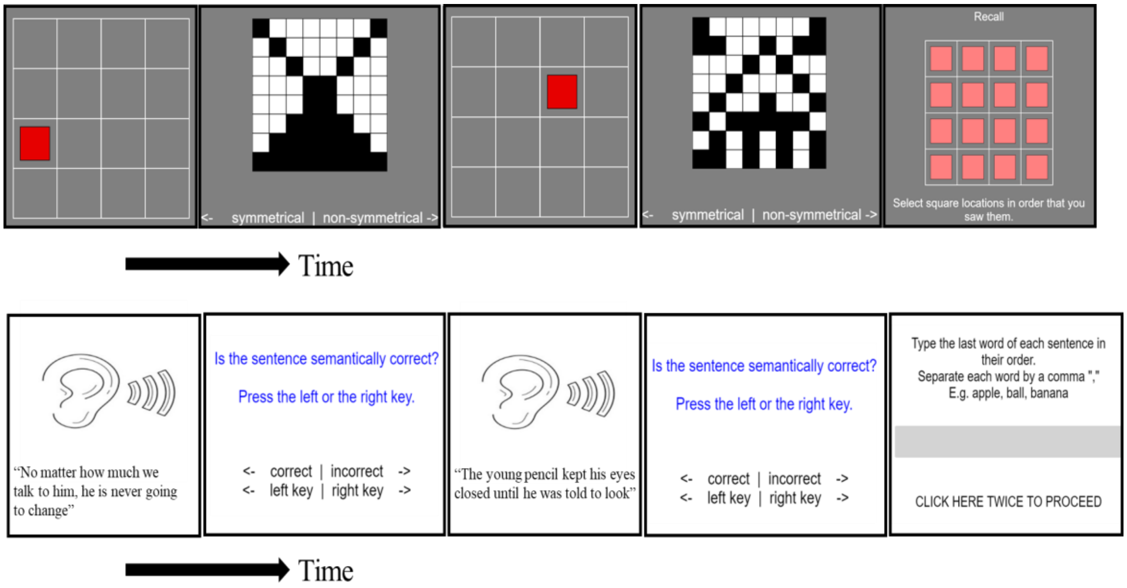


Note. In 1:1 mapping condition, the word "*damu*" co-occurs most frequently with the referent (the green object) for 6 times across trials. In 2:1 mapping condition, the word "*tiga*" and "*dabu*" both co-occur most frequently with the same referent (the blue object) for 6 times across trials.

Spatial Working Memory Task (SWM). Participants completed a Symmetry Span Task (modified from Foster et al., 2015; Kane et al., 2004) to recall the locations and sequences of flashing squares while performing a symmetry-judgment task. In a 4×4 grid, squares randomly turned red for 650 ms one after another. A black-and-white picture on a 8×8 matrix appeared after each flashing red square. Immediately after each black-and-white picture appeared, participants were asked to make a judgment on whether the matrix was symmetric about its vertical axis before the next red square showed up. The pictures were half symmetrical and half non-symmetrical (the pictures were from a pool of 15 symmetrical and 15 non-symmetrical 8×8 matrices). After 2-to-5 flashing squares, participants were instructed to recall the squares' location and order accurately and fast. Participants completed a total of 8 trials of 28 squares (two sets of trials with 2, 3, 4, and 5 squares per trial); trial order was counterbalanced across participants. **Figure 2** (Upper Panel) depicts the procedure of the SWM task. Prior to the task, participants completed 2 practice trials (2 squares per trial) to get familiar with the procedure before testing. The SWM task lasted about 8 minutes. Scores were calculated in the partial scoring system, which was the sum of red squares recalled in the correct location and serial order, regardless of whether the entire trial was recalled correctly (Blacker et el., 2017; Kane et al., 2004). All trials were included in data analysis regardless of symmetry accuracy.

Figure 2

Procedure of SWM and PWM



Select square locations in order that you saw them.

"No matter how much we talk to him, he is never going to change"

Is the sentence semantically correct?

Press the left or the right key.

"The young pencil kept his eyes closed until he was told to look"

Is the sentence semantically correct?

Press the left or the right key.

Type the last word of each sentence in their order.
Separate each word by a comma ","
E.g. apple, ball, banana

Note. The **upper panel** depicts the procedure of the SWM task. The example shows one trial of 2 flashing squares. The **lower panel** depicts the procedure of the PWM task. The example displays one trial of 2 sentences.

Phonological Working Memory Task (PWM). Participants completed a Listening Span Task in English, which was modified from a Reading Span Task (Kane et al., 2004). Participants heard several sentences (2, 3, 4, or 5 sentences per trial) and were asked to recall the last word of each sentence after all sentences in a trial were presented. Immediately after hearing each sentence, participants judged whether the sentence was semantically correct or not. Half of the sentences were semantically correct (e.g. "*No matter how much we talk to him, he is never going to change*"), while the other half was semantically incorrect (e.g. "*The young <u>pencil</u> kept his eyes closed until he was told to look*"). After hearing all sentences in a trial, participants were instructed to type all the last words of the heard sentences into a textbox on the computer screen. **Figure 2** (Lower Panel) depicts the procedure of the PWM task. There were a total of 12 trials of 48 sentences (three sets of trials with 2, 3, 4, and 5 sentences per trial); trial order was counterbalanced across participants. **Appendix C** contains all the sentence stimuli for the PWM task in English. Participants completed 3 practice trials (2 sentences per trial) to get familiar with the procedure before testing. The PWM task lasted about 10 minutes. Scores were calculated by summing up the correctly recalled words per trial according to the level of trial difficulty [e.g. if a participant successfully recalled 3 last words in a 5-sentence trial, the score for that trial would be 15 (3*5)].

All participants completed PWM English (English as an instructional language and in the auditory sentences). Bilinguals who also spoke Spanish or Mandarin Chinese additionally completed a PWM task in the other language (PWM Spanish for Spanish-English bilinguals and PWM Chinese for Mandarin Chinese-English bilinguals). PWM in the other languages (PWM Spanish and PWM Chinese) is not reported in the current document.

Language Background Questionnaire (LBQ). A Language Background Questionnaire recorded participants' demographic backgrounds and language use information (modified from Language History Questionnaire 1.0 and 3.0, Li et al., 2006, 2020). Demographic background questions included participants' education, income, age, gender, permanent residency, and race/ethnicity. Language use covered participants' experience with English and language(s) other than English, including age of acquisition, self-rated proficiency (in listening, speaking, reading, and writing), language mixing, activities in using each language (e.g. thinking, talking, and using numbers), and cultural assimilation in each language (e.g. from the perspective of life, food, and sports).

Participants were coded as bilinguals if they indicated their knowledge of a second language, and as monolinguals if not.

