There is no association between visuospatial and speech anticipation abilities in L1 and L2 speakers of Spanish

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(working draft)

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# 1. Introduction

When we learn a new language, we need to create new associations. For instance, we need to learn that a new way to call the concept that the word “house” /haʊs/ in English represents would be /’ka.sa/ (*casa*) in Spanish. Associations are created at multiple levels. In some languages, we need to learn that if a noun is plural, the determiner coming before should also be plural. Hence, if in languages like Spanish a listener hears *los* (“themasc-sg”) they will expect the following noun to have masculine and plural suffixes, such as “niños” (childrenmasc). These associations facilitate language processing, because the hearer anticipates the outcome (masculine plural suffixes in the noun) based on available information (masculine plural determiner, e.g., Federmeier, 2007; Wicha, Bates, Moreno, & Kutas, 2003). The listener, therefore, does not need to pay close attention to all information coming in and can make up for the information that is lost due to external reasons, such as noise.

There are two types of models that account for how learners create associations. One type is domain-general learning. Another type is domain-specific learning. These two types of models make opposite predictions as to how associations are created and how abilities in other cognitive domains influence acquisition of skills during learning. The goal of this paper is to study transfer of anticipatory skills from the visuospatial domain to speech to acquire and process associations of lexical stress-verb tense suffix for speech. This mapping is difficult to acquire, and even proficient L2 speakers have issues in using it for easier processing (Sagarra & Casillas, 2018), and the relationship between speech and the visuospatial domain has not been extensively researched outside of populations with dyslexia. In addition, this paper seeks to explore how domain-general mechanisms mediate transfer of domain-specific skills. Thus, this paper will inform models of cognition and learning about how processing mechanisms in typical individuals can be shared by cognitive domains in different modalities (visual vs auditory).

# 2. Background

Language anticipation is essential for language processing (e.g., Federmeier, 2007; Wicha et al., 2003). Ability to process sounds, words, grammatical structures correctly results in better comprehension. While monolingual speakers generate predictions constantly (e.g., Huettig & Janse, 2016; Söderström, Horne & Roll, 2017), it requires time to acquire an L2 and develop the ability to generate predictions in that L2 (e.g., Lew-Williams & Fernald, 2010; Sagarra & Casillas, 2018). Two types of models have been proposed with mechanisms that account for acquisition and learning of a (second) language. Models that prioritize domain-general learning mechanisms posit that different brain domains are connected to each other, such that the acquisition of a skill in one of them may influence learning of unrelated skills. This influence, or transfer, takes place because and to the extent that the skills depend on domains that share common features (Thorndike, 1901) and cognitive elements (Anderson, 1990), in the form of perceptual and conceptual information (Singley & Anderson, 1989). In learning settings, transfer that occurs between two closely related domains is called near-transfer, like between calculus and arithmetic; when transfer occurs between distant domains, it is far-transfer, like between math and geography (Mestre, 2006). In models in which domain-specific learning mechanisms are more relevant, brain domains are independent and unrelated to each other. The more developed a skill is, the more domain-specific the features will be, reducing the likelihood of transfer (Ericsson & Charness, 1994; Gobet, 2015). In consequence, improvement of skills in a brain domain will have little to no influence in other domains. While domain-general and domain-specific learning models focus on different mechanisms, learning of a language is likely to be determined by both types of mechanisms. The question is, where the transition lies.

Most research has traditionally focus on language-specific mechanisms. However, some scholars have recently started to highlight the need for a more holistic view of language in research (Ellis, 2019; Ryskin, Levy, & Fedorenko, 2020). For these scholars, language learning investigation should include the usages, the contents, the participants, and the contexts (Ellis, 2019). When we consider the participants, we are not only considering social factors such as socioeconomic status or when they started to learn a new language. We should also consider the characteristics of that individual that extend beyond language, the cognitive capacities and the cognitive abilities.

Some cognitive investigations have included executive control as factors for language acquisition and processing, in the form of attention (Darcy, Mora, & Daidone, 2014), inhibitory control (Giezen, Blumenfeld, Shook, Marian, & Emmorey, 2015; Mercier, Pivneva, & Titone, 2014), and especially, working memory (e.g., Huettig & Janse, 2015; Linck & Weiss, 2015; Smith-Spark & Fisk, 2007). Enhancement of these domain-general mechanisms has been researched through training of domain-specific skills (e.g., chess, music, for reviews, see Gobet, 2017; Simons, 2016; Strobach, 2016). The idea behind this training is that training domain-specific skills may result in positive far-transfer to domain-general mechanisms, such as working memory (Taatgen, 2016). An issue that arises is whether transfer could be even farther-reaching, such that enhancement of domain-general mechanisms through domain-specific skills in turn affects specific skills to other domains, or even, whether domain-specific skills can affect directly specific skills in other domains, withouth necessarily having domain-general mechanisms as a transition.

Apart from the executive control, each speaker is born with varying capacities for processing information. Crucially, individual differences manifest in auditory processing of speech (Zheng, Saito & Tierney, forthcoming). Individual differences condition the strength of the connection between auditory and speech motor cortices (Assaneo, Rimmele, Perl, & Poeppel, 2020) and a speaker’s ability to perceive lexical stress in an L2 (Dupoux, Sebastián-Gallés, Navarrete, & Peperkamp, 2008). One source of individual differences may be that some people are innately more gifted in a domain, for example sounds, while others in a different one, for instance visuospatial organization. If there is transfer of domain-specific mechanisms, speakers may be aided or hindered by better or worse innate abilities in other domains that may affect language, even if they have not had a chance to develop higher skills through expertise in the source domains.

The influence of innate cognitive abilities in specific domains other than language on second language acquisition has not been a primary research focus. And yet, language interacts with other domains on a regular basis. One of these domains is the visuospatial domain. Language interacts with the visuospatial domain to create and update our representation of space and the way we refer to it. Languages can talk about space in egocentric or in geocentric terms (Levinson, 1997), affecting our spatial reasoning (Levinson, Kita, Haun, & Rasch, 2002). Depending on whether a language allows a speaker to create phrases like “to the left of the tree” or “north of the tree,” a speaker will conceptualize space differently. This organization of space in a language results in linguistic and non-linguistic spatial representations relying on a common axis-structure, at least in English (Crawford, Regier, & Huttenlocher, 2000; Huttenlocher, Hedges, & Duncan, 1991). Speakers use these representations to gauge space and distance in relation to themselves, other speakers and other referents to use spatial deixis and to make other spatial references. In addition to space cognition being influenced by the language we speak, speaking several languages that code space differently affect categorical perception of space, which makes bilinguals speakers’ space categories more flexible across languages than monolingual speakers’ are (Holmes, Moty, & Regier, 2017).

Studies on reading abilities and on atypical populations also suggest that these two domains may be closely interconnected in processing of language and of visuospatial information. Studies on reading in children demonstrate that visuospatial skills are a reliable indicator of reading abilities in the L1 at the initial stages of reading development (Helland & Morken, 2016), and reading skills are a predictor of visuospatial abilities in the next literacy level (Lin, Sun, & Zhang, 2016). Studies on reading in adults indicate that visuospatial interference in language is larger in deep languages, that is, languages where a letter or string of letters may correspond to more than one sound, like in English, than it is in shallow languages, like Italian or Spanish (Estes & Barsalou, 2018)

Atypical populations that have been researched in regard to the language-vision/space association are populations with Williams Syndrome, with autism, with dyslexia, and blind individuals. Individuals with Williams Syndrome have issues comprehending visuospatial language and locating objects, especially in the horizontal axis (Landau & Hoffman, 2005; Phillips, Jarrold, Baddeley, Grant, & Karmiloff-Smith, 2004). Individuals with autism show a smaller repertoire of spatial terms in comparison to non-autistic controls (Bochynska, Vulchanova, Vulchanov, & Landau, 2020). A large body of literature has produced controversial results about developmental dyslexia, where children with dyslexia have better (e.g., Swanson, 1984; von Károlyi & Winner, 2004), worse (e.g., Benton, 1984; Winner et al., 2001) and similar visuospatial abilities as control age-matched children (e.g., Siegel and Ryan, 1989; Sinatra, 1988; Winner et al., 2001). A meta-analysis of the findings about dyslexia reveals that dyslexic population samples yield lower means of performance in visuospatial tasks, although within-group variability is higher than in control groups (Chamberlain, Brunswick, Siev, & McManus, 2018). As they grow up, individuals with dyslexia tend to perform similarly to typical individuals in many visuospatial tasks (Von Károlyi & Winner, 2004). Finally, research on blind individuals has shown that traditionally visual brain regions are recruited during verbal tasks such as Braille reading (e.g., Kupers et al., 2007; Uhl, Franzen, Lindinger, Lang, & Deecke, 1991), verb generation in response to nouns (e.g., Amedi, Raz, Pianka, Malach, & Zohary, 2003; Burton, Snyder, Diamond, & Raichle, 2002) and sentence comprehension (e.g., Bedny, Pascual-Leone, Dodell-Feder, Fedorenko, & Saxe, 2011; Röder, Rösler, & Neville, 2000), although only when the individual was already blind as a child (Bedny, Pascual-Leone, Dravida, & Saxe,2012).

