Bilingualism: Language and Cognition

cambridge.org/bil

Bilinguals differ from monolinguals in attentional resource allocation during spoken language processing: pupillometry evidence

Wenfu Bao[1,2,3], Claude Alain[4,5,6,7], Michael Thaut[2,6,7,8] and Monika Molnar[1,2]

[1]Department of Speech-Language Pathology, University of Toronto, Toronto, Ontario, Canada; [2]Rehabilitation Sciences Institute, University of Toronto, Toronto, Ontario, Canada; [3]Department of Speech, Language, and Hearing Sciences, The University of Texas at Austin, Austin, Texas, United States; [4]Rotman Research Institute, Baycrest Academy for Research and Education, Toronto, Ontario, Canada; [5]Department of Psychology, University of Toronto, Toronto, Ontario, Canada; [6]Institute of Medical Sciences, University of Toronto, Toronto, Ontario, Canada; [7]Music and Health Science Research Collaboratory, University of Toronto, Toronto, Ontario, Canada and [8]Faculty of Music, University of Toronto, Toronto, Ontario, Canada

Research Article

Cite this article: Bao, W., Alain, C., Thaut, M. and Molnar, M. (2025). Bilinguals differ from monolinguals in attentional resource allocation during spoken language processing: pupillometry evidence. *Bilingualism: Language and Cognition* 1–10. https://doi.org/10.1017/S1366728925100795

Received: 6 November 2024
Revised: 6 September 2025
Accepted: 24 October 2025

Keywords:
attentional resources; pupillometry; listening effort; bilingualism; spoken language processing

Corresponding author:
Wenfu Bao;
Email: wenfu.bao@mail.utoronto.ca

This research article was awarded Open Data and Open Materials badges for transparent practices. See the Data Availability Statement for details.

Abstract

Bilingual experience may enhance attentional control, but little work has addressed whether monolinguals and bilinguals differ in allocating attentional resources. Focusing on speech processing, we examined listening effort via pupillometry in English monolinguals and simultaneous bilinguals, while they listened to passages in a familiar or unfamiliar language. Results demonstrated similar pupil responses across conditions in bilinguals, yet monolinguals showed significantly larger pupil size when listening to the unfamiliar language than the familiar one. Further, more English exposure (especially a longer stay in an English-speaking family) correlated with smaller pupil size in the familiar language condition. Overall, our findings suggest that bilinguals tend to exhibit greater listening effort than monolinguals, and a more cognitively demanding situation (i.e., listening to an unknown language) requires more effort in monolinguals. With this, we broadened the scope of research on bilingual cognition and demonstrated that bilingualism affects attentional resource allocation in spoken language processing.

Highlights

- We focused on monolingual and bilingual native speakers of English.
- We measured their attention allocation to spoken language using pupil dilation.
- Bilinguals and monolinguals allocate attentional resources differently.

1. Introduction

In recent decades, myriads of studies have investigated the bilingualism effects on cognition. While debated, the extant literature suggests that bilingual experience can lead to domain-general cognitive benefits, which is termed the *bilingual cognitive advantage* (e.g., Adesope et al., 2010; Bialystok, 2017; Grundy, 2020; cf. Bao et al., 2024; Lehtonen et al., 2018; Lowe et al., 2021). For example, bilinguals have shown better executive functions in the nonlinguistic domain relative to monolinguals (e.g., Crivello et al., 2016; Stocco et al., 2012). As a possible mechanism, attention has been argued to explain such effects. For example, according to the attentional control framework, bilingual experience can enhance *attentional control*, a repertoire of processing operations that higher level cognition uses to accomplish goals (Bialystok, 2017; Bialystok & Craik, 2022). Especially the continuing need to manage two languages results in more efficiency in utilizing attentional resources even in nonlinguistic settings (Bialystok & Craik, 2022).

Attention entails at least two aspects: the *control processes* and the *processing resources* (e.g., Bialystok & Craik, 2022; Kahneman, 1973; Shiffrin & Schneider, 1977). The former are necessary for managing cognitive or motor tasks, and the latter for supporting those activities (Bialystok & Craik, 2022). Nevertheless, much of the bilingualism research has primarily studied attentional control (e.g., Krizman et al., 2014; Ooi et al., 2018; Soveri et al., 2010; Stafford, 2011). While investigators may speculate the amount of attentional resources involved in certain cognitive tasks, such assumptions have rarely been tested explicitly. We thus designed this study to examine whether monolinguals and bilinguals differ in attentional resource allocation – an underexplored area in the bilingual attention literature – quantified via pupil dilation (i.e., increased pupil diameter). Specifically, we contextualized this question within spoken language processing, which extends the pivot of the bilingual cognitive advantage to the linguistic domain.

As a well-established physiological measure, pupil dilation has been used to index attention allocation changes (e.g., Hess & Polt, 1960; Laeng et al., 2012) and indicate attentional effort

© The Author(s), 2025. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

exerted in a cognitive task (e.g., Kahneman, 1973; van der Wel & van Steenbergen, 2018). In auditory processing, increased pupil dilation has been considered a proxy of greater *listening effort*, which refers to the deliberate allocation of attentional resources in goal pursuit when carrying out a listening task (Pichora-Fuller et al., 2016). Research also suggests that the pupil response is sensitive to input- and listener-based variables (e.g., Zekveld et al., 2018). For example, larger pupil size is associated with increases in stimulus complexity and processing demands (e.g., McCloy et al., 2017; Piquado et al., 2010), and with bilingual status when comparing monolinguals to second language (L2) learners, who are usually sequential bilinguals that learned L2 after the age of three (e.g., Borghini & Hazan, 2018, 2020; further discussed below). However, the relationship between pupil size and individual linguistic/cognitive abilities remains unclear given mixed results (e.g., better abilities associated with larger pupil size in Koelewijn et al., 2012 and Zekveld & Kramer, 2014, but with smaller pupil size in Koelewijn et al., 2014 and Zekveld et al., 2014).

2. Pupil dilation in spoken language processing in prior bilingualism research

Some studies have demonstrated that increased pupil dilation reflects greater listening effort or processing load in bilinguals during spoken language processing. For instance, Borghini and Hazan (2018, 2020) observed significantly larger pupil size in Italian-English bilinguals than in English monolinguals when listening to English sentences, both in quiet and noisy environments. They interpreted this as evidence that bilinguals exert more effort when processing speech in an L2. Similarly, Francis et al. (2018) reported that native Dutch speakers with varying L2-English proficiency showed greater pupil dilation when processing spoken sentences in English compared to their first language (L1). In developmental research, Brännström et al. (2021) found that bilingual Swedish children (ages 7–9) had more pupil dilation when processing spoken passages in a typical classroom condition than in a favorable setting with less noise, again supporting the idea that bilingual language processing may demand more listening effort.

The picture, however, becomes more complicated when considering individual differences (e.g., language proficiency and use, cognitive ability). For example, the modulatory role of L2 proficiency in the relationship between pupil dilation and effort appears inconsistent. In a picture–word matching experiment, Schmidtke (2014) examined English spoken word recognition among English monolinguals and Spanish-English bilinguals who learned English either in childhood or adulthood. He found that bilinguals with higher English proficiency showed smaller pupil dilation, suggesting that increased proficiency may ease processing and reduce effort. However, Borghini and Hazan (2018, 2020) showed that bilinguals' linguistic profiles (e.g., self-reported English proficiency and use) did not reliably predict pupil size. Yet, Beatty-Martínez et al. (2021) found that early Spanish-English bilinguals with more code-switching experience (i.e., alternating between two languages in conversation) and better attention ability (measured by the elevator counting task) had larger pupil dilation when processing code-switched speech – indicative of greater cognitive engagement.