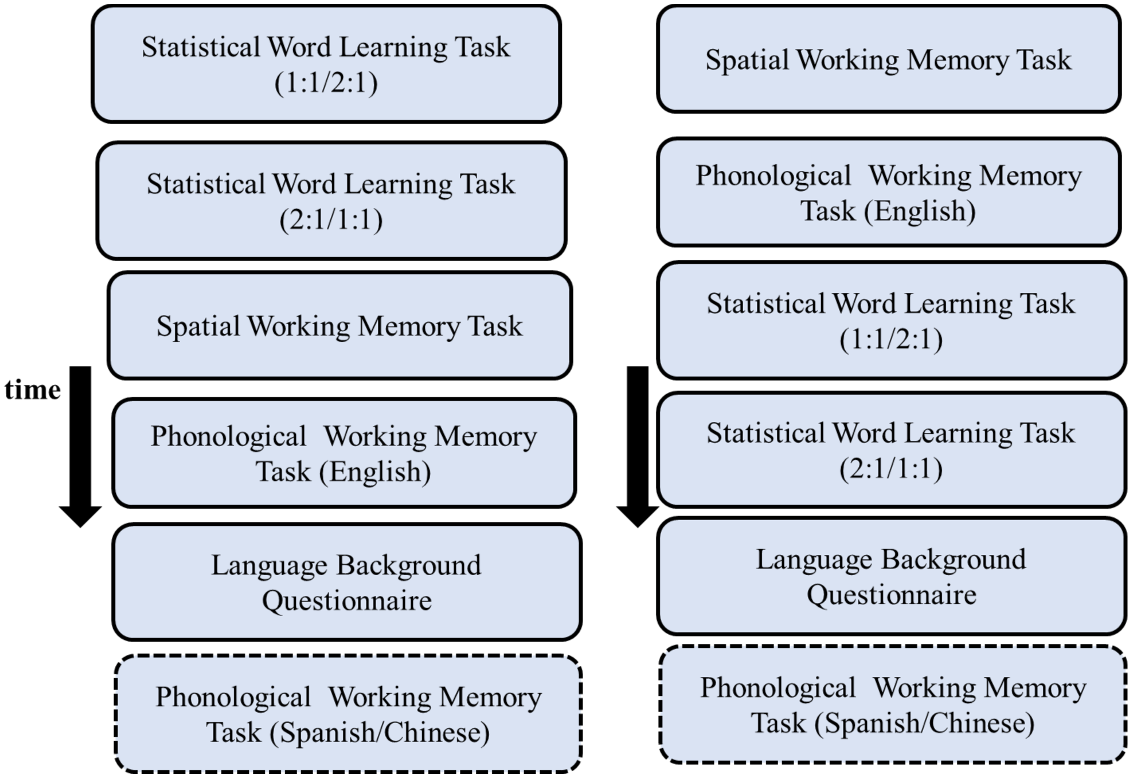
3. Procedure

All tasks (SWL, SWM, PWM) were built in PsychoPy3 (version 2020.2.10; Peirce et al., 2019) and transferred to Pavlovia for online testing (https://pavlovia.org/; Bridges et al., 2020). The questionnaires were designed in Qualtrics (https://www.qualtrics.com). Due to COVID-19 restrictions for in-person data collection, the study was conducted online via a video conference platform (Zoom: https://zoom.us/). Two experimenters instructed participants (a maximum of five participants at a time) to complete all tasks. The roles of the experimenters included providing experiment links, monitoring task progress, and addressing technical difficulties. To augment task engagement, participants were instructed to turn on their camera and update the experimenters on their progress each time they completed a task via the private zoom chat function. After the experiment, participants were debriefed.

Before the experiment, participants were provided an electronic consent form detailing that their participation was voluntary and they could withdraw anytime during the experiment. After providing consent, participants began the experiment. Each participant completed the study in one of the four possible orders: SWL tasks followed by working memory tasks (see the left panel in **Figure 3**) or working memory tasks followed by SWL tasks (see the right panel in **Figure 3**). The order of the SWL tasks was counterbalanced across participants while the order of the working memory tasks was not (participants always completed the SWM task followed by the PWM task). Spanish-English and Chinese-English bilinguals additionally completed a PWM task in Spanish or in Mandarin Chinese at the end of the entire session. The entire study lasted about 50 minutes for monolinguals (and bilinguals who spoke another language other than Spanish or Chinese), and about 60 minutes for Spanish-English and Chinese-English bilinguals.

Figure 3

Study Procedure



Note. The **left panel** denotes the possible orders when the word learning tasks precede the working memory tasks (PWM and SWM). The **right panel** denotes the possible orders when the working memory tasks precede the word learning tasks. The tasks in the dashed box are displayed for Spanish-English or Chinese-English bilinguals only.

Results

1. Descriptives

Table 3 depicts means and standard deviations by language group for the word learning accuracy in the two SWL tasks, for the subjective rating of learning in the two SWL tasks, for the accuracy in the SWM task, and for the accuracy in the PWM task.

Descriptives of Statistical Word Learning. According to the analysis plan in the prospectus, to examine whether adults learned in the current paradigm, we used one-sample t-tests to compare the word learning accuracy against chance (0.5). For each participant, we aggregated the scores across test trials (each test trial was scored as 1-correct or 0-incorrect) to generate two mean accuracy rates in each condition (1:1 and 2:1 mapping conditions). **Table 3** (Top-Left) depicts the descriptive statistics of SWL according to mapping type and language group. Results showed that both language groups were above chance performance in each condition. Specifically, monolinguals exhibited learning in the 1:1 mapping ($t(68) = 8.16$, $p < .001$, $d = .98$) and the 2:1 mapping ($t(68) = 4.41$, $p < .001$, $d = .53$) conditions respectively. Bilinguals also learnt in the 1:1 mapping ($t(87) = 9.52$, $p < .001$, $d = 1.02$) and the 2:1 mapping ($t(87) = 6.97$, $p < .001$, $d = .74$) conditions.

Table 3

Descriptive Statistics of the Tested Variables

	Statistical word learning			**Subjective rating of learning**		
	Mono	**Bi**	**Overall**	**Mono**	**Bi**	**Overall**
1:1 mapping	.72 (.22)	.72 (.22)	.72 (.22)	4.22 (2.91)	3.83 (2.78)	4.00 (2.84)
2:1 mapping	.60 (.18)	.64 (.19)	.62 (.19)	3.01 (2.39)	2.76 (2.30)	2.87 (2.34)
Overall	.66 (.21)	.68 (.21)	**.67 (.21)**	3.62 (2.72)	3.30 (2.60)	**3.44 (2.66)**

	Mono	**Bi**	**Overall**
PWM	.83 (.18)	.76 (.19)	.79 (.19)
SWM	.53 (.24)	.60 (.19)	.58 (.22)

Note. Means (standard deviation) are depicted for SWL, SRL, PWM, and SWM. The PWM refers to the PWM in English.

2. Effects of Language Experience

The first main question asked how learners of different language experience (monolingual and bilingual) approach SWL when referents have a single name (1:1 mapping condition) vs. two names (2:1 mapping condition).