In sum, there is enough evidence to believe that far-transfer of abilities from the visuospatial domain to language is possible. Much of the research so far on the association between the two domains has been done with static tasks or with tasks that do not measure processing, but offline outcomes. In this study, we adopted another approach. We aimed to examine transfer from the visuospatial domain to language in real time processing of speech in the L1 and the L2, and if and how domain-general mechanisms regulate the transfer. Specifically, we asked whether visuospatial anticipation abilities would transfer for L1 and L2 anticipation based on lexical stress-verb tense suffix associations at intermediate and advanced levels of proficiency, and if there was transfer, whether it was mediated by verbal and visuospatial WM memory. We analyzed transfer at different levels of proficiency because transfer of linguistic skills across languages may vary along with command (Bel, Sagarra, Comı́nguez, & Garcı́a-Alcaraz, 2016; PRIMER EXP; Hopp, 2017), and anticipation abilities in speech using stress-suffix associations also improve over time [Sagarra and Casillas (2018); PRIMER EXP]. Hence it is possible, that transfer of anticipation skills also varies depending on the proficiency of the speaker.

To measure visuospatial prediction abilities, we implemented a task in which stimuli moved and participants guessed the timing of the trajectory. To measure real time processing of speech, we collected data from English and Mandarin learners of L2 Spanish at different levels of proficiency and from an L1 Spanish group using eye-tracking. Eye-tracking has been widely used as a tool to collect data about processing and language anticipation (e.g., Altmann & Kamide, 1999; Kamide, Altmann, & Haywood, 2003; Sagarra & Casillas, 2018). The tenses to be anticipated were the present and preterit tenses in Spanish. To measure verbal and visuospatial WM, we used the operation span task and the Corsi-block tapping test, respectively. In the operation span task, participants need to remember words while being distracted by mathematical additions and subtractions. In the Corsi test, participants need to remember sequences of flashing squares.

Previous studies revealed that L1 Spanish speakers, Mandarin and English advanced learners of Spanish and intermediate English speakers can generate predictions for tense using lexical stress in CVC syllables, especially when immersed in the L2 (**???** EXP), these groups were therefore hypothesized to have no issues in this study either. In the L1 Spanish speakers, no relationship was expected between visuospatial anticipation and speech anticipation. Our reasoning was that the two modalities, auditory (speech) and visual, are too different for there to be any transfer, and thus the “potentially transferable” skills would be too specific to each domain (Ericsson & Charness, 1994; Gobet, 2015). Verbal WM was not expected to be associated either (**???** EXP; Sagarra & Casillas, 2018), due to L1 speakers’ practice in generating the predictions overriding WM differences. Visuospatial WM was, for the same reason, not predicted to have any influence. No association between anticipation in the visuospatial domain and the speech domain was hypothesized in L2 speakers either, for the same reasons as in monolingual speakers. Therefore, it would not matter what the L1 or the L2 is, or the proficiency in the L2: increased abilities to anticipate movements in space through vision would not be associated with speech in any way. Following previous findings about the relationship between verbal WM and anticipation abilities, verbal WM was not predicted to be associated with speech anticipation performance in L2 groups (**???** EXP; Sagarra & Casillas, 2018). Were our predictions borne out, they would corroborate that far-transfer between domains is unlikely, especially when they are related to different modalities or perception mechanisms. These findings would thus support a domain-specific learning mechanism where highly specific skills pertain to the domain in which they developed, or at least to domains that are fed through the same perceptual channels.

# 4. Methods

## 4.1. Participants

Participants proceeded from five different pools: 30 monolinguals speakers of Spanish (SS, females = 20), 33 L2 Spanish intermediate with L1 English (IE, females = 24), 32 L2 Spanish advanced with L1 English (AE, females = 24), 32 L2 Spanish intermediate with L1 Mandarin (IM, females = 26), and 32 L2 Spanish advanced with L1 Mandarin (AM, females = 26). All participants grew up in monolingual regions and houses but were living in Spain at data collection. All were aged 18-45 (SS: mean = 26.2, *SD* = 8.82; IE: mean = 26.1, *SD* = 4.21; AE: mean = 27.5, *SD* = 4.83; IM: mean = 24.5, *SD* = 3.95; AM: mean = 24.8, *SD* = 4.37). Participants were all right-handed. All had completed at least high school, and none had received bilingual education. Participants had normal to corrected-to-normal hearing and vision and no motor disability.

The monolingual speakers were native to a Peninsular variety of Spanish and did not speak any other language fluently. The English natives came from English-speaking countries. They spoke no other language apart from English and Spanish. IE had spent in Spain between 3 months and 6 years, AE between 6 months and 14 years. The Mandarin speakers came from Mandarin-speaking regions in China, except for one participant who originated in Taiwan. Some of the Chinese speakers also spoke English, but at a maximum of intermediate proficiency. They had never lived in an English-speaking country. IM had resided in Spain between 6 months to 11 years, and AM for 2 months 16 years.

The L2 speakers were matched for proficiency (advanced groups: *t*(61.69) = -0.0971, *p* = 0.923; intermediate groups: *t*(62.85) = -1.006, *p* = 0.318). They were all late learners of Spanish (start learning Spanish in years IE: mean = 17.5, *SD* = 6.35; AE: mean = 15.1, *SD* = 4.35; IM: mean = 19.9, *SD* = 4.01; AM: mean = 17.9, *SD* = 2.83). On average, all L2 groups used Spanish less than 50% of the time on a normal week (self-reported; in percentages, IE: mean = 28.2, *SD* = 17.3; AE: mean = 38.6, *SD* = 16.2; IM: mean = 36.7, *SD* = 20.7; AM: mean = 46.6, *SD* = 21.8).

## 4.2. Materials

Participants completed two screening tasks, two anticipation tasks and two WM tasks.

### 4.2.1. Screening tasks.

A proficiency test categorized participants into intermediate and advanced. The proficiency test was a shortened version (Sagarra & Herschensohn, 2010) of the *Diploma de Español como Lengua Extranjera* (‘Certificate of Spanish as a Foreign Language’, by Instituto Cervantes). The test consisted of 56 questions: 16 on grammar, 10 on vocabulary, and 20 on reading comprehension. Participants whose scores ranged from 25 to 39 were assigned to the intermediate groups, and participants whose scores were located at or above 40 were assigned to the advanced groups.

Participants also completed a language background questionnaire. The background questionnaire contained questions related to social, such as age, level of studies, sports played and driving skills, and linguistic factors, such as language use percentages and other languages spoken.

### 4.2.2. Anticipation task.

#### 4.2.2.1. Linguistic anticipation task.

An eye-tracking visual-world paradigm task assessed the ability to form stress-suffix predictive associations in speech. Participants read two verbs on a computer screen (*salta* ‘s/he jumps,’ *saltó* ‘s/he jumped’) and heard a sentence containing one of the two verbs (*El ladrón saltó la valla* ‘the thief jumped over the fence’) in Spanish. They had to select the verb they had heard as fast as possible by pressing the right- or left-shift key. When they made their selection, a green rectangle appeared around the selected verb. There were 4 practice sentences, 16 experimental sentences, and 80 fillers.

The eye movements while hearing the sentences were recorded through an EyeLink 1000 Plus desktop mount eye-tracker from SR Research (sampling rate: 1k Hz; spatial resolution was less than .05o; averaged calibration error: .25-.5o). The monitor used to show the target verbs was a BenQ XL2420TE at a resolution of 1920 x 1080 pixels.

*Visual stimuli.* The words that appeared on the screen were presented as images created with PhotoScape X version 3.0.3., set with Helvetica font and the size 300. The size of each image was set at 1920 x 1080 pixels. The background was white and the color of the letters black. The position of the target words on each side of the screen was counterbalanced.

The experimental words were all verbs. There were 16 pairs of verbs. Each verb consisted of the same verb conjugated in the present and preterit tenses. The verbs were regular, had two syllables and had a CVC initial syllable. All belonged to the -ar conjugation and were conjugated in the 3rd person present and preterit tense. Spanish regular verbs ending in -ar have 2 cues to tense: initial syllable stress and word ending morphology. Stressed initial syllables indicate that the tense is present (*salta* ‘s/he jumps’), and unstressed initial syllables indicate that the tense is past (preterit, *saltó* ‘s/he jumped’). The verb suffix indicates tense, person and aspect.