In addition, contextual factors (e.g., task demands) also shape pupillary responses. In an earlier study with highly proficient Finnish-English bilinguals, Hyönä et al. (1995) observed smaller pupil size during active listening compared to more demanding tasks (e.g., repetition or simultaneous interpretation), suggesting a positive link between processing difficulty and pupil dilation. Taken together, prior findings in the literature illustrate that pupil dilation may not simply be associated with listening effort but reflect the combined effects of individual differences and contextual factors. Nonetheless, it seems that sequential bilinguals often require more listening effort when processing L2 compared to L1, and relative to monolinguals processing the same language (e.g., Borghini & Hazan, 2018, 2020; Francis et al., 2018). Yet the influence of age of acquisition (AoA) and proficiency complicates interpretations of pupil data (e.g., Schmidtke, 2014; cf. Francis et al., 2018).

Notably, little research has investigated the processing of a shared L1 among monolinguals and simultaneous bilinguals. In contrast to sequential bilinguals, simultaneous bilinguals are those who learned both languages before the age of three and typically have comparable proficiency across languages. This is the entry point of our work in terms of the population being compared and the language being tested. Specifically, we chose to test simultaneous bilinguals because it enables us to understand more about the effects of a bilingual vs. monolingual environment on cognition, while minimizing the confounding influences of AoA and language proficiency across language groups.

3. The current study

The goal of our study was to investigate how listening effort, indexed by pupil dilation, is influenced by language environment and individual difference (e.g., language proficiency, cognitive ability) factors in monolinguals and simultaneous bilinguals during spoken language processing (pre-registered on the Open Science Framework at https://osf.io/csz3a). We approached this goal through the lens of attentional resources, an aspect of attention overlooked in bilingualism research. While bilinguals are suggested to have enhanced attention control especially in the nonlinguistic domain (e.g., Bialystok, 2017; Bialystok & Craik, 2022), it is often assumed that this benefit stems from their practice of language switching. Focusing on listening effort in speech processing, our study probed into the origin of the bilingual advantage by shifting the spotlight from the nonlinguistic domain to a linguistic context and examining effects that contribute to monolingual vs. bilingual differences beyond language switching.

3.1. Population

Considering bilingualism as a continuum (e.g., Luk & Bialystok, 2013; Marian & Hayakawa, 2021), we tested two groups of native Canadian English speakers with comparable age and socioeconomic status (SES) background: monolinguals and simultaneous heritage bilinguals who had similar AoA of English. These two groups represent the two endpoints of the bilingualism spectrum with distinct linguistic environments. For example, compared to monolinguals, simultaneous bilinguals have less English exposure but higher linguistic complexity (e.g., more phonological and syntactic variabilities from different languages). Additionally, we were able to minimize the effects of various confounders that differ across monolinguals and sequential bilinguals (e.g., AoA, language proficiency), and consider factors that vary within our simultaneous bilingual sample.

3.2. Factors

Combining the categorical and continuous approaches to bilingualism (Kremin & Byers-Heinlein, 2021), we assigned participants

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

to a monolingual or bilingual group while also factoring into continuous individual variations within each group. As such, we analyzed not only the categorical variable of language group, but also continuous variables related to language environment (e.g., language exposure, linguistic complexity) and individual differences (e.g., language proficiency, cognitive ability). By doing so, we assessed the modulatory role of various environmental and individual variables on pupil responses, which has not been systematically addressed in previous bilingualism research on spoken language processing.

3.3. Conditions

We designed two conditions where participants listened to speech varied by language familiarity. In an active listening task, participants were presented with passages spoken in a familiar (English) or unfamiliar (Hebrew) language. Neuroimaging evidence from monolinguals has shown that speech processing of an unfamiliar language, without semantic support, is more effortful than that of L1. For example, Cotosck et al. (2021) found that the brain network associated with attention demanding tasks was activated in Brazilian listeners only when a story was presented in an unknown language (Japanese) to the participants but not in their L1 (Portuguese). Similar results were also obtained by Hernández et al. (2019) among Spanish speakers. Further, developmental studies suggest that simultaneous bilingual infants and toddlers appear to be more attentive to novel linguistic information, which can be possibly explained by their cognitive adaptations to the bilingual environment that features more novelty and variance than its monolingual counterpart (e.g., Costa & Sebastián-Gallés, 2014; Kovács, 2015; Molnar et al., 2021). Whether this is the case in adulthood, by the time more linguistic experience is accumulated, remains unclear.

Surrounding the bilingualism effects on listening effort indicated by pupil dilation during spoken language processing, we asked three research questions described as below. Our overarching hypothesis was that bilingual experience would alter pupillary response. To test it, we implemented a categorical comparison (i.e., monolingual vs. bilingual participants) in question (*i*), adopted a continuous approach (via language exposure) in question (*ii*) and examined the role of other control variables (i.e., language proficiency, cognitive ability) in question (*iii*).

(i) Is there a difference in pupil size between monolinguals and bilinguals when they listen to passages in different conditions: spoken in a familiar or unfamiliar language? We predicted that the unfamiliar language condition would elicit larger pupil size in monolinguals since it is more cognitively demanding, considering evidence from brain imaging data (e.g., Cotosck et al., 2021; Hernández et al., 2019). Further, as bilinguals have less English exposure and show increased pupil dilation in previous studies (e.g., Borghini & Hazan, 2018, 2020), we hypothesized that they may have larger pupil size than monolinguals when listening to the familiar language.

(ii) What are the effects of language exposure (e.g., the amount of English exposure, length of stay in an English-speaking environment) and linguistic complexity (e.g., the number of languages known) on participants' pupil size during speech processing? Given previous evidence suggesting smaller pupil dilation in monolinguals than bilinguals when listening to English (e.g., Borghini & Hazan, 2018, 2020), we hypothesized that monolingual characteristics, such as more English exposure, a longer stay in an English-speaking environment and fewer languages known, would correlate with smaller pupil size in the familiar language condition.

(iii) Are participants' language proficiency and cognitive ability associated with their pupil size during spoken passage processing? In light of mixed findings about the relationship between pupil dilation and linguistic/cognitive capabilities (e.g., Beatty-Martínez et al., 2021; Koelewijn et al., 2012; Schmidtke, 2014; cf. Koelewijn et al., 2014; Zekveld et al., 2014), we considered this as an exploratory question and thus did not have a specific hypothesis.

4. Methods

4.1. Participants

We recruited 73 young adults through flyers, word of mouth, and online posts in Toronto, Ontario, Canada. A great majority (82.19%) were undergraduate and graduate students at the University of Toronto, with the rest mainly being alumni and employees in the neighboring community. To be eligible to participate, participants had to be: (i) aged between 18 and 25 years; (ii) born in or immigrated to Canada before the age of three; (iii) either an English-speaking monolingual or an English-speaking bilingual who learned both or all languages before the age of three and do not know Hebrew (as it was the unfamiliar language in the experiment); (iv) with normal hearing and normal or corrected-to-normal vision. Some monolingual participants may have passive exposure to another language (e.g., overhearing another language at school or work settings, as defined in Castro et al., 2022), but we only included those who reported ≤20%; we acknowledge that this criterion was post hoc when defining our monolingual group. Before participation, we obtained written informed consent from all participants, who were compensated $15 per hour after the experiment. The University of Toronto Health Sciences Research Ethics Board reviewed and approved the ethics protocol.

