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ARTICLE

Touching while listening: Does infants' haptic word processing speed predict vocabulary development?

Kayla BEAUDIN[1,*], Diane POULIN-DUBOIS[1] and Pascal ZESIGER[2]

[1]Concordia University, Canada
[2]University of Geneva, Switzerland
*Corresponding author. Kayla Beaudin, Concordia – Psychology, 7141 Sherbrooke Street West, Montreal, Quebec H4B 1R6, Canada. E-mail: kayla.beaudin@concordia.ca

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Abstract
The present study examined the links between haptic word processing speed, vocabulary, and inhibitory control among bilingual children. Three main hypotheses were tested: faster haptic processing speed, measured by the Computerized Comprehension Task at age 1;11, would be associated with larger concurrent vocabulary and greater longitudinal vocabulary growth. Second, early vocabulary size would be associated with greater vocabulary growth at 3;0 and 5;0. Finally, faster haptic processing speed would be associated with greater concurrent inhibitory control, as measured by the Shape Stroop Task. The results revealed that haptic processing speed was associated with concurrent vocabulary, but not predictive of later language skills. Also, early decontextualized vocabulary was predictive of vocabulary at 3;0. Finally, haptic processing speed measured in the non-dominant language was associated with inhibitory control. These results provide insight on the mechanisms of lexical retrieval in young bilinguals and expand previous research on haptic word processing and vocabulary development.

Keywords: bilingualism; language development; word processing

Introduction

Word knowledge rapidly develops during the second year of life (De Houwer, Bornstein & Putnick, 2014; Fernald, Zangl, Portillo & Marchman, 2008). Vocabulary in children aged 2;0 predicts greater short-term and long-term vocabulary development (Fernald, Perfors & Marchman, 2006; Marchman & Fernald, 2008). Similarly, early word processing speed has been found to predict later vocabulary growth. A number of studies have reported that visual processing speed consistently predicts later vocabulary growth among both monolingual and bilingual children (Fernald & Marchman, 2012; Hurtado, Gruter, Marchman & Fernald, 2014; Marchman, Fernald & Hurtado, 2010; Smolak, Hendrickson, Zesiger, Poulin-Dubois & Friend, 2021). However, haptic word processing (i.e., touch response)

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has not been found to be predictive of long-term vocabulary among monolingual children (Smolak et al., 2021) but predictive of short term vocabulary growth in bilinguals (Legacy, Zesiger, Friend & Poulin-Dubois, 2018). It has been proposed that bilinguals' haptic processing speed may have stronger predictive ability than that of monolinguals due to bilinguals' enhanced cognitive skills. More specifically, intentional haptic response required during a forced-choice word comprehension test likely involves executive function skills, such as inhibitory control. Thus, individual variability in these skills is considered a potential contributor to variability in haptic latencies unrelated to vocabulary comprehension. Given that bilingual toddlers have been found to display stronger inhibition skills than monolingual toddlers (Poulin-Dubois, Blaye, Coutya & Bialystok, 2011), haptic word processing skills may be more efficient among bilingual children; however, this has not been well studied in the extant literature. The main goal of the present study was to expand upon previous research with young monolinguals (Smolak et al., 2021) by assessing whether early vocabulary size and haptic processing speed predicts vocabulary growth among children with a wide range of second-language exposure. We additionally expand upon Legacy et al. (2018), who examined bilingual vocabulary growth over a shorter time period than that covered in the present study. Finally, we assessed the link between bilinguals' haptic processing speed and inhibitory control.

Documenting the relation between word processing speed and vocabulary development during infancy and toddlerhood is an important step in cognitive and literacy development. Early delays in word knowledge may impact school achievement (Dickinson, Golinkoff & Hirsh-Pasek, 2010; Morgan, Farkas, Hillemeier, Hammer & Maczuga, 2015) and cognitive development throughout childhood (Marchman & Fernald, 2008). Additionally, understanding the mechanisms of lexical retrieval has important longitudinal implications, as both language processing and vocabulary growth influence the development of skills in other domains. For example, speed of language processing and vocabulary each predict IQ in adulthood (Sternberg, 1984), and may also be predictive of cognitive skills (Kail & Salthouse, 1994). Finally, early vocabulary skills are a necessary precedent for literacy development (Lonigan, Burgess & Anthony, 2000).

Decontextualized Vocabulary

Decontextualized versus contextualized vocabulary

Decontextualized vocabulary consists of words that children understand independent of the context in which those words were learned (Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979; Friend, Smolak, Liu, Poulin-Dubois & Zesiger, 2018; Smolak et al., 2021). For example, if a child can identify an apple when it is sliced, growing on a tree, and placed on a teacher's desk, that child has decontextualized knowledge of the word "apple." Children with larger receptive, decontextualized vocabularies in early childhood have been shown to have greater vocabulary growth throughout childhood (Smolak et al., 2021). Additionally, decontextualized word knowledge indicates strong word-referent associations that are less prone to interference (Friend et al., 2018; Friend, Smolak, Patrucco-Nanchen, Poulin-Dubois & Zesiger, 2019; Suanda, Mugwaynya & Namy, 2014). Alternatively, contextualized vocabulary includes context-bound words (Godwin-Jones, 2018), such as those measured by the MacArthur-Bates Communicative Development Inventories (MCDI), a parent report measuring contextualized vocabulary (Fenson, Marchman, Thal, Dale, Reznick & Bates, 2007). If the word "apple" was context-bound, a child may only be able to identify an apple when it is growing on a tree, but not when it is sitting on a teacher's desk. Contextualized vocabulary tends to have weaker word-referent associations that are more easily interfered with (Friend et al., 2018, 2019).