There were three types of filler words. The first type were nouns in anaphora ambiguities (*papel* ‘sheet of paper’ vs. *plano* ‘map’). The second type were adjectives for gender agreement (*nuevo* ‘newmasc’ vs. *nueva* ‘newfem’). The third type was a variety of nouns and adjectives that completed idiomatic expressions.

*Auditory stimuli.* Each verb pair was embedded in the same sentence where the only difference between tense conditions was the conjugated verb. Since each of the 16 verbs was could be conjugated in the present or preterit tense, there were 32 sentences total. The sentences were distributed into blocks by means of a Latin square design. There were 8 blocks. Each block contained only two experimental sentences: one sentence of each condition, and 6 filler sentences, two of each type. The blocks appeared in a randomized order. Within and across the blocks, the sentences were pseudo-randomized to avoid two experimental sentences of the same condition appearing one after the other.

The experimental sentences (*El ladrón saltó la valla* ‘The thief jumped over the fence’) had all identical syntactic structure and length: 5 words. The verb was only preceded by an NP (the subject) to avoid possible biases towards the present or the preterit verb. The object following the verb was also a NP. A given participant was only exposed to one of the two conditions for a given verb pair (e.g., for sentence number 6, participant Y was only exposed to condition 1, and for sentence 7 to condition 2). In total, each participant was exposed to 16 experimental sentences (half with present verbs and half with preterit verbs).

There were three types of filler sentences: anaphora ambiguity (*Mientras el secretario interrumpe al arquitecto, está guardando un papel en el armario* ‘While the clerk interrupts the architect, he is putting a sheet of paper away in the cabinet’), gender agreement of adjectives based on determiner and noun (*Dice que su colegio nuevo cuesta mucho dinero* ‘He says that his new school is very costly’), and idiomatic expressions (*La niña no cambia por nada del mundo su muñeca* ‘The little girl does not change her doll for anything in the world’). There were four practice sentences, one of each type of sentence.

#### 4.2.2.2. Visuospatial anticipation task.

An adapted version of the ZBA task (*Zeit- und Bewegungsantizipation* “Time and Movement Anticipation,” Schuhfried Wiener Testsystem, 2013) was used to measure visual-spatial predictive associations. A car on the screen moved from left to right or right to left at three different speeds: low (3.342 cm/s), medium (5.160 cm/s), and fast (7.087 cm/s). The car then disappeared behind a mountain. The participants had to calculate according to the size of the mountain and the speed of the car when the car should reappear from the other side of the mountain, marked with a checkered flag. When they thought the car should reappear, participants were to press a key. The trial ended automatically at key press, and the following trial started.

There were 8 trials for each speed and direction, therefore 48 experimental trials. There were four additional trials serving as practice. The speed in those trials was set at either 4 cm/s or 6 cm/s. The car would move in an opposite direction in each of the two trials for each speed. The task was administered in PsychoPy v3.2.

### 4.2.3. Working memory tasks.

#### 4.2.3.1. Verbal WM task.

An adapted version of Unsworth et al.’s (2005) Operation Span task (henceforth, OSpan) was used to assess verbal WM span. This task generates independent measures of storage and processing speed. In a single trial, participants heard a word followed by a simple mathematical problem that could be either true or false (e.g., 2 + 2 = 4). For the mathematical problems, they had to decide as fast as possible whether what they heard was true or false by pressing the left- or right-shift key. When they made their selection, their choice on the screen turned blue. This process would repeat a certain number of times until a set was complete. At the end of each set, participants were prompted to write down the individual words they had heard before each problem in the same order they had heard them. The whole task was administered in the participant’s L1.

There were two practice trials of 3 words and mathematical problems, and three experimental sets of three, four, five and six words and mathematical problems. The words and mathematical problems that participants heard in the sets appeared in a fixed order across participants. The words TRUE and FALSE that participants needed to select in response to the mathematical problems appeared counterbalanced on each side across participants. No feedback was ever provided. The task was administered in PsychoPy v3.2.

### 4.2.3.2. Visuospatial WM task.

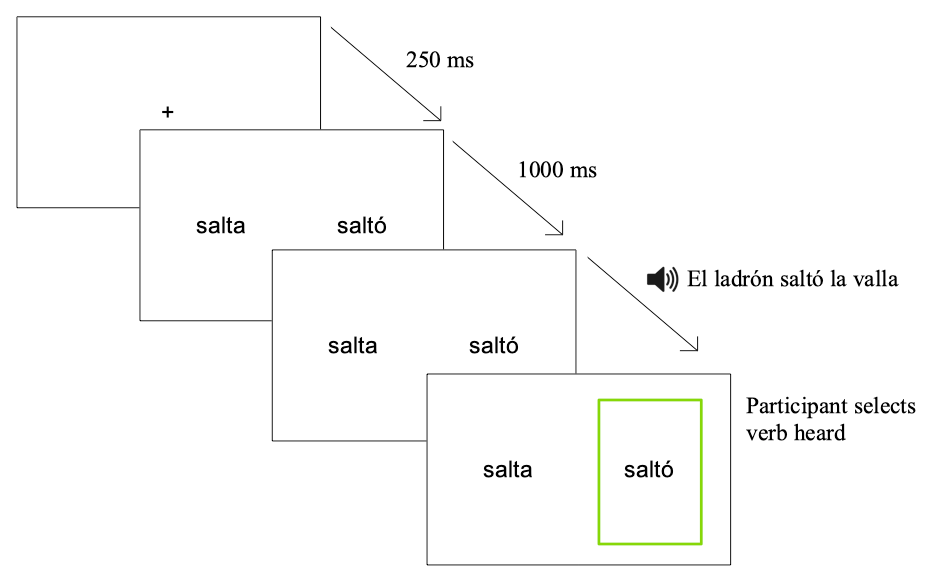
An adapted version of (Milner, 1971)’s Corsi-blocks tapping test served to assess visuospatial WM. In each trial, participants saw a grid of 4 x 4 empty squares on a white background. Some of the squares would flash red for 1 s. and then turn white again one by one. Participants had to recreate the sequence of flashed squares. There were no time constraints. There were two practice sequences, and 21 sequences split into sets of three. The first set started with sequences of 3 squares. Then, a new set of three sequences one square longer started. The longer trials had sequences of 9 squares. The sequences were random. No feedback was provided. The task was administered in PsychoPy v3.2.

## 4.3. Procedure

Data collection took place in a single session of about 1 hour and 30 minutes. All interaction between researcher and participants happened in Spanish. Participants completed the tasks in this order: Spanish proficiency test (only L2 learners; 15-20 minutes), language background questionnaire (10 minutes), linguistic anticipation task (25 minutes), visuospatial anticipation task (10 minutes), Corsi-blocks task (10 minutes), and OSpan (15 minutes). First, participants listened to an overview of the tasks and signed the consent form. Participants provided oral responses for the language background questionnaire. They completed the remaining tasks in a computer, using a 24" computer monitor and Sol Republic 1601-32 headphones. In all tasks, the instructions were given both orally and in written. The oral instructions were in Spanish; the written instructions were in the participant’s L1.

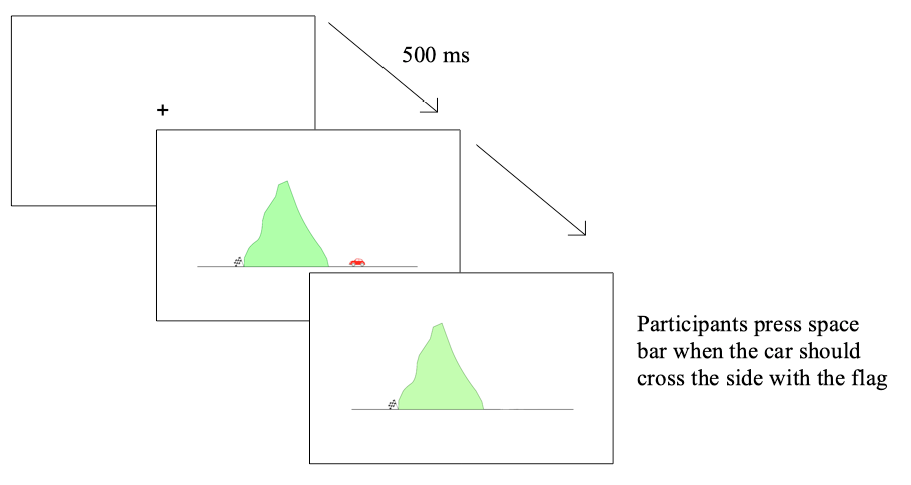
*Linguistic anticipation task*. For the visual-world paradigm, participants rested their head on a chin rest, and completed an 11-point grid calibration task. They could ask questions after the practice trials. Both the practice and the experimental trials followed the same order. See Figure 1 for an example of an experimental trial. First, a fixation sign appeared in the middle of the screen for 250 ms.