Seventy participants (36 monolingual, 34 bilingual) were included in the final analysis because three bilinguals had missing pupil data due to excessive amounts of blinks (i.e., <50% usable trials; see Oliva, 2018; Olmos-Solis et al., 2018). This sample size was determined based on previous pupillometry studies with similar designs (e.g., Borghini & Hazan, 2020). Participants' language background was assessed using an online questionnaire adapted from the *LEAP-Q* (Language Experience and Proficiency Questionnaire; Marian et al., 2007). For English listening proficiency, all participants reported an 8 (very good) or above on a scale from 0 (none) to 10 (perfect). Notably, we observed a heterogeneous heritage language background in our bilingual sample, which reflected the diverse linguistic profile of the Toronto metropolitan area: the additional languages they knew included French, Cantonese, Mandarin, Spanish, Arabic, Korean, Greek, Italian, Vietnamese, Tamil or Urdu. We also assessed SES by scoring participants' highest level of education and family or personal income. Moreover, participants' language proficiency and cognitive ability were evaluated via CELF-5 (Clinical Evaluation of Language Fundamentals Fifth Edition; Wiig et al., 2013) and TONI-4 (Test of Nonverbal Intelligence Fourth Edition; Brown et al., 2010), respectively (see Section 4.3 for more details). Table 1 summarizes key participant characteristics.

We conducted *t*-tests (see Supplementary Table S1 for detailed results) and found significant group comparisons for three

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

Table 1. Participant characteristics

	Monolingual	Bilingual
Number of participants	36	34
Sex distribution (M:F)	15:21	17:17
Age (in years)	21.03 (2.02)	20.50 (2.35)
English exposure***	.97 (.06)	.7 (.15)
Years spent in an English-speaking family**	20.89 (2.04)	16.27 (8.02)
Years spent in an English-speaking school/ workplace	18.81 (2.66)	18.47 (3.51)
Number of languages known***	1.31 (.62)	2.71 (.8)
SES score (combining highest level of education and family or personal income)	2.81 (1.37)	2.38 (1.02)
CELF-5 score	10.78 (1.78)	11.41 (1.45)
TONI-4 score	104.64 (7.74)	107.06 (9.57)

Note: Values in the group columns are means (*standard deviation* or *SD*). Asterisks indicate significant group comparisons (***$p < .001$, **$p < .01$).

measures: English exposure ($p < .001$), years spent in an English-speaking family ($p = .002$) and the number of languages known ($p < .001$). As expected, monolinguals had significantly greater exposure to English, longer residence in an English-speaking family and fewer languages known than bilinguals. However, the two groups had similar years of staying in an English-speaking school/workplace. Further, comparable SES, CELF-5 and TONI-4 scores demonstrate that participants' SES background, language proficiency and cognitive ability were matched.

4.2. Materials

Materials used in this study are accessible at https://doi.org/10.5683/SP3/HBPALF.

4.2.1. Auditory materials

Auditory materials consisted of 20 spoken passages: 10 in English as the familiar language and 10 in Hebrew as the unfamiliar language. Two passages (one in each language) were used for practices and the remaining 18 for study trials. Passages were excerpts from travel guides describing cities worldwide and were recorded by three highly proficient Hebrew-English female bilingual Canadians. Recordings were processed using *Adobe Audition* to reduce noise and normalize intensity. In terms of duration, these passages lasted for 29.92 seconds on average, ranging from 28.52 to 30.76 s. Given the shortest duration, 28 s were used as the cutoff across trials in analysis.

Moreover, questions were recorded by a female native Canadian English speaker in a soundproof booth using a SONY digital recorder. These questions asked whether the participant heard a specific word in the spoken passage (e.g., "Did you hear the word 'beautiful'?"). In the unfamiliar language condition, we used cognates with similar meanings/pronunciations to English (e.g., "Italy," "auto") for half of the target words, and words that were totally unknown to participants for the other half. The speaker who recorded the questions was trained on how to pronounce these Hebrew words. Additionally, we varied where the target word occurred in the passage (i.e., at the beginning, in the middle, in the end, or did not occur) to prevent participants from anticipation.

4.2.2. Visual materials

Three screensavers (duration: 26–30 s) were used to maintain the participants' gaze on the display. Adopted from Nencheva et al. (2020), these videos were made isoluminant to minimize the luminance effects on pupil dilation.

4.3. Procedure

Before the experiment, participants spent 10–15 minutes filling out an online language and SES background questionnaire. For language background, participants were asked to report their acquisition of, exposure to, and proficiency in each language they knew. For SES, questions were about participants' highest level of education and family or personal income (contingent on whether they received financial support from family).

Participants sat in a sound-attenuated room during the experiment and completed an active listening task. The task began with two practice trials (the first in English, the second in Hebrew) to familiarize participants with the task, followed by 18 study trials equally divided into two blocks and randomized within each block. Participants started with either the familiar language or the unfamiliar language block. At each trial (Figure 1A), they listened to a spoken passage over headphones for about 30 s while looking at a screensaver on a 24-inch DELL monitor. To ensure that participants were paying attention while listening, a question asking whether they heard a specific word was embedded 2 s after each passage. Participants responded by pressing corresponding keys on a keyboard within 10 s. The correct response to most trials was yes, except for two it was no. This setup was designed to encourage participants to remain listening and be attentive during the task. Participants' eye movement data were recorded via an EyeLink 1000 Plus desktop mount eye tracker (SR Research) at a sampling rate of 500 Hz (Figure 1B). The experiment was programmed with

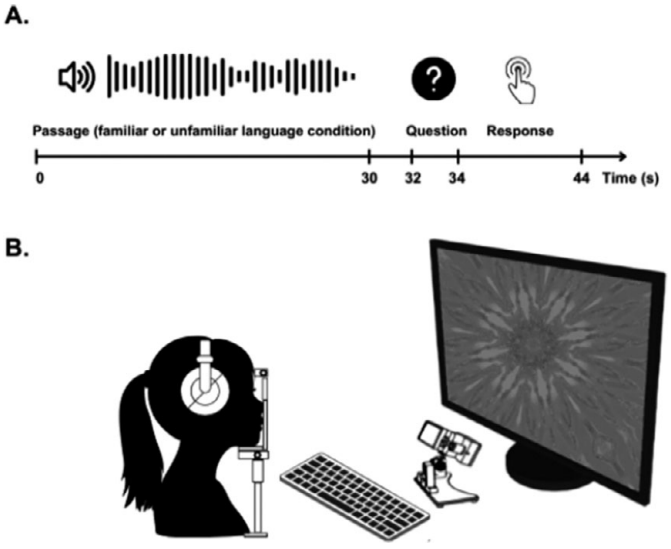


Figure 1. Trial process and recording setup of the active listening task. (A) Trial schema. At each trial, participants listened to a passage, spoken in either a familiar or unfamiliar language, for about 30 s. After a brief interval, they were asked whether they had heard a word in the passage. Then, they had 10 s to respond by pressing a key on the keyboard. (B) Recording setup. During the task, participants listened to the passages via headphones while looking at an isoluminant screensaver (to minimize the luminance effects on pupil size) on the display. A chinrest was used to ensure head stability. Pupil data were recorded via a desktop mount eye tracker.

