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Does Language Entropy Shape Cognitive Performance? A Tale of Two Cities

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Research Article

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Abstract

Research examining the cognitive consequences of bilingualism has increasingly relied on continuous measures to capture the degree and nature of bilingual experience, using such variables as proficiency, age of acquisition, and language environments. One such measure, language entropy, indexes the social diversity of contexts in which each language is used. The construct was developed in a particular bilingual context, Montréal, Canada. The present study investigated the extent to which it also applies to a context in which social language use is substantially different from that of Montréal – namely, Toronto, Canada. Following the procedures in the original study, participants were assigned an entropy score and performed the AX-Continuous Performance Task (AX-CPT). Performance was associated with self-rated language proficiency, but unlike the results from Montréal, was not associated with entropy scores. Therefore, differences in the language context influence whether language entropy is related to behavioral performance on a cognitive task.

Introduction

Research investigating the effect of bilingualism on cognitive functioning has moved away from categorical comparisons between participants classified as monolingual or bilingual to continuous measures that reflect the degree of bilingual experience within a diverse sample (Anderson, Mak, Keyvani Chahi & Bialystok, 2018; DeLuca, Rothman, Bialystok & Pliatsikas, 2019, 2020). These studies have shown that variations in bilingual experience, measured with such variables as age of acquisition, proficiency, and frequency and nature of language use, are incrementally related to changes in cognitive performance and brain outcomes. For example, DeLuca and colleagues (2019, 2020) found that the extent to which a second language was used in the community and the age of second language acquisition were associated with structural and functional adaptations in the brain such that greater experience was accompanied by increased changes in cognitive and brain outcomes. This research was based on an instrument developed by Anderson et al. (2018) in which the degree of bilingualism was quantified by computing a composite score from three factors: home language use and non-English language proficiency, social language use, and English proficiency. Higher bilingualism scores indicated more frequent, more intense, or more prolonged experience in using two languages in daily life.

Another approach to the quantification of bilingual experience is through the notion of language entropy. Language entropy indexes the diversity of language usage across communicative contexts. Estimates of which language or languages are used in specific settings or for specific purposes (such as home, work, school, healthcare, and social media) are used to produce a value indicating the diversity of language use across situations, with higher entropy values indicating greater diversity and less predictability (Gullifer & Titone, 2020). Data from language history questionnaires (Anderson et al., 2018; Li, Zhang, Tsai & Puls, 2014; Marian, Blumenfeld & Kaushanskaya, 2007) that quantify language use in various contexts can be converted to proportions and transformed into a score by use of Shannon's entropy formula (Shannon, 1948) to produce a measure of uncertainty about the use of a specific language in each context. The scores range from 0 to 1 for individuals who speak two languages, or 0 to 1.56 for individuals who speak three languages. Lower entropy scores indicate that a single language is likely to be used and higher scores indicate an increased likelihood that more than one language may be selected in that context. Thus, lower entropy scores represent relatively compartmentalized language use and higher entropy values indicate a more fluid use of languages across contexts. This measure adds an important dimension to the characterization of individual differences in bilingual experience.

Studies in various locations have reported an association between entropy scores and several linguistic and cognitive outcomes. For example, in Montréal, Canada where mean entropy values range from 0.60–0.94, higher entropy values were associated with better subjective and objective assessment of second-language proficiency and accentedness, increased connectivity in the anterior cingulate cortex, and more efficient engagement of proactive control (Gullifer, Chai, Whitford, Pivneva, Baum, Klein & Titone, 2018; Gullifer Kousaie, Gilbert, Grant, Giroud, Coulter, Klein, Baum, Phillips & Titone, 2020; Gullifer & Titone, 2021). In a study conducted in Krakow, Poland, the mean entropy value was 0.55, and researchers found that higher language entropy was associated with poorer vocabulary but higher self-confidence in using a second language (Kałamała, Szewczyk, Chuderski, Senderecka & Wodniecka, 2022). A study conducted in Milan, Italy, reported mean entropy values of 0.70 and found that higher language entropy was associated with the organization of structural brain networks responsible for executive and language control (Sulpizio, Del Maschio, Del Mauro, Fedeli & Abutalebi, 2020). Finally, an association between language entropy and performance on a switching task in both a university and non-university population was reported in a study in Groningen, Netherlands (van den Berg, Brouwer, Tienkamp, Verhagen & Keijzer, 2022). In this case, higher language entropy was associated with slower overall reaction times in the university population, which had a mean entropy value of 0.43; but in the non-university population, which had mean entropy values ranging from 0.73–0.95, higher entropy values were associated with smaller switching costs. Together these studies point to relations between language entropy and brain, cognitive, and linguistic outcomes, although the details of those relations are different in each case. Notably, the higher the mean entropy values, the more likely that entropy is related to cognitive and brain outcomes.