This allowed the researcher to recalibrate manually when necessary. Then, two words appeared on the screen side to side. Once the words had been on the screen for 1000 ms, the sentence started playing. A green rectangle appeared on the screen around the word participants had selected. The sentence did not stop when participants selected the word they heard. Response recording was set up to be registered only when the press happened after the start of the verb in the sentence; previous presses were not recorded. The setting therefore forced participants to press again if they pressed to soon. No feedback was provided.



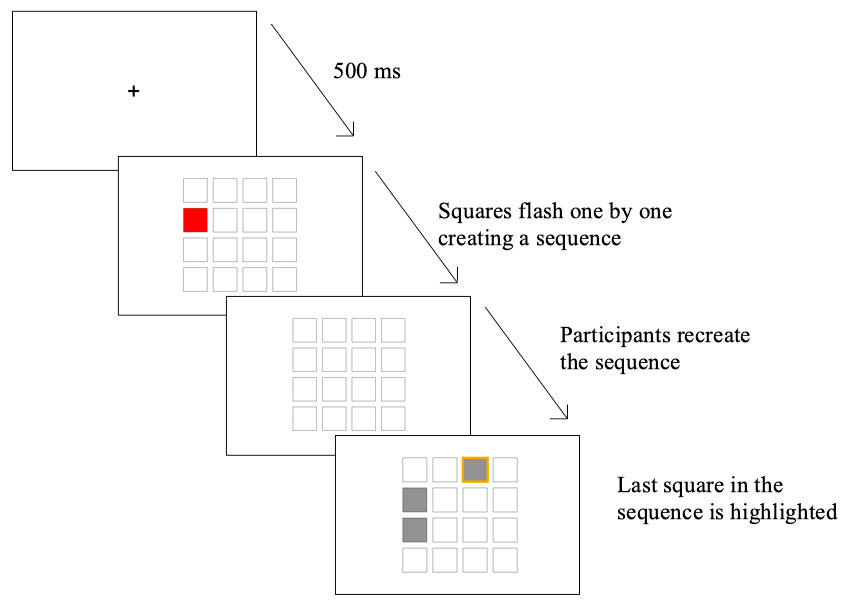
*Figure* *1*. Sample trial of the visual-world paradigm.

*Visuospatial anticipation task*. In the first two practice trials, participants saw the car’s position as feedback upon pressing the spacebar, to learn if they had calculated the reappearance moment correctly; in the last two practice trials, they did not receive any feedback, just like in the experimental trials. In the experimental trials, the trial would automatically finish upon the space bar press. There was a fixation cross for 250 ms between trials. Figure 4 shows a trial of the task.



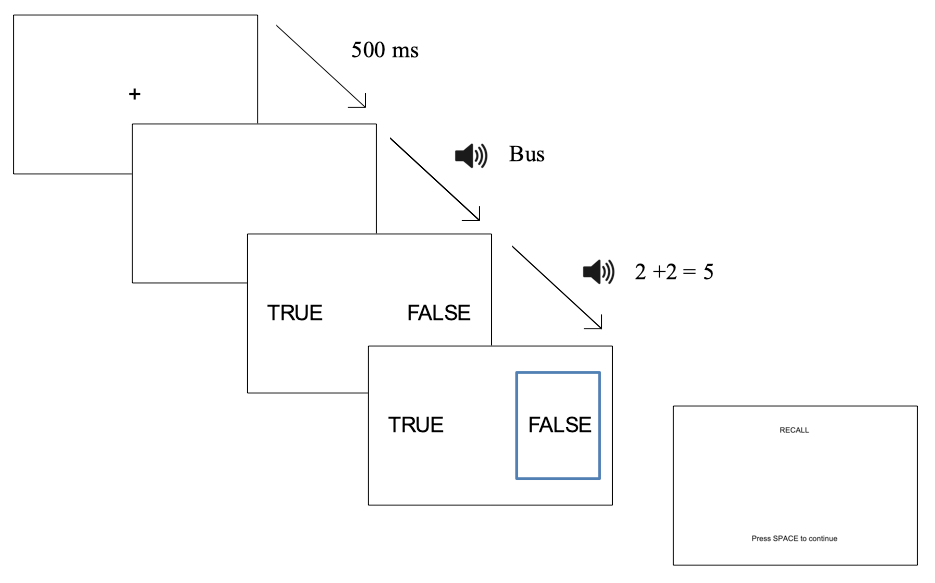
*Figure* *2*. Sample trial of the visuospatial anticipation task

*Visuospatial WM task*. The Corsi-blocks task consisted of recreation of flashing square sequences previously seen. In this task participants completed 2 practice sets, and then the experimental section began. Once they had clicked the same number of squares as in the original sequence, a fixation cross appeared for 500 ms in the center of the screen, and then the next sequence started (see Figure 5 for a sample trial).



*Figure* *3*. Sample trial of the Corsi-blocks tapping task

*Verbal WM task*. The OSpan task was divided into practice and experimental trials. For each trial, participants first heard a word in their L1 and then heard a simple equation, like 2+2=5, also in their L1. During the mathematical problems, participants saw the words TRUE or FALSE on each side of the screen, and they had to press the corresponding key (left-shift key for the word on the left, right-shift key for the word on the right) depending on whether the equation was correct or not. After each equation, they saw a fixation point for 500 ms and another pair of word-equation was presented. This process was repeated until the word RECALL or a linguistic equivalent in the L1 of the participant was shown on the screen, at which moment participants had to write on paper the words they had heard in the order they were presented. Chinese speakers were allowed to write their answers in pinyin. If homophones were written, they were considered correct (e.g., Adam for atom). Figure 6 shows a sample trial.



*Figure* *4*. Sample trial of the OSpan

## 4.4. Data analysis

Statistical analyses were conducted on R (Team & others, 2013). Given that speakers of different languages have different average spans, verbal WM variance was used as homogeneity measure (*K2*(2) = 6.376e-15, p = 1). Verbal WM was calculated as the z-score of number of sets that participants got completely right (all words in correct order).

Once we made sure groups were comparable, we calculated Corsi scores and visuospatial anticipation measures. The Corsi score was compounded by z-score conversion of the number of sequences recreated exactly. In the visuospatial anticipation task, key presses were stored taken as referent 0 the ms in which the car was meant to reappear from behind the mountain. Key press timings could thus be negative if they happened before, or positive if they happened afterwards. Trials where the participant took too long to respond and the car should have “left” the screen were discarded. Visuospatial anticipation was calculated as the random effects in a model that estimated key-press time as a function of speed and direction.

Then we prepared the linguistic anticipation data. Participants’ key presses were considered accurate if they pressed the key corresponding to the verb in the sentence. Only the sentences with accurate responses were included in the statistical analyses. In the statistical analyses, proportion and count of fixations on the verbs over time in the sentence were analyzed. From the eye-tracking data, we analyzed fixations on the target and on the distractor (Barr, 2008). These data were downsampled to 50 ms bin and converted through an empirical logit transformation. The moment of interest was offset of the first syllable of the verb, henceforth target syllable, right after the cue appears but the outcome is not available yet. We filtered the time window to be from 200 ms before and 600 ms after target syllable offset. The gaze-fixation data was shifted 200 ms to account for the time it takes to plan and launch a saccade (e.g., Fischer, 1992; Saslow, 1967).

After cleaning all the data, a growth curve analysis (GCA, Mirman, 2016) was fit using the package *lme4* (Bates, Mächler, Bolker, & Walker, 2014). GCA was implemented to observe effects over time, as linguistic information becomes available. Group, lexical stress condition (sum-coded present and preterit), visuospatial WM, and visuospatial anticipation were fixed effects. The time terms included were linear, quadratic and cubic orthogonal polynomials. Logit fixations were the outcome. By-subject and by-item random intercepts and slopes were included to account for the different familiarity of each subject with each of the verbs in both tenses. Main effects and interactions were tested by means of nested model comparisons.

SS and present tense were the baseline. Pairwise comparisons using the package *multcomp* (Hothorn et al., 2016) contrasted the data between the L2 groups in terms of L1 and in terms of proficiency.