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

the SR Research Experiment Builder software (v2.3.1; SR Research Ltd., 2020) and took around 15 min to complete.

After the experiment, participants' language proficiency and cognitive ability were measured. Focusing on expressive language, three subtests of CELF-5 were used: Recalling Sentence, Sentence Assembly, and Formulated Sentence. Considering the participant's age, raw data obtained from these subtests were converted to scaled scores and then averaged as an overall CELF-5 score. Afterward, TONI-4 was administered to evaluate participants' cognitive ability and raw data were converted to index scores. It took approximately 45 min to complete these two tests.

4.4. Data processing

Pupil data were preprocessed using the *PupilPre* package (v0.6.2; Kyröläinen et al., 2019) in *R* (v4.3.2; R Core Team, 2023). Based on the sample report generated from the EyeLink Data Viewer software (v4.1.1; SR Research Ltd., 2019), we aligned pupil data to the stimulus onset and created a time series for subsequent processing and modelling. As most participants had the right eye as the dominant eye (also see Reiss & Reiss, 1997), we used data from the right pupil across the sample, which consisted of 1260 trials (70 participants × 18 study trials). We removed 149 trials that had sparse data (<50%) in the baseline period (0–300 ms, which was the average time range for our auditory stimuli to initiate) and in the critical window (2–28 s; data visualization suggested that it took 2 s for the pupil size to stabilize in our design, see time evolution in Supplementary Figure S1). Afterward, we performed baseline correction by subtracting the average pupil size in the baseline period from that in the critical window. Then, we downsampled pupil data to 25 Hz to reduce autocorrelation between neighboring data points. Since pupil size was returned as arbitrary pixel units from the EyeLink system, we used a printed artificial eye for pupil calibration and then converted pupil size to millimeter (mm).

4.5. Data analysis

To analyze pupil data, we decided to build linear mixed effects models via the *lme4* package (v1.1-35.1; Bates et al., 2015) after consulting a statistician. This model approach was deemed better relative to generalized additive mixed modeling (GAMM; Wood, 2017), considering our relatively long interest period and that it was also used in previous studies with a similar length of interest period (e.g., Fawcett, 2022; Nencheva et al., 2020; Thoma, 2023). Estimated *p*-values for model fit and comparisons were calculated using the *lmerTest* package (v3.1-3; Kuznetsova et al., 2017). The dependent variable was mean pupil size (in mm), measured in the time window from 2 s (i.e., the time point when pupil size stabilized after stimulus onset) to 28 s (i.e., the time point when stimuli terminated at the earliest) while the spoken passages were presented. For fixed effects, we included the following independent variables: *Condition* (categorical: familiar language vs. unfamiliar language), categorical bilingual variable *Language Group* (monolingual vs. bilingual), continuous bilingual variables with significant group differences (ref. Table 1) *English Exposure*, *Years Spent in an English-Speaking Family*, and *Number of Languages Known*, as well as control variables *CELF-5 score*, *TONI-4 score*, and *SES score*. For random effects, we included a random slope for *Condition* by participants.

Fixed and random effects were fitted separately in a stepwise forward manner. First, we created a null model with a random intercept for participants. We evaluated whether adding a new component (i.e., a predictor or an interaction) significantly contributed to the model fit via the likelihood ratio test, implemented using the *anova* function that compares a complex model and its simpler version. We inspected the estimated *p*-value derived from model comparison and the Akaike information criterion (AIC) values associated with each model. The complex model was favored when the resulting difference was significant ($p < .05$) and its AIC value was smaller; otherwise, the simpler model was selected (Matuschek et al., 2017). Following this model comparison approach (see Lewis et al., 2010; Stephens et al., 2005), we tested the significance of a predictor or an interaction. Once the optimal model was determined, based on it, we conducted multiple comparisons for significant interactions using the *emmeans* package (v1.8.9; Lenth, 2023), while applying the Tukey adjustment method to guard against Type I error; significant comparisons ($p < .05$) were reported below. For data visualization, we used the *ggplot2* (v3.4.4; Wickham, 2016) package to plot the estimates of marginal means and standard errors that were obtained from the best fit model.

5. Results

We first examined how accurately monolinguals and bilinguals responded to questions under familiar and unfamiliar language conditions by calculating the mean accuracy rate (i.e., the percentage of correct responses). The two groups performed similarly both across conditions (monolinguals: 57.87%, bilinguals: 60.13%; $t(63.24) = .89$, $p = .375$) and within each condition (see Supplementary Table S2 for further details). Additionally, we compared accuracy rates between conditions both across groups and within each group, but observed no significant differences (see Supplementary Table S2). In sum, there were no significant differences in accuracy between groups or conditions. The relatively low accuracy rates may reflect the difficulty of our task, which resembled a foil paradigm designed to maximize participants' attention during listening. Given this, we retained all trials in the pupil data analysis regardless of response accuracy.

We then investigated how bilingual experience influenced participants' pupil size in the two conditions. Using the model comparison approach, we found a significant effect of *Condition* ($p < .001$) along with three relevant significant interactions: *Condition* × *Language Group* ($p < .001$), *Condition* × *English Exposure* ($p < .001$) and *Condition* × *Years Spent in an English-Speaking Family* ($p = .016$). Adding an interaction term significantly improved the model fit compared to a reduced model containing only the main effects. However, due to multicollinearity, we analyzed each interaction separately in individual models. Notably, no other predictors yielded significant effects (e.g., *Number of Languages Known*: $p = .750$; *CELF-5 Score*: $p = .933$; *TONI-4 Score*: $p = .913$; *SES Score*: $p = .204$).

Focusing on the interaction between *Condition* and *Language Group*, we identified the optimal model (see Table 2). Post hoc comparisons revealed that monolinguals exhibited significantly larger pupil size when listening to the unfamiliar language compared to the familiar one ($p = .042$); however, no other comparisons reached significance. This interaction is visualized in Figure 2. Although visual inspection indicates that bilinguals tended to have larger pupil size than monolinguals across conditions (particularly in the familiar language condition) and that their pupil responses remained relatively similar between conditions, these patterns were not statistically significant.

Similarly, we built separate models to examine the other two significant interactions: *Condition* × *English Exposure* (see optimal

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

Table 2. Model summary: Pupil size predicted by the interaction between *Language Group* and *Condition*

Linear mixed effects model fit by restricted maximum likelihood (*t*-tests use Satterthwaite's method)				
Fixed effects	Estimate	Standard error	*t*	*p*
Intercept	1.99654	.09231	21.628	<2e–16 ***
Language Group: Bilingual	.04972	.13245	.375	.7085
Condition: Unfamiliar	.07363	.03615	2.037	.0455 *
Language Group: Bilingual × Condition: Unfamiliar	−.04062	.05186	−.783	.4362
Random effects	Name	Variance	*SD*	Correlation
Subject	Intercept	.30669	.5538	
	Condition: Unfamiliar	.04686	.2165	−.26
Residual		.33520	.5790	
Number of observations: 606,583; number of subjects: 70				

Note: ***p < .001, **p < .01, *p < .05.