How is decontextualized vocabulary measured?

In recent years, direct lab-based assessments, such as the Looking-While-Listening paradigm (LWL; Fernald et al., 2008) and the Computerized Comprehension Task (CCT; Friend & Keplinger, 2003, 2008), have been developed to measure decontextualized vocabulary (e.g., Friend et al., 2019; Legacy et al., 2018; Marchman, Bermúdez, Bang & Fernald, 2020; Poulin-Dubois, Bialystok, Blaye, Polonia & Yott, 2012). While the LWL paradigm assesses decontextualized vocabulary by measuring children's visual word processing, the CCT assesses decontextualized vocabulary by measuring haptic word processing (i.e., latency to touch a correct word referent). Also note that while the CCT can be used to measure visual word processing (see Smolak et al., 2021), its primary focus is haptic processing. Both the LWL paradigm and the CCT include a forced-choice procedure where the goal is to determine both accuracy and response time of word recognition. However, unlike the LWL paradigm, the CCT includes a wide range of both familiar and unfamiliar words to better estimate the size of children's decontextualized vocabularies.

The CCT is a valid diagnostic tool for identifying vocabulary and linguistic delays as well as school readiness. Additionally, the CCT has a practical advantage over the LWL paradigm, as touchscreen measures are cheaper and more user-friendly than eye-tracking paradigms (Friend et al., 2018, 2019). However, only CCT accuracy scores have been validated; the predictive ability of haptic reaction time on later linguistic skills has not been extensively studied.

Decontextualized vocabulary and lexical growth

It is well established that early decontextualized vocabulary is associated with both concurrent and later language outcomes among bilingual and monolingual children (Friend et al., 2019; Legacy et al., 2018; Marchman et al., 2020; Patrucco-Nanchen, Friend, Poulin-Dubois & Zesiger, 2019). For example, around two years of age, bilinguals' performance on the CCT is associated with concurrent contextualized vocabulary size, as measured by the MCDI (Friend & Keplinger, 2008; Friend et al., 2018; Legacy et al., 2018; Poulin-Dubois et al., 2012). Additionally, there is evidence for long-term stability between decontextualized vocabulary and later language skills. In bilinguals' dominant language, CCT scores at 1;5 have been linked to greater decontextualized vocabulary growth 6 months later (Legacy et al., 2018). Additionally, Friend and colleagues (2018) found that bilinguals' CCT scores at 1;11 was associated with decontextualized language abilities at 4;0 in children's dominant language. Similar within-language stability was found in a study measuring sequential bilinguals' decontextualized vocabulary using the LWL paradigm; dominant language vocabulary at 2;0 was predictive of dominant language outcomes at 4;6 (Marchman et al., 2020). As well, researchers noted cross-language effects: early dominant language vocabulary predicted later non-dominant vocabulary size. Overall, past results suggest that by the second year bilinguals' language comprehension may have lasting effects on their language skills throughout early childhood. In the present study, we expect that bilingual participants with larger decontextualized vocabulary at 1;11, as measured by the CCT, will have stronger vocabulary growth up to 5;0.

Speed of word processing and lexical growth

Children's vocabularies rapidly develop during the first two years of life. By age 1;3, infants understand roughly 70 to 150 words; however, by 2;0 infants' receptive vocabularies consist of roughly 600 to 700 words (Biemiller, 2009). At the same time, infants' lexical processing becomes increasingly more efficient. At 1;3 infants can process familiar words by looking at a target picture in roughly 1000 milliseconds and by 2;1 they can process familiar words in under 800 milliseconds (Fernald et al., 2006). Thus, word processing and vocabulary seem to develop in tandem. Indeed, both monolingual and bilingual children become more efficient in processing word meanings as their vocabularies expand (DeAnda, Hendrickson, Zesiger, Poulin-Dubois & Friend, 2018; Fernald et al., 2006; Legacy et al., 2018).

The association between word processing and vocabulary knowledge is bidirectional; these factors work together to support lexical growth and build complex language models (Fernald et al., 2006). There is rich evidence that visual word processing, as measured with the LWL paradigm, is linked with vocabulary growth (e.g., Marchman, Loi, Adams, Ashland, Fernald & Feldman, 2018). Children with more efficient lexical retrieval are believed to have more cognitive and attentional resources available to identify various speech cues and learn new words spoken during conversation (Dapretto & Bjork, 2000; Fernald & Marchman, 2012; Marchman et al., 2010; Storkel, 2002). Past research suggests that these associations hold among bilingual children: more efficient lexicon retrieval predicts future vocabulary growth (Fernald & Marchman, 2012; Hurtado et al., 2014; Legacy et al., 2018; Marchman et al., 2020, 2018).