Statistical Word Learning. According to the analysis plan in the prospectus, to examine the first main question, we adopted a two-way mixed ANOVA to investigate the effects of condition (1:1 and 2:1 mapping) and language group (monolingual and bilingual) on statistical word learning. Results suggest that the main effect of condition was significant ($F(1,155) = 21.69$, $p < .001$, $eta^2 = .06$). But the main effect of language group was not significant ($F(1,155) = .84$, $p = .36$, $eta^2 = .00$). Further, the condition×language group interaction was not significant ($F(1, 155) = .88$, $p = .35$, $eta^2 = .00$). **Table 3** (Top-Left) and **Figure 4** depict the descriptives of SWL by language group and mapping type. In summary, performance in the 1:1 mapping condition was significantly higher than that in the 2:1 mapping condition. However, monolinguals and bilinguals showed no differences in learning for both types of mapping[4].

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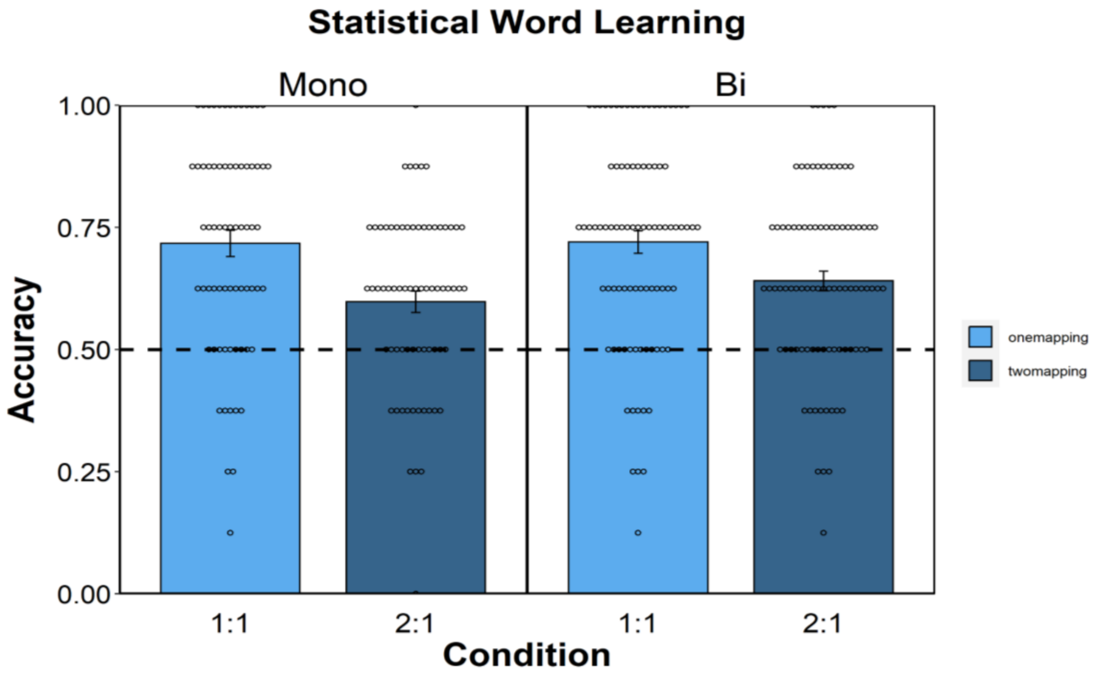
[4] Further, we tested whether the difference of learning between conditions resulted from the mapping type *per se* or an order effect (e.g. a carry-over effect from the first test session to the second test session). We conducted a paired sample t-test to investigate the learning as a function of test order (the first or the second test session) (the analysis in this section was not planned in the prospectus). Results showed a non-significant difference in learning when the condition was tested either first ($M = .65$, $SD = .21$) or second ($M = .69$, $SD = .21$) ($F(1, 156) = 3.17$, $p = .08$, $eta^2 = .01$). To conclude, this piece of further evidence expels the possible confound that the difference in learning between

Figure 4

Statistical Word Learning as a Function of Condition and Language Group



Note. Mean accuracy (and standard error of the mean) for SWL in the *1:1 mapping* condition and *2:1 mapping* condition for the two language groups (monolinguals and bilinguals). The dashed line denotes chance performance (0.5). Dots stand for individual data points.

Subjective Rating of Statistical Word Learning. Additionally, to explore the effects of language groups in other domains, we further analyzed the differences between language groups in subjective rating of statistical word learning, and working memory performance in PWM and SWM. We conducted a mixed two-way ANOVA test to address learners' subjective rating of learning (SRL) immediately after each condition as an effect of condition and language group (the analysis in this section was not planned in the prospectus). Results suggested a similar trend as that of SWL: the main effect of

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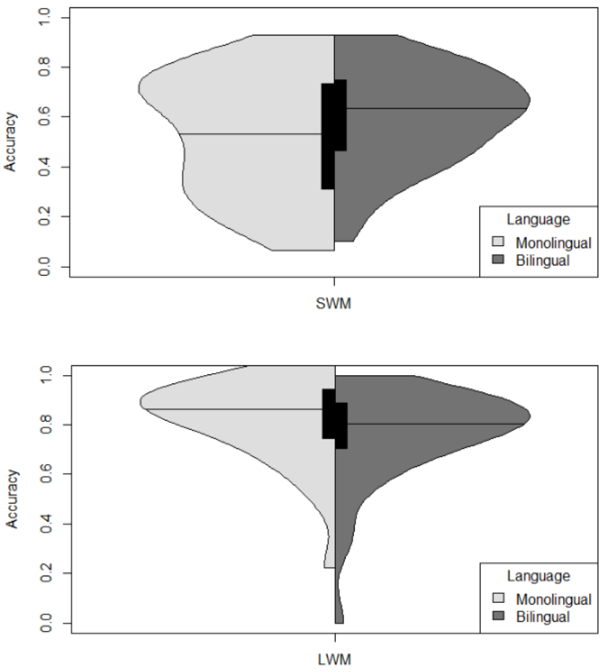
conditions results from a test order effect, and further supports a robust learning difference between the mapping types *per se*.

condition was significant ($F(1,155) = 23.45$, $p < .001$, $\eta^2 = .05$). The main effect of language group was not significant ($F(1,155) = .86$, $p = .36$, $\eta^2 = .00$). The condition×language group interaction was not significant ($F(1, 155) = .08$, $p = .77$, $\eta^2 = .00$). **Table 3** (Top-Right) depicts the descriptives of SRL by language group and mapping type. To summarize, participants' confidence in learning words in the *1:1 mapping* condition was significantly higher than that in the *2:1 mapping* condition. However, monolinguals and bilinguals did not differ in their confidence ratings in each condition.