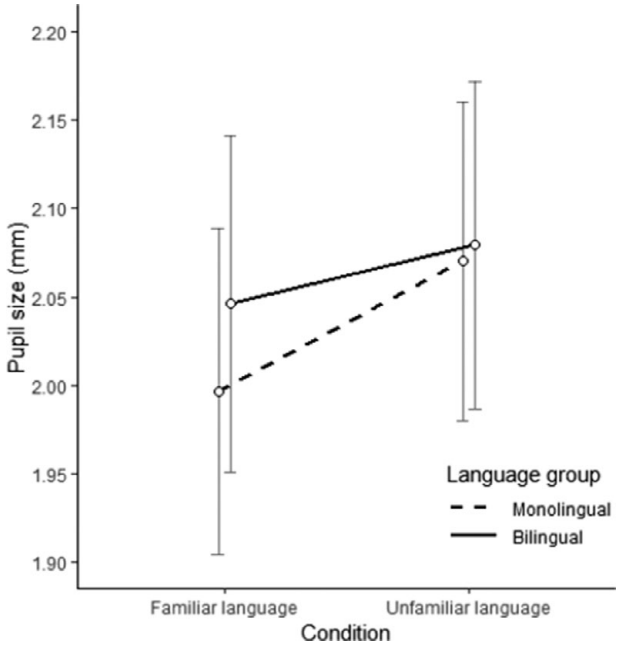


Figure 2. Pupil size was predicted by the interaction between *Condition* and *Language Group*. Based on the optimal model, estimated marginal means and standard error bars were plotted. Applying the Tukey adjustment method, multiple comparisons suggest that only in monolinguals (the dashed line), listening to an unfamiliar language elicited significantly larger pupil size than listening to a familiar language (p = .042).

model summary in Supplementary Table S2) and *Condition* × *Years Spent in an English-Speaking Family* (see summary in Supplementary Table S3). Both models revealed a consistent pattern: greater English exposure and a longer duration of residence in an English-speaking family (i.e., toward the monolingual end of the spectrum) were associated with smaller pupil size, particularly in the familiar language condition.

6. Discussion

Studying bilingualism is important from the perspective of equity and diversity, as at least half of the global population is bilingual (Giannini, 2024); hence, experimental findings should be representative to a significant portion of the entire population. Most studies thus far have focused on comparing monolingual and bilingual abilities. While this approach has given us a glimpse into the bilingual mind, its explanatory power about bilingual language processing is limited. Subsequently, there have been recent calls to increase the explanatory power of studies conducted on bilinguals, in a way that we can build more detailed theoretical models relevant to language and cognition (e.g., Blanco-Elorrieta & Caramazza, 2021; Marian & Hayakawa, 2021). Responding to these calls, we included both categorical and continuous variables of bilingualism in the analyses. More importantly, our study quantified auditory attention allocation during speech processing via pupil dilation – providing a novel angle for understanding attention in bilingualism research. While changes in pupil size can reflect various cognitive processes (e.g., attention, memory, and arousal; see Fink et al., 2024 for a review), we focused on gauging attentional resources – equivalent to listening effort defined by Pichora-Fuller et al. (2016). We also acknowledge that the relation between attention and effort remains debated, with some accounts treating them as overlapping but distinct constructs (e.g., Bruya & Tang, 2018).

Most theoretical frameworks describing differences between monolingual and bilingual cognition have primarily focused on attentional control in the nonlinguistic domain (e.g., Bialystok & Craik, 2022; Green & Abutalebi, 2013). Conversely, our study investigated attentional resources (or listening effort) during spoken language processing in two groups of native English speakers: monolinguals and simultaneous heritage bilinguals. Using an active listening task, we presented participants with passages in two conditions: spoken in a familiar (English) or unfamiliar (Hebrew) language. Combining the categorical and continuous approaches to bilingualism (Kremin & Byers-Heinlein, 2021), we compared pupil responses between the two language groups and examined the modulatory role of various environmental and individual factors on pupil dilation. Overall, we hypothesized that greater English exposure/proficiency would be associated with less pupil dilation.

We observed a significant effect of the experimental condition (familiar vs. unfamiliar language) and its interactions with language groups and with environmental variables, such as the amount of English exposure and length of stay in an English-speaking family.

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

Specifically, a group distinction arose when comparing the two conditions: listening to an unfamiliar language evoked larger pupil size than listening to a familiar one in monolinguals only, whereas bilinguals had similar pupil responses across conditions. It should also be noted that though not statistically significant, bilinguals tended to exhibit larger pupil size than monolinguals, and the difference was more pronounced in the familiar language condition (i.e., while listening to English; Figure 2). Further, consistent results were found when evaluating participants on the spectrum of bilingual experience: more English exposure and a more extended stay in an English-speaking family correlated with smaller pupil size, particularly in the familiar language condition. Note that we minimized the effects of AoA by only including simultaneous bilinguals, and those with more English experience exhibited more monolingual-like patterns. Taken together, our findings suggest that listening effort is related to an individual's overall linguistic experience, especially the amount of early language exposure at home. There seems to be a gradient of the relation across participants: processing a completely unknown language is most effortful, processing a language that was learned early in life but not the primary language spoken at home is less effortful, and processing a language that was the dominant language at home from infancy is the least effortful (further discussed in Section 6.2).

In addition, individual English language proficiency scores obtained from a standardized test were not associated with participants' pupil dilation. This finding suggests that it is not the level of English proficiency but the amount of English exposure that seems relevant to listening effort expanded in speech processing. However, there was no significant difference in proficiency scores between our monolingual and bilingual participants, which was unsurprising because our simultaneous heritage bilinguals were also native English speakers. Finally, individual cognitive ability scores were not linked to pupil size changes either. Likewise, there was no significant group difference in this cognitive measure among our participants, who were mostly university students. Therefore, it may be that our data did not have enough variation in terms of cognitive scores to show an effect on pupil responses.

6.1. Language group comparison: monolinguals vs. bilinguals

We first asked if there was a difference between monolinguals and bilinguals in pupil responses during speech processing varied by language familiarity, and we predicted that listening to an unfamiliar language would elicit larger pupil size in monolinguals than listening to a familiar language. This prediction was confirmed by our data, which are consistent with previous neuroimaging data obtained from monolinguals (e.g., Cotosck et al., 2021; Hernández et al., 2019) suggesting that speech processing of an unknown language is more cognitively demanding than that of a known one. Further, we hypothesized that bilinguals would have larger pupil size than monolinguals when listening to the familiar language. This prediction was borne out too, but the group difference did not reach the significance level. Our result suggests that simultaneous English bilinguals may not require significantly more listening effort than monolinguals when processing English-spoken passages. While this finding seems to contrast with those of Borghini and Hazan (2018, 2020), it should be noted that they tested Italian L1–English L2 sequential bilinguals, who were included as long as they had lived in the United Kingdom for over three or 10 months (Borghini & Hazan, 2018, 2020). Thus, it is possible that we did not find a significant group difference because we included simultaneous bilinguals whose AoA is similar to that of monolinguals.

Moreover, our finding supports the attentional control framework regarding situations when the language group difference would occur. Specifically, it is postulated that monolinguals and bilinguals tend to exhibit differences under high attentional control demand (Bialystok & Craik, 2022). We observed significantly larger pupil size in the unfamiliar language condition than the familiar language one in monolinguals only, while bilinguals had similar pupil responses across conditions. A possible explanation is that higher linguistic complexity in the bilingual environment potentially facilitates the adaptation to novelty in a linguistic auditory scene, whereas monolinguals are habituated to monotonous linguistic input and thus would allocate more attentional resources to process unfamiliar spoken language (also see Kovács, 2015). Similar findings have been demonstrated in Spanish monolingual and bilingual toddlers listening to novel syntactic constructs (Molnar et al., 2021).