While the CCT is typically a measure of haptic word processing, it was recently used as a measure of visual word processing using manually-coded looking time. Among a sample of English-speaking monolinguals, Smolak and colleagues (2021) reported that faster visual processing speed at 1;10 predicted larger vocabulary size at ages 1;10, 3;1, and 3;11. These findings corroborate previous results highlighting the stable association between early visual processing speed and vocabulary development typically found using the LWL paradigm (Fernald & Marchman, 2012; Hurtado et al., 2014; Marchman et al., 2010). In contrast, when measuring haptic processing speed, Smolak and colleagues (2021) did not find a significant correlation with vocabulary size at any wave. This finding is consistent with that of Legacy and colleagues (2018), who found neither concurrent nor short-term longitudinal associations between haptic word processing and vocabulary knowledge among monolingual participants. However, among bilingual participants, Legacy and colleagues reported that haptic processing speed at 1;4 predicted vocabulary growth at 1;10. While visual processing speed has been consistently linked with vocabulary among both monolingual and bilingual infants, it is possible that haptic processing speed is a reliable measure of word knowledge only among bilingual infants. In the present study, we aimed to expand upon Legacy and colleagues' study by assessing whether longitudinal links between haptic processing speed and vocabulary are found among children with any amount of second-language exposure.

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Haptic processing speed and inhibitory control

In order to account for the lack of predictability of word processing speed in monolingual children when measured in the haptic modality, it has been argued that when measured with a forced-choice procedure, lexical retrieval may not be entirely dependent on linguistic abilities but also rely on cognitive skills, such as inhibitory control (Fernald & Marchman, 2012; Kail & Salthouse, 1994; Smolak et al., 2021). As such, differences in individuals' cognitive abilities may also lead to differences in processing efficiency. Also recall that lexical retrieval is most efficient when ample cognitive and attentional resources are available to quickly identify speech cues (Fernald & Marchman, 2012). Considering this information, Smolak and colleagues (2021) hypothesized that haptic processing speed may require greater inhibitory control than visual processing speed, as children must ignore the distractor image and plan a motor response to touch the target image during the CCT. Thus, the authors speculated that a link between haptic processing speed and vocabulary growth could be found among bilinguals (see Legacy et al., 2018), but not monolinguals (see Legacy et al., 2018; Smolak et al., 2021), as greater inhibitory control skills have been reported in bilingual infants. Indeed, previous findings have suggested that bilingual children outperform monolingual children on measures of both attentional inhibition (Carlson & Meltzoff, 2008; Poulin-Dubois et al., 2011; Sorge, Toplak & Bialystok, 2016) and response inhibition (Beaudin & Poulin-Dubois, 2022; Lowe, Cho, Goldsmith & Morton, 2021). Seemingly contradictory to Smolak et al.'s (2021) hypothesis, monolingual and bilingual infants have comparable haptic processing speeds in their dominant language. However, bilinguals possess efficient word processing despite having smaller dominant language vocabularies than monolinguals (DeAnda et al., 2018; Legacy et al., 2018). Additionally, bilinguals have similar haptic processing speeds in both their dominant and non-dominant languages (Legacy et al., 2018). As bilinguals can quickly process words, even with smaller vocabularies, their haptic word processing may not solely rely on word knowledge and may also be strengthened by inhibition skills. The present study aimed to assess whether stronger inhibitory control was associated with faster haptic processing speed among young children with exposure to two languages.

While we expected that inhibitory control and haptic processing speed would be associated in bilingual children's dominant and non-dominant languages, we expected that inhibition would be more strongly associated with bilinguals' non-dominant language processing. Among adult bilinguals, greater inhibitory control may be linked to their experience suppressing their non-active language when another language is activated (Colomé, 2001; Kroll, Bobb, Mista & Guo, 2008). Further, Meuter and Allport (1999) reported that there are unbalanced switching costs between bilinguals' two languages. Specifically, when a bilingual's non-dominant language is activated, their dominant language must be suppressed; however, when the dominant language is active, less suppression of the non-dominant language is required. Thus, inhibitory control may be more strongly associated with haptic processing speed in the non-dominant language, opposed to the dominant language.

The present study

The present study tested Smolak and colleagues' (2021) hypothesis that a link between haptic processing speed and vocabulary growth might exist among bilinguals and that this link would be partially due to bilinguals' strong inhibition skills. While Legacy et al. (2018) provided preliminary longitudinal evidence for this link over a six-month timespan, the present study expands upon Legacy and colleagues' study in three important ways. First, the predictive ability of the CCT on later language skills was assessed over a three-year timespan. Additionally, we directly assessed the links between haptic processing speed and inhibition; to our knowledge, this has never been assessed. Finally, the present study sampled a more diverse sample of bilinguals. We included children with any amount of second language exposure to determine whether the tested associations were prevalent at any level of bilingualism.

Using a longitudinal design, the present study aimed to determine whether haptic measures of decontextualized vocabulary predict concurrent and longitudinal vocabulary skills among children exposed to two languages. Specifically, the links between vocabulary size, haptic processing speed, and vocabulary growth were assessed. If an association between haptic processing speed and vocabulary growth exists among bilinguals, we expected that it would be explained by inhibition skills. Three hypotheses were tested: first, we predicted that participants with faster haptic processing at 1;11 would have larger concurrent and longitudinal vocabulary. Second, we expected that larger decontextualized and contextualized vocabularies at 1;11 would be linked to greater vocabulary growth at 3;0 and 5;0. Finally, we expected that faster haptic processing would be associated with greater concurrent inhibition skills, particularly in participants' non-dominant language.