# 5. Results

The full model summary is available in Appendices A (fixed effects) and B (random effects). Pairwise comparisons are available in Appendices C-F. Probabilities are included as Appendix G. Only the linear term was kept for the multiple-factor interactions. The estimated probabilities indicate that all groups except IM were above chance in fixating their gaze on the target word at offset of target syllable but before onset of suffix. IM was mostly at chance level. We take the fixations above chance as an indication of suffix prediction based on lexically stressed and unstressed initial syllables. We can therefore consider main effects, interaction effects and pairwise comparisons.

There was a main effect at the intercept (*γ*00 = 1.784, SE = 0.177, *t* = 10.096, *p* = < .001), which suggests the SS were fixating on the target comparably more to on the distractor or elsewhere in both conditions at target syllable offset. There was a main effect of the linear (*γ*01 = 5.751, SE = 0.506, *t* = 11.356, *p* = < .001) and cubic time terms too (*γ*21 = −1.219, SE = 0.181, *t* = −6.733, *p* = < .001). The effect on the linear term indicates that the slope for the L2 speakers is steeper, meaning they tend to increase their gaze fixations on the target faster than SS once they know what they are going to hear. The effect on the cubic term indicates that the curves are more bowed in the L2 groups, and that the inflection points form an inverse N shape. There was also a main effect of each group (AE: *γ*31 = −0.770, SE = 0.204, *t* = −3.784, *p* = < .001; AM: *γ*02 = −0.666, SE = 0.203, *t* = −3.273, *p* = .001; IE: *γ*12 = −0.815, SE = 0.202, *t* = −4.045, *p* = < .001; IM: *γ*22 = −1.252, SE = 0.202, *t* = −6.188, *p* = < .001). The negative trend of these effects suggest that all L2 groups anticipated less than SS across conditions.

Chart

Description automatically generated

*Figure* *5*. Growth curve estimates of target fixations as a function of visuospatial WM z-score for each group and lexical stress pattern during the analysis window. The higher the score, the better the performance in the visuospatial WM task. Symbols and lines represent model estimates, and the transparent ribbons represents ±SE. Empirical logit values on y-axis correspond to proportions of 0.12, 0.50, 0.88, and 0.98. The horizontal dotted line represents the 50% probability of fixating on the target. The vertical dotted line indicates 200 ms after the offset of the target syllable.

The model also estimated interactions. The first significant interaction is of stress in the quadratic term (*γ*33 = 0.308, SE = 0.121, *t* = 2.557, *p* = .011). This estimate points that the number of fixations on the target verb in the preterit conditions was higher than in the present tense. The increased number of fixations thus suggests preterit was slightly easier to anticipate. There was an effect on the interaction between visuospatial WM and the cubic term (*γ*25 = −0.215, SE = 0.109, *t* = −1.976, *p* = .048). This estimate indicates the curves in the cubic term were more bowed in the present tense than in the preterit tense.

Chart

Description automatically generated

*Figure* *6*. Growth curve estimates of target fixations as a function of visuospatial anticipatory abilities for each group and lexical stress pattern during the analysis window. Symbols and lines represent model estimates, and the transparent ribbons represents ±SE. Empirical logit values on y-axis correspond to proportions of 0.12, 0.50, 0.88, and 0.98. The horizontal dotted line represents the 50% probability of fixating on the target. The vertical dotted line indicates 200 ms after the offset of the target syllable. 0 for movement anticipation corresponds to the ms when the car reappears. Negative values in the legend indicate earlier key presses. Positive, later key presses.

Simple interactions with the linear, quadratic and cubic time terms and multiple interactions at the linear time term were kept because they improved the model (*β*(4) = 14.4533, *p* = .006). There was an interaction between AE and the linear (*γ*35 = 1.491, SE = 0.582, *t* = 2.563, *p* = .010) and quadratic time terms (*γ*36 = 2.309, SE = 0.471, *t* = 4.898, *p* = < .001). The linear interaction suggests the fit slope was steeper for AE, as they tend to increase their gaze on the target faster than the other groups. The quadratic interaction means the curve in AE is more closed than the one for SS. Therefore, AE appear to be anticipating later than SS. There is also an interaction with the quadratic term in the other L2 groups (AM: *γ*00 = 2.208, SE = 0.471, *t* = 4.683, *p* = < .001; IE: *γ*10 = 2.252, SE = 0.467, *t* = 4.825, *p* = < .001; IM: *γ*20 = 2.039, SE = 0.469, *t* = 4.351, *p* = < .001). As in the interaction with AE, these effects reflect a more bowed curved for all L2 groups, who start anticipating later than SS.

Lastly, there were two multiple interactions. There first one is between stress x corsi x quadratic term (*γ*02 = 0.397, SE = 0.082, *t* = 4.860, *p* = < .001). This interaction suggests that visuospatial WM influenced differently the ability to anticipate depending on the tense condition, as can be seen in Figure 5. Specifically, variability in visuospatial WM capacity determined more strongly ability to anticipate the preterit, such that individuals with higher WM started to anticipate earlier. In the present tense, in contrast, visuospatial WM did not exert such a great impact. The second multiple interaction is between visuospatial anticipation x visuospatial WM x cubic time term (*γ*03 = −1.045, SE = 0.469, *t* = −2.228, *p* = .026). This interaction suggests that individuals with higher visuospatial WM were those who also tended to wait longer to signal the car in the visuospatial anticipation task would appear, and these individuals tended to anticipate better. This effect was plotted in Figure 6.

Pairwise comparisons for proficiency and L1 provided more insights. Within the English speakers’ groups, there was an interaction effect between stress x visuospatial anticipation x visuospatial WM in the linear time term (*γ*19 = −2.667, SE = 1.198, *t* = −2.225, *p* = .026). This interaction indicates that the slope for IE in the present tense was steeper, while for AE was steeper in the preterit tense. Moreover, the higher the visuospatial WM and the better the visuospatial anticipation score, the faster participants focused on the predicted target in the preterit tense. For Mandarin speakers, those at the intermediate level anticipated less than those at the advanced level (*γ*08 = −0.586, SE = 0.181, *t* = −3.244, *p* = .001). In addition, Mandarin speakers with better visuospatial prediction and WM scores increased fixations on the target faster in the preterit tense. This effect is particularly clear for AM, although IM also shows a trend, such that anticipation performance was significantly faster in the advanced group when compared to the intermediate one. Across L1s, the slope for AE was steeper than the slope of AM (*γ*18 = −1.117, SE = 0.522, *t* = −2.141, *p* = .032). This effect indicates AM increased their fixations on the target slower than AE once they started predicting. Also in the linear time term, there was an interaction between stress x visuospatial anticipation abilities x visuospatial WM (*γ*19 = 2.491, SE = 0.879, *t* = 2.836, *p* = .005). This result stems from participants in both groups diverting their gaze more rapidly to the target in the preterit tense, especially AM, when their visuospatial WM score was higher and they anticipated the reappearance of the car closer to the specific ms but tended to wait longer. Estimates for all participants in each group are the same in the present tense regardless of their visuospatial abilities. At intermediate proficiency, there was an effect at the intercept (*γ*08 = −0.048, SE = 0.509, *t* = −0.095, *p* = .924), such that IM anticipated slower than IE. Finally, there was an effect of stress x visuospatial anticipation abilities x visuospatial WM in the linear term (*γ*19 = 2.491, SE = 0.879, *t* = 2.836, *p* = .005). Participants in both groups with higher visuospatial WM and who were closer to anticipating the reappearance of the car but tended to wait longer increased fixations on the target more quickly in the preterit tense, although in the Mandarin group this pattern is not as stable and still predict more slowly. In the present tense there was no variability depending on visuospatial abilities.

Figure 1 plots the model estimates from the GCA and We report the results for the M group and then provide comparisons with and between the learner groups. The model intercept estimates the log odds of M fixating on the target, averaging over the time course and lexical stress. The log odds were *γ*00 = 1.78 (proportion: .86). The linear, quadratic, and cubic polynomial time terms captured the sigmoid shape of the time course and were retained in the model (γ10 = −0.00; SE = 0.08; *t* = −0.00; *p* = .996; γ20 = 0.10; SE = 0.24; *t* = 0.40; *p* = .691; γ30 = 0.07; SE = 0.06; *t* = 1.18; *p* = .238).

# 6. Discussion

We set out to examine transfer effects from the visuospatial domain to language in terms of anticipation skills. Monolingual Spanish speakers and Mandarin and English learners of Spanish completed a linguistic and a visuospatial linguistic task and a visuospatial WM task. The results show that visuospatial WM influences anticipation abilities by tense, and it also interacts with visuospatial anticipation abilities in determining linguistic anticipation abilities. These results suggest that executive control skills may be transferring to domain-specific tasks in both the visuospatial and linguistic domains.