6.2. Language environment factors: language exposure and linguistic complexity

Our second question sought to determine what language environment variables influence pupil responses during spoken language processing, with a focus on language exposure and linguistic complexity. We hypothesized that when listening to the familiar language, participants would show smaller pupil size if they were more monolingual-like, namely having more exposure to English and more extended stay in an English-speaking environment along with knowing fewer languages. This was partially corroborated by the association between smaller pupil size and more English exposure. This finding is in line with the interactions between listener- and input-based variables frequently reported in previous studies (e.g., McCloy et al., 2017; Piquado et al., 2010) and reveals the complex processes involved in attentional resources allocation during auditory processing.

Further, as discussed earlier, our results reveal a gradient relation between language experience and listening effort, which highlights the role of early language exposure during infancy. Different processing patterns between monolinguals and simultaneous bilinguals can be partially attributed to the amount of early exposure to English, which may not be the dominant language spoken at home among many of our heritage bilingual participants. This is consistent with prior work showing that early exposure to a particular language can predict later language processing abilities (e.g., Hurtado et al., 2013; Schmidtke, 2014). However, pupil responses to both languages of bilinguals need to be measured, so as to disentangle the effects as a result of exposure to multiple languages (e.g., when bilinguals have equally larger pupil size for both of their languages relative to that of monolinguals listening to their native language) or exposure to their L1 only (e.g., when bilinguals' pupil size is only larger than that of monolinguals for English but not for their heritage language).

We did not find effects of the length of stay in an English-speaking professional setting, which could be attributed to the fact that our two groups had a comparable number of years spent in an English-speaking school/workplace. Additionally, no effect was found for how many languages the participants knew either, even though bilinguals knew significantly more. A possible explanation is that the number of languages known only represents an approximate estimate of linguistic complexity, and thus, it may not capture the kernel of this multidimensional construct. We acknowledge this as a limitation of our study and suggest further investigations focusing on linguistic complexity and its multiple facets (e.g.,

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

measuring the linguistic distance between languages known by the bilingual participants). Alternatively, bilinguals and multilinguals might rely on similar attentional resources, which could also be further explored in future research.

6.3. Individual difference factors: language proficiency and cognitive ability

Our third question concerned interindividual differences in language proficiency and cognitive ability. We hypothesized that participants' CELF-5 and TONI-4 scores may be related to their pupil responses, but neither was a significant predictor. While our results differ from some published research (e.g., Beatty-Martínez et al., 2021; Schmidtke, 2014), they are consistent with those of Koelewijn et al. (2014) and Zekveld et al. (2014). It should also be noted that our study used two standardized tests to assess language and cognitive abilities separately, which, however, are often measured together without distinction through one test or task in prior work. For example, Koelewijn et al. (2012) measured linguistic/cognitive abilities via cognitive tests with substantial verbal components (e.g., reading span and listening span tests that assess verbal working memory capacity) and referred to those two abilities interchangeably (also see Zekveld et al., 2014; Zekveld & Kramer, 2014). Yet, given mixed results in this area, more research is needed to establish a clear association between pupillary responses and language and cognitive abilities.

6.4. Limitations

Statistically, various methods are available to analyze pupil data. We chose the current technique as it is most suitable for our research design, considering experimental conditions and the trial duration (also see Fawcett, 2022; Nencheva et al., 2020; Thoma, 2023). Another technique commonly used in the field is GAMM. As a time-series approach, GAMM can include nonlinear interactions between pupil dilation and experimental predictors while handling variability and autocorrelation within the data (van Rij et al., 2019). However, it has been only used for time periods much shorter than our trial duration (e.g., 2–3 s; Chuang et al., 2021; van Rij et al., 2019). It is unclear whether GAMM is appropriate for much longer time periods (i.e., 28 s in our design). For full disclosure, we had conducted preliminary exploratory analyses using GAMM across the whole trial duration, but it has not yielded meaningful results and the model often did not even converge. We also considered analyzing shorter segments of the trial; however, we could not rely on any framework that could have guided trial truncation (i.e., duration of shorter segments).

7. Conclusions

Using pupil dilation as an index of listening effort, we investigated whether monolinguals and bilinguals differ in allocating their attentional resources – an overlooked aspect of cognition in the existing bilingualism literature and frameworks as they primarily focus on attentional control. Importantly, we approached this question in a linguistic context of spoken language processing, which addresses the origin of the bilingual advantage extensively studied in the nonlinguistic domain. Through testing two groups of native English speakers across the monolingual–bilingual spectrum, we not only compared monolinguals and simultaneous heritage bilinguals, but also explored the modulatory role of language environment and individual difference factors on pupil dilation. For the first time, our findings on pupillary responses provide support for neuroimaging evidence that phonological processing of an unknown language is more effortful than that of a native language in monolingual speakers. Further, they confirm the postulation that monolingual and bilingual differences are more observable in cognitively demanding situations. We conclude that simultaneous bilinguals differ from monolinguals in their attentional resource allocation, especially when listening to a novel linguistic input.

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/S1366728925100795.

Data availability statement. The data that support the findings of this study along with the materials used are openly available in Borealis (the Canadian Dataverse Repository) at https://doi.org/10.5683/SP3/HBPALF.

Acknowledgments. This work was supported by the Natural Sciences and Engineering Research Council of Canada awarded to M.M. (RGPIN-2019-06523).

Competing interests. The authors declare none.

References

Adesope, O. O., Lavin, T., Thompson, T., & Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Review of Educational Research*, **80**(2), 207–245. https://doi.org/10.3102/0034654310368803.

Bao, W., Alain, C., Thaut, M., & Molnar, M. (2024). Is there a bilingual advantage in auditory attention among children? A systematic review and meta-analysis of standardized auditory attention tests. *PLoS One*, **19**(5), e0299393. https://doi.org/10.1371/journal.pone.0299393.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, **67**(1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Beatty-Martínez, A. L., Guzzardo Tamargo, R. E., & Dussias, P. E. (2021). Phasic pupillary responses reveal differential engagement of attentional control in bilingual spoken language processing. *Scientific Reports*, **11**(23474). https://doi.org/10.1038/s41598-021-03008-1.

Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin*, **143**(3), 233–262. https://doi.org/10.1037/bul0000099.

Bialystok, E., & Craik, F. I. M. (2022). How does bilingualism modify cognitive function? Attention to the mechanism. *Psychonomic Bulletin & Review*, **29**, 1246–1269. https://doi.org/10.3758/s13423-022-02057-5.

Blanco-Elorrieta, E., & Caramazza, A. (2021). On the need for theoretically guided approaches to possible bilingual advantages: An evaluation of the potential loci in the language and executive control systems. *Neurobiology of Language*, **2**(4), 452–463. https://doi.org/10.1162/nol_a_00041.

Borghini, G., & Hazan, V. (2018). Listening effort during sentence processing is increased for non-native listeners: A pupillometry study. *Frontiers in Neuroscience*, **12**, 152. https://doi.org/10.3389/fnins.2018.00152.

Borghini, G., & Hazan, V. (2020). Effects of acoustic and semantic cues on listening effort during native and non-native speech perception. *The Journal of the Acoustical Society of America*, **147**, 3783. https://doi.org/10.1121/10.0001126.