Method

Participants

The present study included archival longitudinal data initially collected in 2016. Participants were recruited in Montréal, Canada and Geneva, Switzerland through birth lists provided by government agencies in each city. Participants had no visual or hearing impairments nor any neurological, motor, or developmental delays. At Wave 1, a total of 74 participants were included (27 females); 46 participants were from Montréal and 28 from Geneva. Note that participants from Geneva were initially recruited as monolinguals for a cross-linguistic, longitudinal study (M_{L2} = 10.71%, SD = 5.88%) and participants from Montréal were recruited as bilinguals (M_{L2} = 34.09%, SD = 9.26%). Alternatively, the present study included participants with a wide range of exposure to a second language (5% - 50%) in order to measure bilingualism on a continuum (Luk & Bialystok, 2013). The average second language exposure of the sample was 25.24%, which corresponds to the threshold that has been applied in past literature (see Byers-Heinlein & Werker, 2009; Gervain & Werker, 2013; Poulin-Dubois, Neumann, Masoud & Gazith, 2021; Ramon-Casas, Swingley, Sebastián-Gallés & Bosch, 2009).

Measures

Language exposure

The Language Exposure Assessment Tool (LEAT; DeAnda, Bosch, Poulin-Dubois, Zesiger & Friend, 2016) is a semi-structured interview that was conducted with the participants' parents at the first wave of data collection. Parents were asked to report who had communicated with their child on a regular basis (i.e., daily or weekly) throughout the child's life, which languages were spoken by each person, and how often each person had contact with the child. The goal of the LEAT was to yield a percentage estimate of time the child has heard each language since birth.

Inhibitory control

The Shape Stroop Task (SST; adapted from Kochanska, Murray & Harlan, 2000) was used as a measure of children's attentional inhibition. This task was only administered to the participants at Wave 1 in the child's dominant language (either French or English). As the Geneva participants were not administered the SST at the time of testing, analyses included only the SST scores for the Montréal participants *(n* = 44).

The SST was adapted from a battery of executive function tasks used with children as young as 1;10 (Carlson, 2005; Carlson & Meltzoff, 2008; Poulin-Dubois et al., 2011). The SST is a conflict task, where the participants must inhibit a distractor image to focus on the target image and appropriately complete the task. It began with an identification phase, during which an experimenter presented the participant with a large and small image of three fruits (apple, banana, and orange) and labelled each image by size and fruit. The experimenter then removed the small images and asked the participant to point to each fruit as they were named. Verbal reinforcement was given for correct answers, and verbal corrections were given for incorrect answers.

Following the identification phase were three test trials; during a trial, children were presented with an image of a small fruit embedded in an image of a larger fruit (e.g., an image of an orange embedded in a larger image of an apple). During each trial, children were asked to point to the smaller fruit, thus requiring them to inhibit the image of the larger fruit to point to the correct referent. For each touch to the target image, children received one point. Children's final score was the number of correct touches out of three points maximum.

Contextualized vocabulary

The MacArthur-Bates Communicative Development Inventories: Words and Sentences (MCDI; Fenson et al., 2007) is a parent checklist that yields an estimate of children's expressive, contextualized vocabulary. This checklist includes 680 words and is suitable for children aged 1;4 to 2;6. The MCDI was administered at Wave 1 only. Participants were administered one of three MCDI versions, based on their location and dominant language. All participants in Geneva were asked to complete the French adaptation (Kern, 2007; Kern & Gayraud, 2010). English-dominant participants in Montréal were administered the American English adaptation (Fenson et al., 2007), and French-dominant Montréal participants were administered the Québec French adaptation (Trudeau, Frank & Poulin-Dubois, 1999). Non-dominant vocabulary was not assessed in the present study.

Early decontextualized vocabulary and haptic processing speed

The Computerized Comprehension Task (CCT; Friend & Keplinger, 2003, 2008) is a direct assessment of decontextualized vocabulary comprehension, valid for use between 1;4 and 2;6. The CCT was administered at Wave 1. Participants from Geneva were only administered the CCT in their dominant language (French), while Montréal participants completed the CCT in both their dominant and non-dominant languages (French and English) over two sessions. The CCT has been found to have good test-retest reliability, strong internal consistency ($\alpha = .86$ to $\alpha = .93$), and high convergence with the MCDI (Friend & Keplinger, 2008; Friend, Schmitt & Simpson, 2012).

During the CCT, participants sat on their parents' lap, 30 centimeters from a 17-inch touch screen. To reduce interference, parents wore blackout glasses and noise-cancelling

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headphones during the task. While administering the task, a researcher sat to one side of the parent and child. The CCT is an alternative forced choice task; during each trial children were shown two images (e.g., dog and bird) simultaneously on a touch-screen, right and left of center-screen. The researcher asked the child to touch the target image (e.g., "Where's the dog? Touch the dog!"). When the child touched the target image, they received auditory feedback (e.g., a dog barking); however, when they touched the distractor image no auditory feedback was given. Only gross motor function, and not fine motor function, is required to complete the touch responses, as children may touch the 17-inch screen with their entire hand. The position of target images was pseudo-randomized so that targets appeared on the same side of the screen for a maximum of two consecutive trials and target images equally appeared on the left and right side of the screen across trials. Participants were administered four training trials, followed by 41 test trials. Each trial ended when the child touched the screen, or once seven seconds had passed.