Working Memory. In order to investigate the working memory capacities in different language groups, we conducted independent sample t-tests to compare the performance of spatial and phonological WM between monolinguals and bilinguals (the analysis in this section was not planned in the prospectus). Results showed that monolinguals differed from bilinguals in both SWM and PWM. Bilinguals had a higher SWM score ($M = .60$, $SD = .19$) compared with monolinguals ($M = .53$, $SD = .24$) ($t(123.77) = 2.05$, $p = .042$, $d = .35$), but a worse PWM score ($M = .76$, $SD = .19$) compared with monolinguals ($M = .82$, $SD = .18$, $t(138.84) = 2.18$, $p = .031$, $d = .36$). Figure 5 depicts the language group differences in SWM and PWM in violin plots. Note that the language of instruction for PWM was English. Results suggest that English monolinguals outperform English-other bilinguals in the language-related phonological working memory task (when the test is launched in English), but do worse in the language-irrelevant spatial working memory task than their bilingual counterparts.



Note. The differences between language groups are depicted in violin plots for SWM (**top panel**) and for PWM (**bottom panel**). The shaded areas denote the frequency distribution of individual accuracy scores: the wider an area around an accuracy score, the larger the number of participants with that accuracy score. The solid lines denote mean accuracy for each group.

3. Effects of Working Memory

The second main question concerned how individual working memory capacities (spatial and phonological) played a role in SWL abilities for each mapping type. To answer this question, first, we conducted preliminary correlation and regression analyses to examine the *relationship between* working memory and SWL in each condition. Second, a path analysis model was conducted to examine the *relationship among* language experience, working memory, and SWL.

Correlation (and Regression) Between WM and SWL. In order to address how individual differences play a role in statistical word learning, we conducted pearson correlation tests and regression analysis on the 7 tested variables: statistical word learning

(SWL 1:1 and SWL 2:1), working memory (SWM and PWM), and subjective rating of learning (SRL 1:1, SRL 2:1, and SRL post-test) (the analysis in this section was not planned in the prospectus). **Table 4** demonstrates the correlation matrix among the tested variables. Results suggested that SWL in 1:1 mapping significantly correlated with SWM ($r = .22$, $p = .006$) and PWM ($r = .29$, $p < .001$). Interestingly, however, SWL in 2:1 mapping did not correlate with neither SWM ($r = -.09$, $p = .28$) nor PWM ($r = .09$, $p = .26$). By running multiple regression models, **Table 5** (Model 1 and Model 2) further supported that both PWM ($b = .26$, $SE = .09$, $p < .001$) and SWM ($b = .18$, $SE = .08$, $p = .03$) significantly predicted SWL in *1:1 mapping* (the model of PWM and SWM as predictor in SWL 1:1 mapping as outcome was significant, $R^2 = .11$, $p < .001$). But neither PWM ($b = .13$, $SE = .09$, $p = .12$) nor SWM ($b = -.11$, $SE = .08$, $p = .17$) predicted SWL in 2:1 mapping (the model of PWM and SWM in SWL 2:1 mapping was not significant, $R^2 = .02$, $p = .19$).

Surprisingly, SWL in 1:1 mapping and SWL in 2:1 mapping did not significantly correlate with each other ($r = .15$, $p = .06$). Similarly, **Table 5** (Model 3) further corroborated that SWL in 1:1 mapping ($b = .13$, $SE = .07$, $p = .06$) did not predict SWL in 2:1 mapping (the model of SWL 1:1 mapping in SWL 2:1 mapping was not significant, $R^2 = .02$, $p = .06$).

The subjective rating of learning consistently mapped with the actual statistical word learning performance in each corresponding condition. SRL in 1:1 mapping significantly correlated with SWL in 1:1 mapping ($r = .49$, $p < .001$) but not with SWL in 2:1 mapping ($r = .10$, $p = .22$). Similarly, SRL in 2:1 mapping correlated with SWL in 2:1 mapping ($r = .20$, $p = .010$) but not with SWL in 1:1 mapping ($r = .08$, $p = .31$). SRL in the post-test (tested at recall) only correlated with SRL in 1:1 mapping ($r = .28$, $p < .001$) but not with SRL in 2:1 mapping ($r = .09$, $p = .27$). In a series of multiple regression models, **Table 5** (Model 4 and Model 5) further corroborated that only SRL in 1:1 mapping ($b = .04$, $SE = .00$, $p < .001$) predicted SWL in 1:1 mapping (the model of SRL 1:1 mapping, 2:1 mapping, and post-test in SWL 1:1 mapping was significant, $R^2 = .26$, $p < .001$); and SRL in 2:1 mapping may ($b = .02$, $SE = .01$, $p = .03$) predict SWL in 2:1 mapping (but the model of SRL 1:1 mapping, 2:1 mapping, and post-test in SWL 2:1 mapping was not significant, $R^2 = .04$, $p = .11$).

Taken together, the correlation and multiple regression analyses are consistent in showing two findings. *One*, the individual differences of working memory (spatial and phonological) may work differently in statistical word learning of different mapping types. Specifically, individuals with high spatial and phonological working memory have high statistical word learning ability when each referent has one name, but the two working memory capacities fail to predict word learning when each referent has more than one name. *Two*, participants' ability to gauge how well they perform in word learning is dependent on condition. That is, the subjective rating on how much one has learnt in one mapping type (e.g. 1:1 mapping) uniquely predicts his or her actual learning in that specific mapping (e.g. 1:1 mapping), but not in learning overall. The results suggest a synchrony between statistical learning and conscious awareness.

Table 4

Correlation Matrix of Tested Variables

	SWL 1:1	**SWL 2:1**	**SWM**	**PWM**	**SRL 1:1**	**SRL 2:1**	**SRL post-test**
SWL 1:1	1						
SWL 2:1	.15	1					
SWM	.22**	-.09	1				
PWM	.29**	.09	.32**	1			
SRL 1:1	.49**	.08	.12	.25**	1		
SRL 2:1	.10	.20**	.02	.03	.38**	1	
SRL post-test	.28**	.09	.11	.10	.66**	.43**	1

Note. Asterisks indicate significant correlation (* *p* < .05; ** *p* < .01).

Table 5

Regression Model of Tested Variables

Model 1: Working memory predicts SWL 1:1 mapping

Coefficients	*b*	*SEb*	*t*	*p*
PWM	0.26	0.09	2.76	<.01**
SWM	0.18	0.08	2.14	.03*
Model 1	R^2	ΔR^2	*F*	*p*
	0.11	0.1	8.85	<.01**

Model 2: Working memory predicts SWL 2:1 mapping

Coefficients	*b*	*SEb*	*t*	*p*
PWM	0.13	0.09	1.55	.12
SWM	-0.11	0.08	-1.39	.17
Model 2	R^2	ΔR^2	*F*	*p*
	0.02	0	1.65	.19

Model 3: SWL 1:1 mapping predicts SWL 2:1 mapping

Coefficients	*b*	*SEb*	*t*	*p*

SWL 1:1	0.13	0.07	1.88	.06
Model 3	R^2	ΔR^2	*F*	*p*
	0.02	0.02	3.53	.06
Model 4: Subjective rating of learning predicts SWL 1:1 mapping				
Coefficients	*b*	*SEb*	*t*	*p*
SRL 1:1	0.04	0	6.1	<.01**
SRL 2:1	0	0	-1.18	.24
SRL post-test	0	0	-0.67	.51
Model 4	R^2	ΔR^2	*F*	*p*
	0.26	0.25	17.75	<.01**
Model 5: Subjective rating of learning predicts SWL 2:1 mapping				
Coefficients	*b*	*SEb*	*t*	*p*
SRL 1:1	.01	.01	0.11	.91
SRL 2:1	.02	.01	2.18	.03*
SRL post-test	0	.01	-.01	.99
Model 5	R^2	ΔR^2	*F*	*p*
	0.04	0.02	2.08	.11