Brännström, K. J., Rudner, M., Carlie, J., Sahlén, B., Gulz, A., Andersson, K., & Johansson, R. (2021). Listening effort and fatigue in native and non-native primary school children. *Journal of Experimental Child Psychology*, **210**, 105203. https://doi.org/10.1016/j.jecp.2021.105203.

Brown, L., Sherbenou, R. J., & Johnsen, S. K. (2010). *Test of nonverbal intelligence fourth edition (TONI-4)*. PRO-ED.

Bruya, B., & Tang, Y.-Y. (2018). Is attention really effort? Revisiting Daniel Kahneman's influential 1973 book *attention and effort*. *Frontiers in Psychology*, **9**(9), Article 1133. https://doi.org/10.3389/fpsyg.2018.01133.

Castro, S., Wodniecka, Z., & Timmer, K. (2022). Am I truly monolingual? Exploring foreign language experiences in monolinguals. *PLoS One*, **17**(3), e0265563. https://doi.org/10.1371/journal.pone.0265563.

Chuang, Y.-Y., Fon, J., Papakyritsis, I., & **Baayen, H.** (2021). Analyzing phonetic data with generalized additive mixed models. In M. Ball (Ed.), *Manuals of clinical phonetics* (1st ed., pp. 108–138). Routledge.

Costa, A., & **Sebastián-Gallés, N.** (2014). How does the bilingual experience sculpt the brain? *Nature Reviews Neuroscience*, **15**(5), 336–345. https://doi.org/10.1038/nrn3709.

Cotosck, K. R., Meltzer, J. A., Nucci, M. P., Lukasova, K., Mansur, L. L., & **Amaro, E.** (2021). Engagement of language and domain general networks during word monitoring in a native and unknown language. *Brain Sciences*, **11**(8), 1063. https://doi.org/10.3390/brainsci11081063.

Crivello, C., Kuzyk, O., Rodrigues, M., Friend, M., Zesiger, P., & **Poulin-Dubois, D.** (2016). The effects of bilingual growth on toddlers' executive function. *Journal of Experimental Child Psychology*, **141**, 121–132. https://doi.org/10.1016/j.jecp.2015.08.004.

Fawcett, C. (2022). Sharing a common language affects infants' pupillary contagion. *Journal of Cognition and Development*, **23**(2), 173–187. https://doi.org/10.1080/15248372.2021.2013225.

Fink, L., Simola, J., Tavano, A., Lange, E. B., Wallot, S., & **Laeng, B.** (2024). From pre-processing to advanced dynamic modeling of pupil data. *Behavior Research Methods*, **56**, 1376–1412. https://doi.org/10.3758/s13428-023-02098-1.

Francis, A. L., Tigchelaar, L. J., Zhang, R., & **Zekveld, A. A.** (2018). Effects of second language proficiency and linguistic uncertainty on recognition of speech in native and nonnative competing speech. *Journal of Speech, Language, and Hearing Research*, **61**(7), 1815–1830. https://doi.org/10.1044/2018_JSLHR-H-17-0254.

Giannini, S. (2024). *Multilingual education: A key to quality and inclusive learning*. The United Nations. https://www.un.org/en/un-chronicle/multilingual-education-key-quality-and-inclusive-learning#:~:text=For%20more%20than%20seven%20decades,to%20achieving%20quality%2C%20inclusive%20learning.&text=Enhanced%20learning.,in%20a%20language%20they%20understand.

Green, D. W., & **Abutalebi, J.** (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, **25**(5), 515–530. https://doi.org/10.1080/20445911.2013.796377.

Grundy, J. G. (2020). The effects of bilingualism on executive functions: An updated quantitative analysis. *Journal of Cultural Cognitive Science*, **4**, 177–199. https://doi.org/10.1007/s41809-020-00062-5.

Hernández, M., Ventura-Campos, N., Costa, A., Miró-Padilla, A., & **Ávila, C.** (2019). Brain networks involved in accented speech processing. *Brain and Language*, **194**, 12–22. https://doi.org/10.1016/j.bandl.2019.03.003.

Hess, E. H., & **Polt, J. M.** (1960). Pupil size as related to interest value of visual stimuli. *Science*, **132**(3423), 349–350. https://doi.org/10.1126/science.132.3423.349.

Hurtado, N., Grüter, T., Marchman, V. A., & **Fernald, A.** (2013). Relative language exposure, processing efficiency and vocabulary in Spanish–English bilingual toddlers. *Bilingualism: Language and Cognition*, **17**(1), 189–202. https://doi.org/10.1017/s136672891300014x.

Hyönä, J., Tommola, J., & **Alaja, A. M.** (1995). Pupil dilation as a measure of processing load in simultaneous interpretation and other language tasks. *The Quarterly Journal of Experimental Psychology*, **48**(3), 598–612. https://doi.org/10.1080/14640749508401407.

Kahneman, D. (1973). *Attention and effort*. Prentice-Hall.

Koelewijn, T., Zekveld, A. A., Festen, J. M., Rönnberg, J., & **Kramer, S. E.** (2012). Processing load induced by informational masking is related to linguistic abilities. *International Journal of Otolaryngology*, **2012**. https://doi.org/10.1155/2012/865731.

Koelewijn, T., Zekveld, A. A., Festen, J. M., & **Kramer, S. E.** (2014). The influence of informational masking on speech perception and pupil response in adults with hearing impairment. *The Journal of the Acoustical Society of America*, **153**, 1596–1606. https://doi.org/10.1121/1.4863198.

Kovács, Á. M. (2015). Cognitive adaptations induced by a multi-language input in early development. *Current Opinion in Neurobiology*, **35**, 80–86. https://doi.org/10.1016/j.conb.2015.07.003.

Kremin, L. V., & **Byers-Heinlein, K.** (2021). Why not both? Rethinking categorical and continuous approaches to bilingualism. *International Journal of Bilingualism*, **25**(6), 1560–1575. https://doi.org/10.1017/S1366728923000433.

Krizman, J., Skoe, E., Marian, V., & **Kraus, N.** (2014). Bilingualism increases neural response consistency and attentional control: Evidence for sensory and cognitive coupling. *Brain and Language*, **128**(1), 34–40. https://doi.org/10.1016/j.bandl.2013.11.006.

Kuznetsova, A., Brockhoff, P. B., & **Christensen, R. H. B.** (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, **82**(13), 1–26. https://doi.org/10.18637/jss.v082.i13.

Kyröläinen, A., Porretta, V., van Rij, J., & **Järvikivi, J.** (2019). PupilPre: Tools for preprocessing pupil size data. R package version 0.6.2. https://CRAN.R-project.org/package=PupilPre.

Laeng, B., Sirois, S., & **Gredebäck, G.** (2012). Pupillometry: A window to the preconscious? *Perspectives on Psychological Science*, **7**(1), 18–27. https://doi.org/10.1177/1745691611427305.

Lehtonen, M., Soveri, A., Laine, A., Järvenpää, J., de Bruin, A., & **Antfolk, J.** (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychological Bulletin*, **144**(4), 394–425. https://doi.org/10.1037/bul0000142.

Lenth, R. (2023). emmeans: Estimated marginal means, aka least-squares means. R package version 1.8.9. https://CRAN.R-project.org/package=emmeans.

Lewis, F., Butler, A., & **Gilbert, L.** (2010). A unified approach to model selection using the likelihood ratio test. *Methods in Ecology and Evolution*, **2**(2), 155–162. https://doi.org/10.1111/j.2041-210x.2010.00063.x.