Both accuracy and haptic response time were automatically recorded by the touch screen. Accuracy was measured as the total correct responses for all completed test trials. Haptic response time was measured as the total time from trial onset to trial end, beginning as soon as the images were presented on the screen and ending once the child touched the screen. Similar to accuracy scores, only correct touches were included when measuring response time, as incorrect responses do not indicate word comprehension. Missing trials are those where the child failed to touch the screen or provided an incorrect answer.

Later decontextualized vocabulary

The Peabody Picture Vocabulary Task – Third Edition (PPVT; Dunn & Dunn, 1997) was administered at Waves 2 and 3. The participants were administered a French adaptation of the task, called the *Échelle de vocabulaire en images Peabody* (EVIP; Dunn, Thériault-Whalen & Dunn, 1993), or the English version as a function of the dominant language.

The PPVT is a direct measure of children's decontextualized vocabulary comprehension, designed for individuals 2;6 and older. The PPVT is a forced choice procedure; during each trial, children were simultaneously presented four images (three distractors and one target). Researchers then promoted children to point to the target image (e.g., PPVT: "Find cherries!" or EVIP: "*Trouve les cerises!*"). Children were tested until they made eight or more mistakes within a 12-trial set. High internal consistency has been reported for both the PPVT ($\alpha = .92$ to $\alpha = .98$; Hayward, Stewart, Phillips, Norris & Lovell, 2008; Smolak et al., 2021) and the EVIP ($\alpha = .81$; Friend et al., 2018).

Procedure

In this longitudinal study, participants were tested across three waves. At each wave children had a brief familiarization period upon arrival to the lab, during which they could play with toys and adapt to the lab environment and the experimenter. At the same time, parents completed a consent and demographics form. At Wave 1, parents were also administered the LEAT during the familiarization period. Once children adapted to the lab environment and parents completed the initial forms, children were brought into a

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testing room to complete the tasks. During Wave 1, children completed the CCT and the MCDI. Additionally, children from Montréal were administered the SST. Participants from Montréal completed the CCT, MCDI and the SST in their dominant language during their initial visit, then completed the CCT in their non-dominant language during a second visit one to two weeks later. Participants from Geneva complete the French adaptations of the CCT and MCDI during a single session. At Waves 2 and 3, participants were administered either the EVIP or the PPVT during a single session. At all waves, parents were given $25, and children received a small toy and certificate of merit after each session.

Results

Data analysis was performed in SPSS 27 (IBM, 2020) and post-hoc power analyses conducted with G*Power (Faul, Erdfelder, Buchner & Lang, 2009; Faul, Erdfelder, Lang & Buchner, 2007). Prior to conducting main analyses, assumptions were checked (see Table 1 for descriptive statistics of study variables). Univariate outliers were first identified by assessing each participant's z-score for all main variables. One participant had a z-score that was ± 3.29 standard deviations from the mean PPVT score at 5;0. This score was removed from the dataset and no other univariate outliers for any of the main variables were identified. Bivariate outliers were identified by creating scatterplots between each combination of main variables: CCT response time, CCT accuracy, MCDI scores, PPVT scores at 3;0, and PPVT scores at 5;0. We removed outlier scores from the dataset, as well as participants who were missing scores for all predictor variables or both independent variables. The process of checking for univariate and bivariate outliers was repeated three times; at the third round no extreme outliers were identified. After the second round, $n = 6$ participants had outlier scores for multiple variables and were removed from the dataset. We also used the final scatterplots created to check for normality, linearity, and homoscedasticity; these assumptions were met. Once all outliers were removed, we assessed the skewness and kurtosis of each variable. All skewness and kurtosis statistics are $< \pm 1$, suggesting normality. Finally, multicollinearity was assessed by calculating the variance inflation factor scores between each predictor variable. No score was equal to nor greater than 10, all scores were relatively close to 1, and the scores were nearly equal (range: 1.11 – 1.44), suggesting that multicollinearity was met. Thus, our cleaned dataset met the assumptions for running correlation and regression analyses. Note that no participants were removed from the

Table 1. Descriptive Statistics of Variables

Variable	N	Mean	SD	Minimum	Maximum	Score Range
Wave 1: HPS (ms)	65	3385.77	762.05	1856.50	5239.74	> 400
Wave 1: CCT Accuracy	66	27.39	6.38	10	37	0 – 41
Wave 1: MCDI	60	175.68	121.25	13	449	0 – 680
Wave 2: PPVT	55	30.65	13.43	10	65	0 – 175
Wave 3: PPVT	41	68.76	17.80	32	102	0 – 175

Note. HPS = haptic processing speed; SD = standard deviation.

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Table 2. Descriptive Statistics

	Wave 1: L2 Exposure	Wave 1: Age	Wave 2: Age	Wave 3: Age
N	74	74	63	41
Mean	25.24%	23.09	36.35	60.93
SD	14.00%	1.20	1.00	1.48
Minimum	5%	20.85	34.05	59.18
Maximum	50%	26.20	39.40	64.93

Note. L2 = second language; SD = standard deviation.

dataset once assumptions were met. Please see Table 2 for participant descriptive statistics.