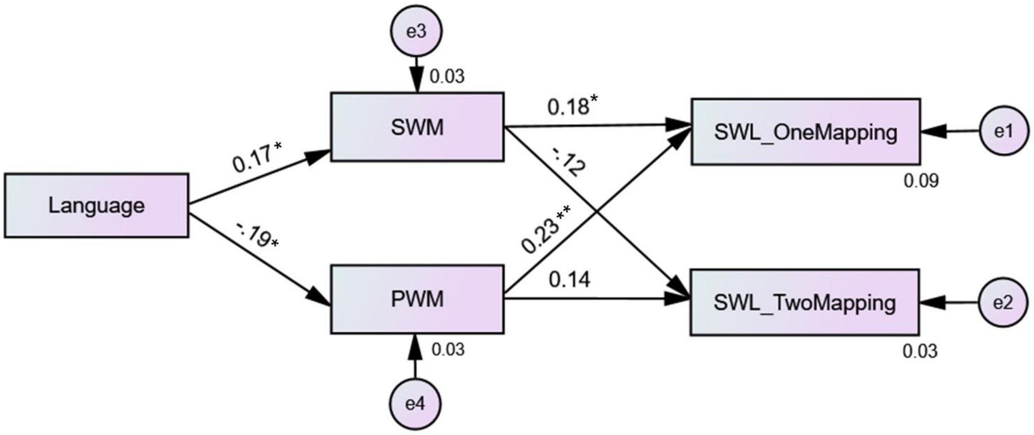
Note. Asterisks indicate significant coefficients and/or overall regression models (* $p < .05$; ** $p < .01$).

Path Analysis of Language experience, WM, and SWL. According to the analysis plan in the prospectus, two mediation models should have been used to investigate the effects of language experience on SWL mediated by SWM and PWM, with SWL in 1:1 mapping and in 2:1 mapping as dependent variables respectively. I did not adopt the original plan for two reasons. First, there should be only one dependent variable in each mediation model. However, each participant participated in both SWL in 1:1 mapping and SWL in 2:1 mapping conditions, which calls for the need of incorporating two dependent variables into the same model. Thus, a path analysis model fits our needs to incorporate both SWL in 1:1 mapping and SWL in 2:1 mapping variables into the same model. Second, by running two mediation models where SWL in 1:1 mapping (or SWL in 2:1 mapping) was the dependent variable, we found a bad model fit for both models. Evaluation of model fit was based on the indices: χ^2 ($p > .05$), TLI (> .93), CFI (> .93), RMSEA (< .10), and SRMR (< .08) (criterion: TLI, CFI, and SRMR, Hu & Bentler, 1999; RMSEA, Browne & Cudeck, 1992).For the mediation model where SWL 1:1 was the dependent variable, results suggested that the hypothesized model represented the data to a fairly bad extent: $\chi^2(1) = 20.18$. ($p < .001$), TLI = -1.81, CFI = .53, RMSEA = .37, and SRMR= .10. For the mediation model where SWL 2:1 mapping was the dependent variable, results suggested that the hypothesized model represented the data to a fairly bad extent: $\chi^2(1) = 20.18$ ($p < .001$), TLI = -2.64, CFI = .39, RMSEA = .37, and SRMR= .10. Given these two reasons, I opted for conducting a path analysis instead.

Therefore, in order to better conceptualize the relationship among language experience, working memory, and SWL, a path analysis was conducted in *lavaan package* (Rosseel, 2012) (R 4.1.0) and graphed the figure(s) via *Amos software* (Arbuckle, 2014). Evaluation of model fit was based on the indices: χ^2 ($p > .05$), TLI (> .93), CFI (> .93), RMSEA (< .10), and SRMR (< .08) (criterion: TLI, CFI, and SRMR, Hu & Bentler, 1999; RMSEA, Browne & Cudeck, 1992). Results suggested that the hypothesized path model represented the data to a fairly good extent: $\chi^2(3) = 6.99$ ($p = .07$), TLI = .72, CFI = .92, RMSEA = .10 with 90% CI= [.00, .19], and SRMR = .05. **Figure 6** outlines the path model and individual standardized coefficients between each two variables. Results suggested that a good portion of direct coefficients were significant (see **Figure 6** for the asterisked pathways), and the indices of the coefficients in the model matched with the relation between each two variables from the correlation and regression analyses above. However, the mediated effect of language→WM→SWL 1:1 mapping was not significant (*b* = -.02, *p* = .71, 95% CI = [-.037, .025]); and the mediated effect of language–WM–SWL 2:1 mapping was also not significant (*b* = -.05, *p* = .06, 95% CI = [-.043, .001]). To conclude, *first*, the results showed that the relations between WM and SWL were consistent with the outcomes from the correlation and regression analyses in the above section. That is, the role of working memory on statistical word learning is dependent on mapping type: both spatial and phonological working memory positively predict word learning when a referent has one name, but not when a referent has more than one name. *Second*, working memory (spatial and phonological) did not mediate the relationship between language experience and statistical word learning in either 1:1 or 2:1 mapping type. *Third*, interestingly, the language-related phonological working memory contributes to statistical word learning (in 1:1 mapping) to a greater extent than the language-unrelated spatial working memory.

Figure 6

Path Analysis of Language Experience, WM, and SWL



Note. The path analysis shows the relation among language experience (monolingual and bilingual), working memory (spatial and phonological), and statistical word learning (1:1 and 2:1 mapping). The dataset only contains the complete individual data (*N* = 143). Values presented are standardized coefficients (***p* < .01, **p* < .05).

Discussion

In this study, we examined how adult learners' language experience (monolingual and bilinguals) and individual differences in working memory (phonological and spatial working memory) affect statistical word learning of different mapping types (1:1 or 2:1 mapping). *First*, no difference was found in learning 1:1 or 2:1 structure between monolinguals and bilinguals. *Second*, individuals' working memory capacities, both phonological and spatial working memory, predicted statistical word learning in the 1:1 mapping condition, but not in the 2:1 mapping condition. *Together*, our results suggest that individual differences in working memory predict statistical word learning when a referent has one name regardless of language experience.