Lowe, C. J., Cho, I., Goldsmith, S. F., & **Morton, J. B.** (2021). The bilingual advantage in children's executive functioning is not related to language status: A meta-analytic review. *Psychological Science*, **32**(7), 1115–1146. https://doi.org/10.1177/0956797621993108.

Luk, G., & **Bialystok, E.** (2013). Bilingualism is not a categorical variable: Interaction between language proficiency and usage. *Journal of Cognitive Psychology*, **25**(5), 605–621. https://doi.org/10.1080/20445911.2013.795574.

Marian, V., Blumenfeld, H. K., & **Kaushanskaya, M.** (2007). The language experience and proficiency questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *Journal of Speech, Language, and Hearing Research*, **50**(4), 940–967. https://doi.org/10.1044/1092-4388(2007/067.

Marian, V., & **Hayakawa, S.** (2021). Measuring bilingualism: The quest for a "bilingualism quotient". *Applied PsychoLinguistics*, **42**(2), 527–548. https://doi.org/10.1017/S0142716420000533.

Matuschek, H., Kliegl, R., Vasishth, S., Baayen, H., & **Bates, D.** (2017). Balancing type I error and power in linear mixed models. *Journal of Memory and Language*, **94**, 305–315. https://doi.org/10.1016/j.jml.2017.01.001.

McCloy, D. R., Lau, B. K., Larson, E., Pratt, K. A., & **Lee, A. K.** (2017). Pupillometry shows the effort of auditory attention switching. *The Journal of the Acoustical Society of America*, **141**(4), 2440–2451. https://doi.org/10.1121/1.4979340.

Molnar, M., Alemán Bañón, J., Mancini, S., & **Caffarra, S.** (2021). The processing of Spanish article–noun gender agreement by monolingual and bilingual toddlers. *Language and Speech*, **64**(4), 980–990. https://doi.org/10.1177/0023830920977050.

Nencheva, M. L., Piazza, E. A., & **Lew-Williams, C.** (2020). The moment-to-moment pitch dynamics of child-directed speech shape toddlers' attention and learning. *Developmental Science*, **24**(1), e12997. https://doi.org/10.1111/desc.12997.

Oliva, M. (2018). Pupil size and search performance in low and high perceptual load. *Cognitive, Affective, & Behavioral Neuroscience*, **19**, 366–376. https://doi.org/10.3758/s13415-018-00677-w.

Olmos-Solis, K., van Loon, A. M., & **Olivers, C. N. L.** (2018). Pupil dilation reflects task relevance prior to search. *Journal of Cognition*, **1**(1), 11. https://doi.org/10.5334/joc.12.

Ooi, S. H., Goh, W. D., Sorace, A., & **Bak, T. H.** (2018). From bilingualism to bilingualisms: Bilingual experience in Edinburgh and Singapore affects attentional control differently. *Bilingualism: Language and Cognition*, **21**(4), 867–879. https://doi.org/10.1017/s1366728918000020.

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C. L., Naylor, G., Phillips, N. A., Richter, M., Rudner, M., Sommers, M. S., Tremblay, K. L., & **Wingfield, A.** (2016). Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL). *Ear and Hearing*, **37**, 5S–27S. https://doi.org/10.1097/AUD.0000000000000312.

Piquado, T., Isaacowitz, D., & **Wingfield, A.** (2010). Pupillometry as a measure of cognitive effort in younger and older adults. *Psychophysiology*, **47**(3), 560–569. https://doi.org/10.1111/j.1469-8986.2009.00947.x.

Team, R. C. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press

Reiss, M., & **Reiss, G.** (1997). Ocular dominance: Some family data. *Laterality*, **2** (1), 7–16. https://doi.org/10.1080/713754254.

Schmidtke, J. (2014). Second language experience modulates word retrieval effort in bilinguals: Evidence from pupillometry. *Frontiers in Psychology*, **5**, 137. https://doi.org/10.3389/fpsyg.2014.00137.

Shiffrin, R. M., & **Schneider, W.** (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review*, **84**(2), 127–190. https://doi.org/10.1037/0033-295X.84.2.127.

Soveri, A., **Laine, M.**, **Hämäläinen, H.**, & **Hugdahl, K.** (2010). Bilingual advantage in attentional control: Evidence from the forced-attention dichotic listening paradigm. *Bilingualism: Language and Cognition*, **14**(03), 371–378. https://doi.org/10.1017/s1366728910000118.

SR Research Ltd. (2019). EyeLink Data Viewer 4.1.1 [Computer software]. SR Research Ltd.

SR Research Ltd. (2020). SR Research Experiment Builder 2.3.1 [Computer software].SR Research Ltd.

Stafford, C. A. (2011). Bilingualism and enhanced attention in early adulthood. *International Journal of Bilingual Education and Bilingualism*, **14**(1), 1–22. https://doi.org/10.1080/13670050903568209.

Stephens, P. A., **Buskirk, S. W.**, **Hayward, G. D.**, & **Martinez Del Rio, C.** (2005). Information theory and hypothesis testing: A call for pluralism. *Journal of Applied Ecology*, **42**(1), 4–12. https://doi.org/10.1111/j.1365-2664.2005.01002.x.

Stocco, A., **Yamasaki, B.**, **Natalenko, R.**, & **Prat, C. S.** (2012). Bilingual brain training: A neurobiological framework of how bilingual experience improves executive function. *International Journal of Bilingualism*, **18**(1), 67–92. https://doi.org/10.1177/1367006912456617.

Thoma, D. (2023). Language-dependent emotions in heritage and second language bilinguals: When physiological reactions deviate from feelings. *International Journal of Bilingualism*, 1–16. https://doi.org/10.1177/13670069231159840.

van der Wel, P., & **van Steenbergen, H.** (2018). Pupil dilation as an index of effort in cognitive control tasks: A review. *Psychonomic Bulletin & Review*, **25** (6), 2005–2015. https://doi.org/10.3758/s13423-018-1432-y.

van Rij, J., **Hendriks, P.**, **van Rijn, H.**, **Baayen, R. H.**, & **Wood, S. N.** (2019). Analyzing the time course of pupillometric data. *Trends in Hearing*, **23**. https://doi.org/10.1177/2331216519832483.

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag New York.

Wiig, E. H., **Semel, E.**, & **Secord, W. A.** (2013). *Clinical evaluation of language fundamentals fifth edition (CELF-5)*. NCS Pearson.

Wood, S. (2017). *Generalized additive models: An introduction with R*. Chapman and Hall/CRC.

Zekveld, A. A., **Koelewijn, T.**, & **Kramer, S. E.** (2018). The pupil dilation response to auditory stimuli: Current state of knowledge. *Trends in Hearing*, **22**, 1–25. https://doi.org/10.1177/2331216518777174.

Zekveld, A. A., & **Kramer, S. E.** (2014). Cognitive processing load across a wide range of listening conditions: Insights from pupillometry. *Psychophysiology*, **51**, 277–284. https://doi.org/10.1111/psyp.12151.

Zekveld, A. A., **Rudner, M.**, **Kramer, S. E.**, **Lyzenga, J.**, & **Rönnberg, J.** (2014). Cognitive processing load during listening is reduced more by decreasing voice similarity than by increasing spatial separation between target and masker speech. *Frontiers in Neuroscience*, **8**(88). https://doi.org/10.3389/fnins.2014.00088.

https://doi.org/10.1017/S1366728925100795 Published online by Cambridge University Press