The model indicates that all speakers except for IM were anticipating. We can therefore proceed to discuss how visuospatial skills may be affecting anticipation in SS, both advanced groups and IE. Differences in visuospatial skills did not manifest across L1s. The lack of interaction of visuospatial skills with any group suggests that whichever interaction there may be takes place with the language capacity in general, regardless of the specific L1 or L2 of the speaker.

The effect of visuospatial WM in the cubic term and the interaction in stress in the quadratic term suggest that visuospatial WM mediates linguistic anticipation. The mediation is particularly strong in the preterit tense, where variability dependent on visuospatial WM was higher. The relationship found in the preterit tense is a positive one, where higher visuospatial WM score is associated with earlier and more certain prediction. In the present tense, however, individuals with higher working memory started anticipating later, although they were also more certain once they started predicting. This difference may stem from an uncertainty as to whether stress is being used as a lexical contrast or with an intonational or pragmatic use. If this hypothesis were true, a stressed syllable may cause uncertainty because it might be signaling, for instance, that the word containing is emphasized for pragmatic purposes. A listener would compare the stress heard with the associations of stress in their mind, and more information about this stress is needed to disambiguate and to discard unapplicable associations.

Visuospatial WM interacted with visuospatial anticipation skills in the cubic term. The patterns for the relationship between visuospatial anticipation and linguistic anticipation were not as clear cut. The lack of a pattern suggests that anticipation abilities in each domain may not have been connected to each other, but they might be due to visuospatial WM. In this case, transfer would not happen between specific domains, but between the general domain onto specific ones.

There was an interaction proficiency, stress, and visuospatial WM and anticipation skills in the linear term. In all groups, higher visuospatial WM was associated with earlier prediction of the preterit tense. If our hypothesis that there was only transfer from domain-general to domain-specific mechanism is true, the interaction with visuospatial anticipation is just a consequence of the transfer to other domains, not necessarily a result of an interaction between the two specific domains. Again, this hypothesis is supported by the lack of a clear direction in the association between visuospatial and linguistic prediction.

The reasoning that speakers were transferring domain-general mechanisms to domain-specific tasks but not skills across specific domains support domain-specific learning models but does not support domain-general learning mechanisms. In domain-specific learning models, brain domains are independent and unrelated to each other. Each domain can develop skills that become increasingly specific, reducing the possibility that transfer takes place (Ericsson & Charness, 1994; Gobet, 2015). The lack of an effect of visuospatial anticipation skills along with the lack of a pattern in the relationship when visuospatial WM is included between anticipation skills further demonstrates that the effect obeys an association simply through the general mechanisms, but not direct associations between specific domains.

In domain-general models, transfer takes place because the domain-specific domains depend on common features (E. L. Thorndike, 1901) or because they share perceptual and conceptual information (Singley & Anderson, 1989). Visuospatial anticipation and speech anticipation do not share any of those. A possible venue where language and vision/space may be more related is in reading, as both types of information would be perceived visually. Future investigations may want to exploit that venue.

In conclusion, the results in this study confirm that transfer is only possible when the specific domains share perceptual and conceptual information (Singley & Anderson, 1989) or, maybe, when they rely on the same physiological structures. These results go against previous findings in atypical populations indicating the existence of a relationship between language and visuospatial abilities (Chamberlain et al., 2018). The association found in previous studies may be due to differences in domain-general mechanisms that underlie domain-specific tasks, or to processing deficits (Laing & Jarrold, 2007) that would extend to other semantic fields as well as the visuospatial one.

# 7. Conclusion

In this study we asked whether there would be transfer from the visuospatial domain to speech to facilitate prediction of suffixes associated to lexical stress cues in L1 and L2 English and Mandarin speakers of Spanish. The results demonstrate that the possibility of direct transfer is dim. Instead, transfer from domain-general abilities is plausible. Visuospatial WM was associated with linguistic prediction abilities in monolinguals, advanced speakers, and in English intermediate speakers. These results support domain-specific learning models in terms of unlikelihood of transfer of domain-specific skills. The results do support, nonetheless, transfer of domain-general mechanisms that may underpin processing performance in various specific domains. These results highlight the need to enhance domain-general skills to facilitate language processing.

# Appendix A

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Estimate | SE | *t* | *p* |
| Intercept (γ00) | 1.784 | 0.177 | 10.096 | < .001 |
| stress\_sum (γ10) | −0.000 | 0.076 | −0.004 | .996 |
| car\_dev (γ20) | 0.098 | 0.245 | 0.398 | .691 |
| corsi (γ30) | 0.072 | 0.061 | 1.179 | .238 |
| Time1 (γ01) | 5.751 | 0.506 | 11.356 | < .001 |
| Time2 (γ11) | −0.733 | 0.382 | −1.916 | .055 |
| Time3 (γ21) | −1.219 | 0.181 | −6.733 | < .001 |
| GroupAE (γ31) | −0.770 | 0.204 | −3.784 | < .001 |
| GroupAM (γ02) | −0.666 | 0.203 | −3.273 | .001 |
| GroupIE (γ12) | −0.815 | 0.202 | −4.045 | < .001 |
| GroupIM (γ22) | −1.252 | 0.202 | −6.188 | < .001 |
| stress\_sum × car\_dev (γ32) | −0.177 | 0.182 | −0.976 | .329 |
| stress\_sum × corsi (γ03) | −0.052 | 0.046 | −1.122 | .262 |
| car\_dev × corsi (γ13) | 0.050 | 0.266 | 0.188 | .851 |
| stress\_sum × Time1 (γ23) | −0.195 | 0.185 | −1.052 | .293 |
| stress\_sum × Time2 (γ33) | 0.308 | 0.121 | 2.557 | .011 |
| stress\_sum × Time3 (γ04) | −0.027 | 0.146 | −0.185 | .854 |
| car\_dev × Time1 (γ14) | 0.918 | 0.827 | 1.109 | .267 |
| car\_dev × Time2 (γ24) | −0.500 | 0.565 | −0.886 | .376 |
| car\_dev × Time3 (γ34) | −0.099 | 0.437 | −0.226 | .821 |
| corsi × Time1 (γ05) | 0.287 | 0.205 | 1.396 | .163 |
| corsi × Time2 (γ15) | −0.232 | 0.140 | −1.653 | .098 |
| corsi × Time3 (γ25) | −0.215 | 0.109 | −1.976 | .048 |
| Time1 × GroupAE (γ35) | 1.491 | 0.582 | 2.563 | .010 |
| Time1 × GroupAM (γ06) | 0.374 | 0.582 | 0.643 | .520 |
| Time1 × GroupIE (γ16) | 0.751 | 0.576 | 1.303 | .193 |
| Time1 × GroupIM (γ26) | 0.702 | 0.578 | 1.214 | .225 |
| Time2 × GroupAE (γ36) | 2.309 | 0.471 | 4.898 | < .001 |
| Time2 × GroupAM (γ00) | 2.208 | 0.471 | 4.683 | < .001 |
| Time2 × GroupIE (γ10) | 2.252 | 0.467 | 4.825 | < .001 |
| Time2 × GroupIM (γ20) | 2.039 | 0.469 | 4.351 | < .001 |
| stress\_sum × car\_dev:corsi (γ30) | 0.200 | 0.557 | 0.359 | .720 |
| stress\_sum × car\_dev:Time1 (γ01) | −0.354 | 0.328 | −1.077 | .281 |
| stress\_sum × car\_dev:Time2 (γ11) | 0.285 | 0.327 | 0.870 | .384 |
| stress\_sum × car\_dev:Time3 (γ21) | −0.141 | 0.327 | −0.431 | .666 |
| stress\_sum × corsi:Time1 (γ31) | 0.084 | 0.084 | 0.996 | .319 |
| stress\_sum × corsi:Time2 (γ02) | 0.397 | 0.082 | 4.860 | < .001 |
| stress\_sum × corsi:Time3 (γ12) | −0.091 | 0.082 | −1.114 | .265 |
| car\_dev × corsi:Time1 (γ22) | −0.230 | 0.896 | −0.257 | .797 |
| car\_dev × corsi:Time2 (γ32) | 0.635 | 0.614 | 1.035 | .301 |
| car\_dev × corsi:Time3 (γ03) | −1.045 | 0.469 | −2.228 | .026 |
| stress\_sum × car\_dev:corsi:Time1 (γ13) | −1.045 | 1.010 | −1.035 | .301 |
| stress\_sum × car\_dev:corsi:Time2 (γ23) | −0.446 | 0.352 | −1.269 | .204 |
| stress\_sum × car\_dev:corsi:Time3 (γ33) | −0.122 | 0.352 | −0.347 | .729 |
| stress\_sum × car\_dev:corsi:GroupAE (γ04) | −0.090 | 0.662 | −0.136 | .892 |
| stress\_sum × car\_dev:corsi:GroupAM (γ14) | −0.304 | 0.632 | −0.481 | .630 |
| stress\_sum × car\_dev:corsi:GroupIE (γ24) | −0.400 | 0.742 | −0.540 | .590 |
| stress\_sum × car\_dev:corsi:GroupIM (γ34) | 0.367 | 0.813 | 0.451 | .652 |
| stress\_sum × car\_dev:corsi:Time1:GroupAE (γ05) | −0.345 | 1.200 | −0.287 | .774 |
| stress\_sum × car\_dev:corsi:Time1:GroupAM (γ15) | 2.146 | 1.147 | 1.872 | .061 |
| stress\_sum × car\_dev:corsi:Time1:GroupIE (γ25) | 2.554 | 1.348 | 1.895 | .058 |
| stress\_sum × car\_dev:corsi:Time1:GroupIM (γ35) | −0.521 | 1.478 | −0.352 | .725 |