Contrary to our hypothesis, we failed to find any differences in SWL between monolinguals and bilinguals in both mapping types. This contradicts previous findings which suggest a bilingual advantage in general word learning (Kan & Kohnert, 2012;

Kaushanskaya & Marian, 2009; Singh et al., 2018) and specifically in SWL (Benitez et al., 2016; Escudero et al., 2016; Poepsel & Weiss, 2016). Poepsel and Weiss (2016) tested monolinguals and bilinguals on a SWL task where each word was mapped with either one object (1:1 mapping) or with two objects (1:2 mapping). Results showed that bilinguals outperformed monolinguals only in the 1:2 mapping condition, but not in the 1:1 mapping condition. The authors explained such an advantage by bilinguals' loosened reliance on the mutual exclusivity assumption due to bilinguals' increased encounters with ME-violating circumstances (e.g. an object has multiple names across languages; Houston-Price et al., 2010). Similarly, dependent on the degree of exposure to multiple languages, 17-18 month-old infants showed similar trends when tested at multiple-to-one word-referent mappings: infants with trilingual language experience demonstrated the least disambiguation in multiple-to-one word mappings, followed by infants with bilingual experience and then monolingual experience (Beyers-Heinlein & Werker, 2009). In this vein, bilinguals could be more adaptive to the linguistic variations from the input, and demonstrate a greater learnability in ME-violating scenarios, such as the learning scenarios of 1:2 or 2:1 mappings.

However, the current findings and other previous research discussed in the Introduction place the robustness of a bilingual effect in SWL under question. It was not always the case that bilinguals are better at learning words in ME-violating circumstances. Benitez et al. (2016) presented monolingual and bilingual adults with a mixture of 1:1 and 2:1 mappings. Across two experiments, the two words for a referent were either differentiated by a linguistic cue, or not. Results showed that bilinguals outperformed monolinguals in the learning of 2:1 mappings only when the two words for a referent were distinctive. The results suggest that bilingual language experience *per se* may not guarantee better learning of 2:1 mappings, but the learning process is also language-input dependent (i.e. a cue differentiating language inputs).

However, whether there is a bilingual effect in 2:1 learning may also depend on which specific cues (and their effectiveness) were presented in the input. Li and Benitez (2022) tested adults on their learning of 2:1 mappings where the two words to the same referent were either differentiated by lexical tonal contours or not. Tonal bilinguals (Chinese-English bilinguals) incurred an advantage in SWL of 2:1 structure over non-tonal bilinguals (Spanish-English bilinguals) and English monolinguals. Yet, no differences in 2:1 learning were found between the non-tonal bilinguals and monolinguals. In sum, based on the limited and mixed results on SWL and its complex interplay with language experience and/or language inputs, it is hard to draw a firm conclusion about whether language experience *per se* may render a direct impact on statistical word learning. In order to obtain a reliable gauge on the effect size, future research should adopt a meta-analysis approach on studies regarding bilingualism and SWL (e.g. Gunnerud et al., 2020), considering the moderators of mapping type, the presences of cues or not, published and unpublished research, the measurements of bilingualism, labs, and age groups (e.g. Benitez et al., 2016, 2020; Ichinco et al., 2009; Li & Benitez, 2022; Poepsel & Weiss, 2014, 2016; Tsui et al., 2021; Vlack & DeBrock, 2017, 2019).

If language experience *per se* is not an efficacious predictor to SWL, then what may matter to SWL? Interestingly, we found a robust effect of working memory capacities on SWL in the 1:1 mapping condition, regardless of language experience. That is, individuals with higher phonological and/or spatial working memory achieved better SWL scores when one word has one name, no matter whether they were monolinguals or bilinguals. The findings are in line with our hypothesis that working memory can play an important role in SWL from a theoretical and empirical point of view. Under high referential ambiguity, learners may tax working memory resources to remember the auditory features of words and hold the visual-spatial information pertaining to objects, both within and across learning trials. Vlach and DeBroch corroborate this claim from children' studies that task-relevant working memory predicts SWL abilities in 1:1 mapping (i.e. visual recognition memory) over and above other factors such as children' vocabulary size and age (2017, 2019). Our results from adults contribute over and above this line of research by demonstrating that task-relevant working memory, specifically phonological working memory and visuo-spatial working memory, is predictive of tracking one-to-one word-referent statistics.

However, such working memory capacities, if essential for tracking 1:1 statistics, do not contribute to the same extent to SWL of 2:1 structure. Interestingly, the fact that working memory capacities specifically pertain to learning 1:1 structure may provide some novel insights to a long-lasting theoretical debate on the learning mechanisms underlying statistical learning: are learners doing hypothesis testing, associative learning, or a combination of both (Ichinco et al., 2009; Sia & Mayor, 2021; Trueswell et al., 2013; Yu et al., 2007)? Possibly, when tracking one-to-one word-referent statistics, learners may very well utilize an ME bias (an object has a single name by default), and strategically anchor one possible word-referent association (or expel an impossible word-referent association) based on *analytical reasoning*. For instance, one may infer that *dax* is the name of an object by conceiving the following mental processes: in the previous trial, when *dax* appears, object A and B appear; this time *dax* is heard again, and object A shows up again but with C; then *dax* must be object A, but not B or C. In this vein, holding an ME bias may help learners to conduct a rule-based learning or hypothesis-testing, where each time they either propose-or-verify a single hypothesis (Roembke & McMurry, 2020).

The hypothesis-testing process can be explicit, tapping into hippocampus-dependent memories (aka. declarative or explicit memories). Specifically, working memory, whose operation activates hippocampus and/or medial temporal lobe (MTL) (Axmacher et al., 2009; Leszczynski, 2011), can play an important role in dealing with "inference problems" where multiple alternatives are processed, held, and operated upon at a time (Mynatt et al., 1993). Therefore, it is theoretically sound that hypothesis testing may be a preferred (or dominant) strategy when learning ME-obeying one-to-one statistics, and working memory is exploited to retain one possible word-referent association one at a time within- and across-trials.

On the contrary, in the 2:1 mapping condition, learners may find it difficult to implement a hypothesis testing approach since ME bias is violated: multiple word candidates can refer to a given referent at a time. If learners make analytical reasoning to whittle down the number of candidates in the 2:1 mapping condition, their intended word-referent pairs may always be proved wrong due to an ME bias. Indeed, consistent with this idea and with previous research, we found a robust learning advantage in the 1:1 mapping condition over the 2:1 mapping condition (Benitez et al, 2016; Benitez & Li, 2022; Ichinco et al., 2009; Kachergis et al., 2012; Poepsel & Weiss, 2012, 2016). A strong ME bias may hinder learning when one object has more than one name. Thus, learners in the 2:1 mapping condition may abandon the hypothesis testing approach, and instead adopt associative learning by accumulating the word-referent co-occurrences (Yu et al., 2007). For instance, one may calculate the number of times each word and referent co-occur incrementally across events: dax co-occurs with object A for 6 times, but with object B for 4 times, and object C for 1 time. Thus, the *dax*-object A word-referent association wins out, compared with other less frequent word-referent pairs of *dax*-object B, and *dax*-object C.