Correlates of dominant-language measures

Haptic processing speed and vocabulary

In line with our first hypothesis, bivariate correlations showed that faster haptic processing speed at 1;11 was negatively associated with greater concurrent decontextualized and contextualized vocabulary, as measured by the CCT and MCDI respectively (see Table 3). Haptic processing speed was also negatively correlated with decontextualized vocabulary at 3;0, as measured by the PPVT; however, the association between haptic processing speed and decontextualized vocabulary was no longer significant at 5;0. These results suggest that faster haptic processing speed was associated with greater concurrent vocabulary and may have predicted vocabulary growth only one year later.

Short-term and long-term vocabulary

Our second hypothesis was that decontextualized vocabulary at 1;11 would be positively associated with decontextualized vocabulary at 3;0 and 5;0. Bivariate correlations showed that greater decontextualized vocabulary at 1;11 was significantly associated with greater decontextualized vocabulary at 3;0, but not at 5;0 (see Table 3). Thus, our second hypothesis was partially supported. Similar associations were noted for contextualized vocabulary as well: contextualized vocabulary at 1;11 has a positive and significant association with decontextualized vocabulary at 3;0, but not at 5;0. Both decontextualized and contextualized vocabulary at 1;11 are linked to vocabulary skills at 3;0; however, the strength of this association diminishes by 5;0. These results are unsurprising given that decontextualized and contextualized vocabulary were significantly associated at 1;11. However, the CCT appears to be a more robust measure of later vocabulary than the MCDI; the association between early decontextualized vocabulary and vocabulary at 5;0 was stronger than that of contextualized vocabulary and vocabulary at 5;0. Interestingly, decontextualized vocabulary at 3;0 and 5;0 had a positive and significant association. Thus, decontextualized vocabulary remained significantly correlated from one wave to the next, but not from 1;11 to 5;0.

Overall, our second hypothesis was partially supported; decontextualized vocabulary at 1;11 was associated with vocabulary at 3;0. Also, decontextualized vocabulary

Table 3. Bivariate Correlations for Haptic Processing Speed and Language Outcomes (with 95% Confidence Intervals)

	Wave 1: MCDI	Wave 1: HPS	Wave 1: CCT	Wave 2: PPVT
Wave 1: HPS				
Correlation	−.320*			
	[−.542, −.057]			
p-value (2-tailed)	.018			
N	54			
Power	**66.65%**			
Wave 1: CCT				
Correlation	.436*	−.557*		
	[.198, .626]	[−.708, −.357]		
p-value (2-tailed)	.001	.000		
N	57	62		
Power	93.37%	99.80%		
Wave 2: PPVT				
Correlation	.304*	−.307*	.463*	
	[.004, .554]	[−.542, −.029]	[.212, .657]	
p-value (2-tailed)	.047	.032	.001	
N	43	49	50	
Power	**51.85%**	**58.41%**	93.45%	
Wave 3: PPVT				
Correlation	−.067	−.191	.229	.470*
	[−.396, .277]	[−.474, .128]	[−.093, .508]	[.167, .692]
p-value (2-tailed)	.705	.237	.161	.004
N	34	40	39	36
Power	**6.62%**	**21.98%**	**29.18%**	84.45%

Note. HPS = haptic processing speed.

sizes at 3;0 and 5;0 were strongly associated. Contrary to our hypothesis, no evidence was found that decontextualized vocabulary at 1;11 was associated with language skills by 5;0.

Second-language exposure and main variables

To ensure that later vocabulary knowledge was indeed influenced by early vocabulary knowledge and haptic processing, rather than degree of bilingualism, we ran bivariate correlations between second-language exposure and each of the main variables. All correlations were non-significant (p-value range = .121 – .709). This suggests that our previous results showing a link between early and late vocabulary were driven by vocabulary, rather than second-language exposure.

Table 4. Hierarchical Regression for Wave 2 Decontextualized Vocabulary

Variable		R^2	F	p	ΔR^2	ΔF	B	t	p
Model 1		.016	.595	.455	.016	.595			.445
	MCDI						.015	.771	.445
Model 2		.285	4.658**	.004	.270	6.599**			.008
	MCDI						–.106	–.675	.504
	HPS						–1.708	–.006	.995
	CCT						1.162**	3.011	.005

Note. ** $p < .01$; N = 39; HPS = haptic processing speed, unstandardized β reported; power for Model 2 is 88.37%.

Predictors of decontextualized vocabulary at 3;0

Given the significant correlations between vocabulary at 1;11 and 3;0, we conducted a hierarchical regression to assess whether contextualized vocabulary, decontextualized vocabulary, or haptic processing speed at 1;11 would predict decontextualized vocabulary at 3;0 (see Table 4). Model 1 did not yield significant results; early contextualized vocabulary (dominant-language MCDI) was not a significant predictor of later decontextualized vocabulary. Alternatively, Model 2 yielded significant results. Specifically, the main effect of early decontextualized vocabulary (dominant-language CCT) significantly predicted decontextualized vocabulary size at 3;0. However, the main effect of haptic processing speed did not significantly predict later vocabulary. Overall, the results from the hierarchical regression do not support our first hypothesis that early haptic processing speed predicts decontextualized vocabulary at age 3;0. However, our second hypothesis that early decontextualized vocabulary size would predict later language comprehension was supported.