Appendix A. Growth curve model fixed effects.

# Appendix B

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Group | Parameter | Variance | SD | Correlations |  |  |  |  |
| Participant | Intercept | 0.449 | 0.670 | 1.00 |  |  |  |  |
|  | stress\_sum | 0.226 | 0.476 | .11 |  |  |  | 1.00 |
|  | Time1 | 4.852 | 2.203 | .11 | 1.00 |  |  | .01 |
|  | Time2 | 1.758 | 1.326 | −.30 | −.10 | 1.00 |  | −.05 |
|  | Time3 | 0.713 | 0.844 | −.07 | −.89 | −.05 | 1.00 | .06 |
| Item | Intercept | 0.200 | 0.447 | 1.00 |  |  |  |  |
|  | Time1 | 1.300 | 1.140 | −.41 | 1.00 |  |  |  |
|  | Time2 | 0.395 | 0.628 | −.89 | .09 | 1.00 |  |  |
|  | Time3 | 0.678 | 0.823 | .33 | −.95 | −.12 | 1.00 |  |
| Residual |  | 14.568 | 3.817 |  |  |  |  |  |

Appendix B. Growth curve model random effects.

# Appendix C

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Estimate | SE | *t* | *p* |
| GroupIE (γ08) | −0.045 | 0.176 | −0.255 | .799 |
| Time1 × GroupIE (γ18) | −0.740 | 0.503 | −1.472 | .141 |
| Time2 × GroupIE (γ28) | −0.057 | 0.407 | −0.139 | .889 |
| stress\_sum × car\_dev:corsi:GroupIE (γ09) | −0.310 | 0.612 | −0.507 | .612 |
| stress\_sum × car\_dev:corsi:Time1:GroupIE (γ19) | 2.899 | 1.112 | 2.606 | .009 |

Appendix C. Pairwise comparisons between English learner groups (AE baseline).

# Appendix D

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Estimate | SE | *t* | *p* |
| GroupIM (γ08) | −0.586 | 0.181 | −3.244 | .001 |
| Time1 × GroupIM (γ18) | 0.328 | 0.517 | 0.635 | .525 |
| Time2 × GroupIM (γ28) | −0.169 | 0.419 | −0.404 | .686 |
| stress\_sum × car\_dev:corsi:GroupIM (γ09) | 0.671 | 0.660 | 1.018 | .309 |
| stress\_sum × car\_dev:corsi:Time1:GroupIM (γ19) | −2.667 | 1.198 | −2.225 | .026 |

Appendix D. Pairwise comparisons between Mandarin Chinese learner groups (AM baseline).

**Appendix E**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Estimate | SE | *t* | *p* |
| GroupAM (γ08) | 0.104 | 0.182 | 0.571 | .568 |
| Time1 × GroupAM (γ18) | −1.117 | 0.522 | −2.141 | .032 |
| Time2 × GroupAM (γ28) | −0.101 | 0.423 | −0.239 | .811 |
| stress\_sum × car\_dev:corsi:GroupAM (γ09) | −0.214 | 0.484 | −0.443 | .658 |
| stress\_sum × car\_dev:corsi:Time1:GroupAM (γ19) | 2.491 | 0.879 | 2.836 | .005 |

Appendix E. Pairwise comparisons between advanced learner groups (AE baseline).

**Appendix F**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Estimate | SE | *t* | *p* |
| GroupIM (γ08) | −0.437 | 0.178 | −2.456 | .014 |
| Time1 × GroupIM (γ18) | −0.048 | 0.509 | −0.095 | .924 |
| Time2 × GroupIM (γ28) | −0.214 | 0.412 | −0.518 | .605 |
| stress\_sum × car\_dev:corsi:GroupIM (γ09) | 0.767 | 0.773 | 0.993 | .321 |
| stress\_sum × car\_dev:corsi:Time1:GroupIM (γ19) | −3.075 | 1.405 | −2.188 | .029 |

Appendix F. Pairwise comparisons between intermediate learner groups (IE baseline).