Such a mental process of associative learning may be implicit (Roembke & McMurray, 2020). Implicit learning process renders hippocampus-independent memories (aka. nondeclarative or implicit memories) (Degonda et al., 2005), and the retrieval of the learning materials can be unconscious and does not occupy the same resources of the central executive as that of explicit learning (Roembke & McMurray, 2020). Studies show that implicit memory can be dissociative of explicit memory, and does not depend on the hippocampus. For instance, patients with hippocampal damage demonstrated deficits on explicit memory tasks, while keeping normal or near-normal performance in implicit memory tasks (Cohen & Squire, 1980, Corkin, 1968, Milner et al., 1968, Warrington & Weiskrantz, 1968). Also, healthy populations showed anatomical dissociations between implicit and explicit memory from functional neuroimaging studies (Cabeza & Nyberg, 2000, Schacter & Buckner, 1998a). Despite that it is still under debate whether implicit memory taps into the hippocampus (Degonda et al., 2005), and how implicit learning and explicit memory may interact (Roembke & McMurray, 2020), it seems to reach a consensus that implicit learning taxes less working memory as that of explicit learning. A recent study investigating fMRI in SWL of 1:1 structure provides strong support to our reasoning that learning is explicit and activates the hippocampus, supporting the claim that learners engage in hypothesis-testing during SWL of 1:1 structure (Berens et al., 2018). If statistical word learning of 2:1 structure is indeed tapping into more implicit associative learning processes compared with that of 1:1 structure, then one prediction is that working memory will underplay in SWL learning of 2:1 structure, with less activation of the hippocampus from neural data- an avenue for future research. At least, such prediction aligns with our behavioral findings that working memory did not predict SWL in 2:1 mappings.

Admittedly, it is clearly beyond the scope of the current study to test out whether learners adopt different underlying learning mechanisms (hypothesis testing v.s. associative learning) for 1:1 mapping and 2:1 mapping respectively, and, if so, how the two mechanisms interact during the learning processes. However, our current results argue for the possibility that different learning mechanisms may be adopted for learning one-to-one and two-to-one statistics, as working memory plays a role in one but not the other. More importantly, the results provide novel insights into future studies to address some research gaps in statistical learning mechanisms. Specifically, we suggest investigating the theoretical debate between hypothesis testing account and associative learning account during statistical learning from three possible aspects (the aspects may work either independently or jointly):

1. Investigate the memory-related brain areas (e.g. hippocampus and/or medial temporal lobe) by using EEG and/or fMRI techniques during

statistical learning under different mapping types, and locate whether and where different cognitive mechanisms play a role in each type.

2. Consider computational models (e.g. Bayesian models) which can adjust parameters to assume biases observed in naturalistic language acquisition (i.e. mutual exclusivity, fast-mapping, and whole-object biases) to test out whether statistical learning of different structures obey these biases in the same or a different way.
3. Target atypical populations (e.g. patients of hippocampal damage) to draw cause-and-effect conclusions on which cognitive mechanism(s) may be crucial, and target a variety of age groups (i.e. infants, children, young and older adults) to look into whether and how the two accounts may be dynamic, complementary, and changing over time.

Lastly, despite that language experience may not serve as an efficacious predictor to SWL, language experience did affect working memory capacities. Specifically, bilinguals were found to have a higher spatial working memory capacity, compared to their monolingual counterparts. The findings align with previous research that long-term dual language use can alter perspectives of executive functions (EF). With two active but competing systems capable of generating linguistic behaviors, bilinguals need a mechanism to control attention to the required system, and ignore the system not currently in use (Bialystok, 2007). Joint activation creates challenges in the bilingual speakers' attention and inhibition that monolingual speakers may encounter less frequently (Bialystok, 2017). Such long-term attention management between linguistic systems might exercise EFs that are not limited to language use (Bialystok, 2011, 2017;

Costa & Sebastián-Gallés, 2014). Studies have suggested a bilingual advantage in nonverbal executive functions tasks, e.g. planning, attention, inhibition, task switching, and working memory (Bialystok, 2017; Bialystok et al., 2009; Gunnerud et al., 2020; Kroll et al., 2015; Namazi & Thordardottir, 2010; Oller, 2005; Prior & MacWhinney, 2010). Specifically, bilinguals are found to be equipped with larger working memory capacities in language-irrelevant EFs, such as spatial working memory (Luo et al., 2013; Morales et al., 2012), and language-relevant EFs, such as phonological working memory (Yoo & Kaushanskaya, 2012, but see Kaushanskaya & Marian, 2009; Luo et al., 2013).

However, we found a disadvantage in bilinguals' phonological working memory, against the rationale reasoned above. The reason for lower phonological memory skills in bilinguals could be because the listening span task used to measure phonological working memory was tested in English for both English monolinguals and English-other bilinguals. According to Grundy and Timmer (2017)'s meta-analysis on bilingualism and working memory, language at test, either in bilinguals' first (L1) or second (L2) languages, matters in verbal working memory tasks. Performing verbal tasks in bilinguals' less dominant language can disadvantage bilinguals, given that they could be slower at lexical retrieval when processing occurs in the less-dominant language (e.g. see Modified Hierarchical Model, Kroll & Stewart, 1994). Consistent with this is the fact that the bilinguals in our study acquired English significantly later than their English counterparts. Further, although bilinguals self-reported their English proficiencies comparable to English monolinguals, bilinguals had significantly less activities in using English (e.g. thinking, talking, and expressing emotions) and less cultural assimilation towards English in various perspectives (e.g. life, food, and music) (see Table 2). As a consequence, due to an imbalanced language use (and cultural assimilation) between bilinguals' two languages, the majority of the bilinguals in the PWM task got tested on their less dominant language–English, so that the results may not reflect phonological working memory *per se* but a combination of PWM and a prolonged lexical retrieval from one's dominant to the non-dominant language. To better investigate PWM, PWM tested in the other languages should be assessed (Spanish for Spanish-English bilinguals, and Chinese for Chinese-English bilinguals). In all, the evidence suggests that language experience plays different roles on cognitive abilities (i.e. working memory) and on word learning (i.e. SWL). The results thus suggest a more careful re-evaluation of a bilingual effect (if true) considering domain-specificity and task relevance.

To conclude, the current study asked whether and how language experience (monolingual and bilingual) and individual differences in working memory (spatial and phonological working memory) play a role in statistical word learning of different mapping types (an object has one name or two). *First*, we do not have evidence to support that language experience plays a role in SWL in both types of mappings. *Second*, individual working memory skills did predict SWL, but only for 1:1 mapping. We propose such dissociation could result from learners' adopting different underlying learning mechanisms by structure (i.e. 1:1 and 2:1 mapping). Specifically, when learning 1:1 structure which obeys mutual exclusivity assumption, learners adopt more explicit processes (i.e. hypothesis-testing); but when learning 2:1 structure which violates such assumption, learners adopt more implicit processes (i.e. associative learning). Future studies can test out the hypotheses proposed above by locating memory-related brain areas (e.g. hippocampus and/or medial temporal lobe) for different types of statistical structure, adopting computational models with biases observed in naturalistic language acquisition, and targeting atypical populations and groups across age ranges.