CCT accuracy mediates link between haptic processing and vocabulary growth

Despite the significant association between haptic processing speed and decontextualized vocabulary at 3;0, haptic processing speed did not emerge as a significant predictor of later vocabulary size. However, in the regression analysis both haptic processing speed and early decontextualized vocabulary were included in the same model, with only early decontextualized vocabulary emerging as a significant predictor of vocabulary growth. Thus, early decontextualized vocabulary may have mediated the correlation between haptic processing speed and later decontextualized vocabulary. To further assess this issue, we ran post-hoc partial correlations. When CCT accuracy was controlled for, the correlation between haptic processing speed and later decontextualized vocabulary was no longer significant ($r(44) = -.024$, $p = .873$, power = **5.29%**). Further, when controlling for haptic processing speed, the association between early and later decontextualized vocabulary remained significant ($r(44) = .398$, $p = .006$, power = 80.66%). Overall, it appears that early decontextualized vocabulary may mediate the relation between haptic processing speed at 1;11 and decontextualized vocabulary at 3;0; however, future research should aim to further assess these associations.

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Haptic processing speed and inhibitory control

In order to examine whether haptic word processing was a predictor of later vocabulary due to greater inhibitory control in children with second-language exposure, we correlated haptic processing speed in participants' dominant and non-dominant languages with inhibitory control, as measured by the Stroop Task at 1;11. The following analyses were conducted only with Montréal participants, as those in Geneva were not administered the CCT in their non-dominant language nor the Stroop Task (see Table 5 for descriptive statistics).

The bivariate correlations showed that inhibitory control was significantly associated with haptic processing speed in participants' non-dominant language, but not in their dominant language (see Table 6). This finding partially supports our third hypothesis as it was expected that inhibitory control would be associated with haptic processing speed in participants' dominant and non-dominant language; however, as hypothesized, inhibitory control was more strongly associated with the participants' non-dominant language haptic processing speed than that of their dominant language. Finally, in addition to assessing the correlations between correct CCT trials and inhibitory control, we analyzed inhibitory control and response times on incorrect trials. Response time in both the dominant and non-dominant language were not significantly correlated with inhibitory control, as would be expected if processing efficiency is linked to word knowledge.

Table 5. Descriptive Statistics of Variables for Montréal Sub-sample

Variable	N	Mean	SD	Minimum	Maximum	Score Range
Wave 1: HPS L1 (ms)	39	3204.23	715.70	1856.50	5239.74	> 400
Wave 1: HPS L2 (ms)	40	3200.55	725.47	2026.58	5087.75	> 400
Wave 1: HPS Incorrect L1 (ms)	45	3207.38	936.88	798.00	4904.17	> 400
Wave 1: HPS Incorrect L2 (ms)	55	3512.23	983.35	1842.33	5902.00	> 400
Wave 1: Inhibitory Control	44	.98	.927	0	3	0 – 3

Note. HPS = haptic processing speed; SD = standard deviation.

Table 6. Bivariate Correlations for Haptic Processing Speed and Inhibitory Control at Wave 1 (with 95% Confidence Intervals)

	HPS L1	HPS L2	HPS Incorrect L1	HPS Incorrect L2
Inhibitory Control				
Correlation	–.010	–.346*	–.044	–.183
	[–.328, .311]	[–.596, –.034]	[–.336, .257]	[–.455, .120]
p-value (2-tailed)	.955	.031	.779	.234
N	38	39	44	44
Power	**5.04%**	**59.17%**	**5.92%**	**22.22%**

Note. HPS = haptic processing speed.

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Discussion

The main goal of the current study was to investigate whether word processing efficiency at 1;11, as measured with a haptic rather than a visual response, predicts concurrent and later vocabulary. As previously discussed, visual word processing speed has been reported to predict vocabulary in monolingual and bilingual children between two and eight years (Marchman & Fernald, 2008; Peter et al., 2019; Smolak et al., 2021). Regarding haptic word processing, to date, only two studies have been conducted and only short-term predictability (from ages 1;4 to 1;10) has been observed in bilinguals (Legacy et al., 2018; Smolak, DeAnda, Enriquez, Poulin-Dubois & Friend, 2019). We extended past work by testing a sample of French–English children with a wide range of second language exposure. Additionally, the long-term predictability of haptic processing speed and language development was assessed between ages 1;11 and 5;0. Finally, we expanded on the results of Smolak et al. (2021), who found no predictive association between haptic processing speed and language development among a sample of monolingual children. Unlike Smolak and colleagues, we found that haptic processing speed was associated with concurrent decontextualized vocabulary size. Additionally, haptic processing speed was significantly correlated with decontextualized vocabulary at 3;0. However, haptic word processing did not account for significant variance in decontextualized vocabulary at 3;0 nor 5;0 beyond vocabulary scores at 1;11.