**Appendix G**

| Group | Lexical stress | Visuospatial WM | Visual pred. | Probability | LB | UB |
| --- | --- | --- | --- | --- | --- | --- |
| SS | present | -1.6153846 | 0.1581907386 | 0.8683663 | 0.8229682 | 0.9034878 |
|  | present | -1.6153846 | -0.0508796412 | 0.8763143 | 0.8388418 | 0.9060496 |
|  | present | -1.6153846 | 0.1042261914 | 0.8704584 | 0.8296119 | 0.9026618 |
|  | present | -0.6538462 | -0.0036157821 | 0.8717552 | 0.8394862 | 0.8983227 |
|  | present | -0.6538462 | 0.4079965825 | 0.8646539 | 0.8157655 | 0.9021257 |
|  | present | -0.6538462 | -0.5057592969 | 0.8799856 | 0.8311815 | 0.9161049 |
|  | present | -0.6538462 | 0.2614363127 | 0.8672196 | 0.8271802 | 0.8991140 |
|  | present | 0.3076923 | -0.1136001837 | 0.8684028 | 0.8359721 | 0.8952251 |
|  | present | 0.3076923 | -0.9476364783 | 0.8645575 | 0.7984470 | 0.9113899 |
|  | present | 0.3076923 | 0.1212674786 | 0.8694688 | 0.8370708 | 0.8962232 |
|  | present | 0.3076923 | 0.1543839024 | 0.8696185 | 0.8368012 | 0.8966517 |
|  | present | 0.3076923 | -0.3542466578 | 0.8673029 | 0.8295389 | 0.8977321 |
|  | present | 0.3076923 | 0.0553230911 | 0.8691702 | 0.8373036 | 0.8955738 |
|  | present | 0.3076923 | -0.4818293748 | 0.8667166 | 0.8243548 | 0.9000999 |
|  | present | 0.3076923 | -0.2438211497 | 0.8678086 | 0.8330957 | 0.8962014 |
|  | present | 0.3076923 | 0.0917721059 | 0.8693353 | 0.8372258 | 0.8958984 |
|  | present | 1.2692308 | 0.3675517358 | 0.8756186 | 0.8225934 | 0.9144435 |
|  | present | 1.2692308 | 0.1663709040 | 0.8704793 | 0.8318673 | 0.9012763 |
|  | present | 1.2692308 | -0.0477877641 | 0.8648109 | 0.8277400 | 0.8949169 |
|  | present | 2.2307692 | 0.2199009453 | 0.8737890 | 0.8168077 | 0.9148932 |
|  | preterit | -1.6153846 | 0.1581907386 | 0.8560112 | 0.8092034 | 0.8928562 |
|  | preterit | -1.6153846 | -0.0508796412 | 0.8220412 | 0.7742545 | 0.8615215 |
|  | preterit | -1.6153846 | 0.1042261914 | 0.8477966 | 0.8032287 | 0.8837312 |
|  | preterit | -0.6538462 | -0.0036157821 | 0.8667421 | 0.8342791 | 0.8936566 |
|  | preterit | -0.6538462 | 0.4079965825 | 0.8996444 | 0.8629162 | 0.9273606 |
|  | preterit | -0.6538462 | -0.5057592969 | 0.8147337 | 0.7496620 | 0.8659163 |
|  | preterit | -0.6538462 | 0.2614363127 | 0.8888498 | 0.8554171 | 0.9153170 |
|  | preterit | 0.3076923 | -0.1136001837 | 0.8927278 | 0.8659758 | 0.9146662 |
|  | preterit | 0.3076923 | -0.9476364783 | 0.8611993 | 0.7977090 | 0.9070838 |
|  | preterit | 0.3076923 | 0.1212674786 | 0.9003930 | 0.8751525 | 0.9209913 |
|  | preterit | 0.3076923 | 0.1543839024 | 0.9014337 | 0.8760993 | 0.9220488 |
|  | preterit | 0.3076923 | -0.3542466578 | 0.8843406 | 0.8517139 | 0.9105425 |
|  | preterit | 0.3076923 | 0.0553230911 | 0.8982914 | 0.8730265 | 0.9189956 |
|  | preterit | 0.3076923 | -0.4818293748 | 0.8796665 | 0.8422251 | 0.9091809 |
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|  | preterit | 0.3076923 | 0.0917721059 | 0.8994578 | 0.8742423 | 0.9200796 |
|  | preterit | 1.2692308 | 0.3675517358 | 0.9179529 | 0.8818080 | 0.9437492 |
|  | preterit | 1.2692308 | 0.1663709040 | 0.9190870 | 0.8939726 | 0.9386608 |
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|  | preterit | 1.9224138 | 0.2745942594 | 0.7653971 | 0.6971918 | 0.8221583 |
|  | preterit | 1.9224138 | 0.1017889971 | 0.7713323 | 0.7190404 | 0.8163770 |
| AM | present | -1.4705882 | 0.4674001817 | 0.6752285 | 0.5639941 | 0.7696738 |
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|  | present | -1.4705882 | -0.1935965835 | 0.5730263 | 0.4907115 | 0.6514858 |
|  | present | -1.4705882 | -0.0711839350 | 0.5473153 | 0.4797897 | 0.6131432 |
|  | present | -0.4901961 | 0.1059271362 | 0.5181078 | 0.4593961 | 0.5763237 |
|  | present | -0.4901961 | 0.0014227125 | 0.5258869 | 0.4695771 | 0.5815458 |
|  | present | -0.4901961 | -0.1583553285 | 0.5377549 | 0.4788217 | 0.5956515 |
|  | present | -0.4901961 | -0.1097565124 | 0.5341489 | 0.4768067 | 0.5906027 |
|  | present | -0.4901961 | -0.1285121719 | 0.5355410 | 0.4776628 | 0.5924774 |
|  | present | -0.4901961 | -0.3972081849 | 0.5554128 | 0.4808388 | 0.6275717 |
|  | present | -0.4901961 | 0.3397413472 | 0.5006770 | 0.4272797 | 0.5740451 |
|  | present | -0.4901961 | 0.2289886200 | 0.5089364 | 0.4437798 | 0.5737908 |
|  | present | -0.4901961 | 0.0829194276 | 0.5198213 | 0.4619052 | 0.5772095 |
|  | present | -0.4901961 | -0.2240602119 | 0.5426237 | 0.4805555 | 0.6033962 |
|  | present | 0.4901961 | -0.1901149178 | 0.5075805 | 0.4462634 | 0.5686704 |
|  | present | 0.4901961 | -0.2654595017 | 0.5027586 | 0.4372534 | 0.5681693 |
|  | present | 0.4901961 | 0.2370601796 | 0.5348657 | 0.4711539 | 0.5974597 |
|  | present | 0.4901961 | -0.1050330650 | 0.5130238 | 0.4549989 | 0.5706997 |
|  | present | 0.4901961 | 0.0161333691 | 0.5207700 | 0.4642597 | 0.5767537 |
|  | present | 0.4901961 | -0.3154510969 | 0.4995590 | 0.4307382 | 0.5683964 |
|  | present | 0.4901961 | 0.1225627930 | 0.5275660 | 0.4690904 | 0.5852949 |
|  | present | 0.4901961 | 0.0738063764 | 0.5244538 | 0.4672541 | 0.5810190 |
|  | present | 0.4901961 | -0.0278332879 | 0.5179602 | 0.4613604 | 0.5741028 |
|  | present | 0.4901961 | 0.3572608748 | 0.5425129 | 0.4705915 | 0.6127048 |
|  | present | 0.4901961 | 0.2566755353 | 0.5361148 | 0.4712301 | 0.5997995 |
|  | present | 0.4901961 | -0.2053133637 | 0.5066079 | 0.4445338 | 0.5684790 |
|  | present | 0.4901961 | 0.0335927092 | 0.5218855 | 0.4652626 | 0.5779515 |
|  | present | 1.4705882 | -0.1855250239 | 0.4759151 | 0.3936100 | 0.5595497 |
|  | present | 1.4705882 | -0.2995683505 | 0.4529318 | 0.3519121 | 0.5579833 |
|  | present | 1.4705882 | 0.1418897194 | 0.5421284 | 0.4673543 | 0.6150516 |
|  | preterit | -1.4705882 | 0.1241045092 | 0.5088419 | 0.4367642 | 0.5805539 |
|  | preterit | -1.4705882 | 0.1057320762 | 0.5011155 | 0.4313936 | 0.5707940 |
|  | preterit | -1.4705882 | -0.2753536716 | 0.3459990 | 0.2658174 | 0.4360033 |
|  | preterit | -1.4705882 | -0.1935965835 | 0.3777461 | 0.3060109 | 0.4552659 |
|  | preterit | -1.4705882 | -0.0711839350 | 0.4272255 | 0.3648896 | 0.4919617 |
|  | preterit | -0.4901961 | 0.1059271362 | 0.5522327 | 0.4950344 | 0.6080815 |
|  | preterit | -0.4901961 | 0.0014227125 | 0.5292253 | 0.4740937 | 0.5836529 |
|  | preterit | -0.4901961 | -0.1583553285 | 0.4938412 | 0.4365168 | 0.5513280 |
|  | preterit | -0.4901961 | -0.1097565124 | 0.5046136 | 0.4486156 | 0.5604961 |
|  | preterit | -0.4901961 | -0.1285121719 | 0.5004562 | 0.4440098 | 0.5568910 |
|  | preterit | -0.4901961 | -0.3972081849 | 0.4411685 | 0.3715227 | 0.5132089 |
|  | preterit | -0.4901961 | 0.3397413472 | 0.6027683 | 0.5329147 | 0.6686701 |
|  | preterit | -0.4901961 | 0.2289886200 | 0.5790346 | 0.5162747 | 0.6393401 |
|  | preterit | -0.4901961 | 0.0829194276 | 0.5471831 | 0.4906702 | 0.6025052 |
|  | preterit | -0.4901961 | -0.2240602119 | 0.4792881 | 0.4193891 | 0.5397885 |
|  | preterit | 0.4901961 | -0.1901149178 | 0.5957228 | 0.5368226 | 0.6519887 |
|  | preterit | 0.4901961 | -0.2654595017 | 0.5940713 | 0.5311682 | 0.6540317 |
|  | preterit | 0.4901961 | 0.2370601796 | 0.6050446 | 0.5442464 | 0.6627580 |
|  | preterit | 0.4901961 | -0.1050330650 | 0.5975852 | 0.5418110 | 0.6509441 |
|  | preterit | 0.4901961 | 0.0161333691 | 0.6002326 | 0.5459317 | 0.6521771 |
|  | preterit | 0.4901961 | -0.3154510969 | 0.5929742 | 0.5268750 | 0.6558705 |
|  | preterit | 0.4901961 | 0.1225627930 | 0.6025532 | 0.5465082 | 0.6560313 |
|  | preterit | 0.4901961 | 0.0738063764 | 0.6014907 | 0.5465897 | 0.6539528 |
|  | preterit | 0.4901961 | -0.0278332879 | 0.5992727 | 0.5448635 | 0.6513397 |
|  | preterit | 0.4901961 | 0.3572608748 | 0.6076542 | 0.5393291 | 0.6720084 |
|  | preterit | 0.4901961 | 0.2566755353 | 0.6054709 | 0.5436017 | 0.6641350 |
|  | preterit | 0.4901961 | -0.2053133637 | 0.5953898 | 0.5357687 | 0.6523228 |
|  | preterit | 0.4901961 | 0.0335927092 | 0.6006136 | 0.5462193 | 0.6526343 |
|  | preterit | 1.4705882 | -0.1855250239 | 0.6952779 | 0.6226706 | 0.7593144 |
|  | preterit | 1.4705882 | -0.2995683505 | 0.7120343 | 0.6220763 | 0.7878809 |
|  | preterit | 1.4705882 | 0.1418897194 | 0.6443197 | 0.5749940 | 0.7080784 |

Appendix G. Model probability estimates at target syllable offset.

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