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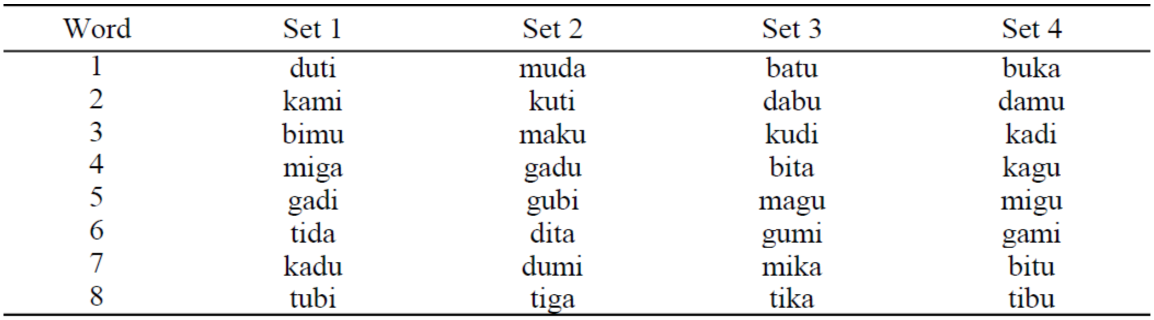
APPENDIX A

NOVEL WORD SETS FOR 1:1 AND 2:1 MAPPING CONDITIONS



Word	Set 1	Set 2	Set 3	Set 4
1	duti	muda	batu	buka
2	kami	kuti	dabu	damu
3	bimu	maku	kudi	kadi
4	miga	gadu	bita	kagu
5	gadi	gubi	magu	migu
6	tida	dita	gumi	gami
7	kadu	dumi	mika	bitu
8	tubi	tiga	tika	tibu

Note. There were four different word sets for two conditions so that no words were the same across conditions (Set 1 for 1:1 mapping and Set 3 for 2:1 mapping; or Set 2 for 2:1 mapping and Set 4 for 1:1 mapping)

APPENDIX B

DECOMPOSITION OF NOVEL WORD SETS

Syllable	Set 1			Set 2			Set 3			Set 4		
	Syllable position			Syllable position			Syllable position			Syllable position		
	initial	final	total	initial	final	total	initial	final	total	initial	final	total
ba	0	0	0	0	0	0	1	0	1	0	0	0
bi	1	1	2	0	1	1	1	0	1	1	0	1
bu	0	0	0	0	0	0	0	1	1	1	1	2
da	0	1	1	0	1	1	1	0	1	1	0	1
di	0	1	1	1	0	1	0	1	1	0	1	1
du	1	1	2	1	1	2	0	0	0	0	0	0
ga	1	1	2	1	1	2	0	0	0	1	0	1
gu	0	0	0	1	0	1	1	1	2	0	2	2
ka	2	0	2	0	0	0	0	2	2	2	1	3
ku	0	0	0	1	1	2	1	0	1	0	0	0
ma	0	0	0	1	0	1	1	0	1	0	0	0
mi	1	1	2	0	1	1	1	1	2	1	1	2
mu	0	1	1	1	0	1	0	0	0	0	1	1
ta	0	0	0	0	1	1	0	1	1	0	0	0
ti	1	1	2	1	1	2	1	0	1	1	0	1
tu	1	0	1	0	0	0	0	1	1	0	1	1
Total	8	8	16	8	8	16	8	8	16	8	8	16

Note. The consonant-vowel combinations (e.g. “*bu*”) appeared approximately the same number of times in word initial position as in “*bu*__” or word final position as in “__*bu*” in both word sets, varying between zero to three times of repetition.

APPENDIX C

LISTENING SPAN TASK SENTENCE STIMULI (ENGLISH)

********* BEGIN PRACTICE *********

Andy was stopped by the policeman because he crossed the yellow heaven.	**N**
During winter you can get a room at the beach for a very low rate.	**Y**
People in our town are more giving and cheerful at Christmas time.	**Y**
During the week of final spaghetti, I felt like I was losing my mind.	**N**
After final exams are over, we'll be able to take a well-deserved rest.	**Y**
After a hard day at the office, Bill often stops at the club to relax.	**Y**

********* END PRACTICE *********

Trial 1

No matter how much we talk to him, he is never going to change.	**Y**
The prosecutor's dish was lost because it was not based on fact.	**N**
Every now and then I catch myself swimming blankly at the wall.	**N**

Trial 2

We were fifty lawns out at sea before we lost sight of land.	**N**
Throughout the entire ordeal, the hostages never appeared to lose hope.	**Y**
Paul is afraid of heights and refuses to fly on a plane.	**Y**
The young pencil kept his eyes closed until he was told to look.	**N**
Most people who laugh are concerned about controlling their weight.	**N**

Trial 3

When Lori shops she always looks for the lowest flood.	**N**
When I get up in the morning, the first thing I do is feed my dog.	**Y**
After yelling at the game, I knew I would have a tall voice.	**N**

Trial 4

Mary was asked to stop at the new mall to pick up several items.	**Y**
When it is cold, my mother always makes me wear a cap on my head.	**Y**

Trial 5

All parents hope their list will grow up to be intelligent.	**N**
When John and Amy moved to Canada, their wish had a huge garage sale.	**N**
In the fall, my gift and I love to work together in the yard.	**N**
At church yesterday morning, Jim's daughter made a terrible plum.	**N**
Unaware of the hunter, the deer wandered into his shotgun range.	**Y**

Trial 6

Since it was the last game, it was hard to cope with the loss.	**Y**
Because she gets to knife early, Amy usually gets a good parking spot.	**N**
The only furniture Steve had in his first bowl was his waterbed.	**N**
Last year, Mike was given detention for running in the hall.	**Y**

Trial 7

The huge clouds covered the morning slide and the rain began to fall.	**N**
After one date I knew that Linda's sister simply was not my type.	**Y**

Trial 8

Jason broke his arm when he fell from the tree onto the ground.	**Y**
Most people agree that Monday is the worst stick of the week.	**N**
On warm sunny afternoons, I like to take a walk in the park.	**Y**
With intense determination he overcame all obstacles and won the race.	**Y**

Trial 9

A person should never be discriminated against based on his race.	**Y**
My mother has always told me that it is not polite to shine.	**N**
The lemonade players decided to play two out of three sets.	**N**

Trial 10

Raising children requires a lot of dust and the ability to be firm.	**N**
The gathering crowd turned to look when they heard the gunshot.	**Y**
As soon as I get done taking this envy I am going to go home.	**N**
Sue opened her purse and found she did not have any money.	**Y**
Jill wanted a garden in her backyard, but the soil was mostly clay.	**Y**

Trial 11

Stacey stopped dating the light when she found out he had a wife.	**N**
I told the class that they would get a surprise if they were orange.	**N**

Trial 12

Jim was so tired of studying, he could not read another page.	**Y**
Although Joe is sarcastic at times, he can also be very sweet.	**Y**
Carol will ask her sneaker how much the flight to Mexico will cost.	**N**
The sugar could not believe he was being offered such a good deal.	**N**