As previously mentioned, faster haptic processing at 1;11 was correlated with vocabulary outcomes at 1;11 and 3;0, but not at 5;0. Thus, haptic processing speed seems to be associated with short-term vocabulary growth; however, unlike visual word processing (Fernald & Marchman, 2012; Hurtado et al., 2014; Marchman et al., 2010; Smolak et al., 2021), haptic processing is not strongly associated with long-term language growth. These findings replicate previous findings for short-term associations in a bilingual sample (Legacy et al., 2018). However, the present study expanded upon the previous findings by assessing the predictive ability of haptic processing speed at 1;11 on decontextualized vocabulary at 3;0. Interestingly, haptic processing speed does not significantly predict later decontextualized vocabulary, suggesting that a third factor is influencing this association. When both haptic processing speed and early decontextualized vocabulary, measured by CCT accuracy, were entered into the same regression model, only early decontextualized vocabulary emerged as a significant predictor of decontextualized vocabulary at 3;0. This finding is particularly salient when considering that we only collected dominant-language CCT scores for our total sample; thus decontextualized vocabulary is a significant predictor of later vocabulary even when using a conservative measure. Additionally, post-hoc partial correlations revealed that when CCT accuracy scores were controlled for, the association between haptic processing speed and decontextualized vocabulary at 3;0 was no longer significant; however, the association between CCT accuracy scores and later decontextualized vocabulary remained significant even when controlling for haptic processing speed. Thus, decontextualized vocabulary knowledge at 1;11 may have mediated the significant association between haptic processing speed and later vocabulary. Future research should further assess these associations.

Considering the lack of predictability observed for haptic word processing efficiency, one explanation for it is the additional demands that such response requires, including executive control and self-regulation (Smolak et al., 2021). We tested this hypothesis by measuring haptic word processing speed among children exposed to two languages, a group that has been shown to have better executive control at 2;0 (Poulin-Dubois et al., 2011). As expected, greater inhibitory control was associated with faster processing speed

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in participants' non-dominant language; however, unexpectedly, there was no significant correlation between dominant language processing speed and inhibitory control. This finding may highlight unbalanced switching costs in bilinguals. Specifically, research shows that stronger inhibitory control is required for lexical retrieval in the less proficient language compared with the dominant language, which may suggest that the dominant language is actively inhibited when non-dominant language processing occurs (Gollan & Ferreira, 2009; Meuter & Allport, 1999). To further support this idea, inhibitory control was not associated with haptic response time on incorrect CCT trials. This finding suggests that the longer response time required to correctly identify a referent in participants' non-dominant language is linked to inhibition of the non-dominant language. When children process both unknown and well-known words in the dominant language, no such inhibition is required.

Another reason for the lack of predictability of haptic speed compared to visual processing speed is that the LWL procedure includes familiar items whereas the CCT includes words at different levels of difficulty. Thus, the CCT is a more conservative assessment of word knowledge than the LWL procedure. This is confirmed by a recent study that conducted fine-grained analyses of visual and haptic responses on the CCT (Hendrickson, Poulin-Dubois, Zesiger & Friend, 2017). Correct touches to the target referent revealed robust understanding and convergence across response modalities, touches to the distractor revealed partial knowledge (i.e., visual response times were comparable to correct touches; nevertheless, infants did not choose the target referent suggesting a representation of the word-referent relation not strong enough to guide overt, volitional responses). Correct touches could thus require robust knowledge that is only linked to concurrent vocabulary. It is worth mentioning that the lack of predictive relationship between being fast at processing words and vocabulary growth has also been reported with the LWL paradigm (Peter, Durrant, Jessop, Bidgood, Pine & Rowland, 2019). It was suggested that children who are faster at processing have an advantage early in the lexicon-building process, but that once vocabulary reaches a critical mass, speed of processing becomes less reliable as a predictor of variance in vocabulary learning.

One limitation of the current design is that only one executive function task was administered to the children and to only a subsample of the children, those typically defined as bilinguals (at least 20% exposure to a second language). Also, at 1;11, there is only one study supporting a bilingual advantage in inhibitory control (Poulin-Dubois et al., 2011). Thus, it is possible that executive functioning was not strong enough to impact speed of haptic processing. Given that it has been established that haptic processing speed increases with age, testing online haptic processing speed at an older age might yield positive findings (Legacy et al., 2018). Another limitation is that the average number of correct touches was 27 (out of 41) with a range from 10 to 37, making latency less reliable as based on a very small number of trials for some children. A third limitation of the present study is that we only measured later vocabulary comprehension and not expressive vocabulary skills at Waves 2 and 3. Although Marchman and Fernald (2008) found that, among a sample of monolinguals, a significant link between visual word processing speed at 2;1 and expressive language at 8;0 was explained by working memory skills, future work should explore the association between early word processing speed and later expressive vocabulary among bilingual children. Finally, the present study is limited by its high attrition rate throughout the three waves of data collection, which contributes to the low power of some correlational analyses. Results with power under 80% should be interpreted with caution. However, note that our sample size is consistent

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with the sample sizes used in past longitudinal studies on the topic (e.g., Fernald et al., 2006; Marchman & Fernald, 2008).

In conclusion, the present study confirms and extends previous research on vocabulary development in monolingual children on whether online haptic word processing can predict concurrent and later language skills. Despite better putative executive function skills, children exposed to two languages showed the same lack of predictive stability of haptic word processing; however, bilingual children's haptic word processing efficiency is similarly related to concurrent vocabulary. We observed that early decontextualized vocabulary skills may mediate the correlation between haptic processing speed and later vocabulary size. Overall, the present study highlights the concurrent and short-term associations between haptic word processing and decontextualized vocabulary among bilingual children. However, the present study had a high attrition rate across the three waves of data collection, resulting in a limited sample size and occasionally low power. Future research should aim to replicate this study with a larger sample of bilingual children in order to confirm the results or uncover missed effects.

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