One motivation for proposing entropy as a measure of variability in bilingual experience is to explain inconsistent results from studies investigating the effect of bilingualism on cognitive performance. The premise is that these effects are mediated by the details and context of language use so changes in these conditions will be associated with different outcomes from bilingualism. The cognitive task most often used in this research to examine the role of entropy is the AX-Continuous Performance Task (AX-CPT), a task that differentiates between proactive and reactive control (Braver & Cohen, 2001; Cohen, Barch, Carter & Servan-Schreiber, 1999; Paxton, Barch, Racine & Braver, 2008). Proactive control is an anticipatory strategy that maintains goal-relevant information prior to cognitively demanding events to bias attention and action toward the goal. It is advantageous in activities that require preparedness, planning, and in situations where behaviors must continually be adjusted to meet a goal successfully (Braver, 2012). However, continuous goal maintenance requires substantial resources, so proactive control is limited by attentional and working memory capabilities, making it less sensitive to changing environmental contingencies. In contrast, reactive control relies on recognizing and resolving interference to respond to stimuli just in time (Braver, 2012). The reactive control strategy is considered a late correction mechanism that re-engages goal maintenance at the onset of a cognitively demanding event. This strategy is more efficient and requires fewer attentional resources than the proactive control strategy. However, reactive control requires repeated re-engagement of goals, making it more vulnerable to transient attentional capture (Braver, 2012). That is, other stimuli may capture attention briefly, resulting in missed cues as reliance on reactive control strategies may limit ability to re-engage goals in time. Effective cognitive performance requires a balance of proactive and reactive control.

Studies comparing AX-CPT performance between groups of monolinguals and bilinguals have been conducted in Grenada, Spain – Morales, Gómez-Ariza, and Bajo (2013) reported that the difference in error rates between trials measuring reactive control and control trials was larger for monolinguals than bilinguals, suggesting that monolinguals are more reliant on contextual cues than bilinguals. Similarly, Morales, Yudes, Gómez-Ariza, and Bajo (2015) found that bilinguals had fewer errors on target, proactive, and reactive trials than monolinguals. The researchers concluded that bilinguals are better able to coordinate proactive and reactive control than monolinguals.

Instead of comparing groups of monolinguals and bilinguals, Gullifer, Chai, Whitford, Pivneva, Baum, Klein, and Titone (2018) investigated the effect of variations in bilingual experience on performance in this task. They reported that earlier second language acquisition was associated with faster reaction times on trials measuring proactive control. Similarly, Bonfieni, Branigan, Pickering, and Sorace (2019) compared bilinguals with varying proficiency and age of second language acquisition in Edinburgh, Scotland and Sardinia, Italy and found that bilinguals with high proficiency, regardless of age of second language acquisition, performed better than lower proficiency bilinguals on reactive control trials than to other trials. Note that there were no monolinguals in these studies.

Gullifer et al. (2018) extended this research by using entropy as the continuous measure of bilingual experience and explored its effect on AX-CPT performance. They tested a sample of bilinguals who varied in entropy scores and found that greater language entropy was associated with faster performance on proactive control trials with no relation to performance on reactive control trials. In a follow-up study, the researchers claimed that social entropy was associated with greater engagement of proactive control, but that work-related entropy specifically was associated with reduced proactive control (Gullifer & Titone, 2021). Further analyses using cross-validated linear mixed effects regression and LASSO regression suggested that language entropy influences cognitive control but that the effects are small (Gullifer & Titone, 2021). To summarize, greater diversity of language use was associated with more proactive control than found for participants with lower entropy values. Therefore, the context in which language is used must be considered in understanding how bilingual experience impacts outcomes. Entropy provides one approach to this objective.

Other theorists have approached the importance of contextual factors in different ways. Green and Abutalebi (2013) proposed the Adaptive Control Hypothesis (ACH) to conceptualize differences in language use contexts. They identified three interactional contexts: single language, in which one language is consistently used in that context; dual language, in which two languages are used but with different speakers so language switching rarely occurs; and dense code-switching, in which two languages are used in the same context and often mixed in a single utterance. Their argument is that each of these contexts is preferentially associated with specific cognitive outcomes because of the unique processing it requires.

Testing this hypothesis, Hartanto and Yang (2016, 2020) compared performance between bilinguals who were in a single-language context or a dual-language context on a task-switching paradigm and found that dual-language context bilinguals had smaller switch costs, indicated by faster reaction times, than single-language context bilinguals. Similarly, Ooi, Goh, Sorace, and Bak (2018) found that bilinguals in dual-language contexts experienced a smaller difference in reaction time between congruent and incongruent trials on an attention network task than did single-language context bilinguals, suggesting better conflict resolution abilities. These results were not replicated in a study by Kałamała, Szewczyk, Chuderski, Senderecka, and Wodniecka

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(2020), who concluded that dual-language context experiences were not associated with better task performance. However, Krakow, Poland, where the study was conducted, may be a limited dual-language context as there is little expectation to speak any language other than Polish outside the home. As noted above, the overall entropy score in this context was 0.55, somewhat lower than that reported for other locations.

Beatty-Martinez, Navarro-Torres, Dussias, Bajo, Guzzardo Tamargo, and Kroll (2020) compared performance of bilinguals from three interactional contexts on the AX-CPT task. The contexts were: separated bilingual context in which individuals use one language in each context; integrated bilingual context in which both languages are used flexibly in the same context; and varied dual-language context in which bilinguals continually monitor their language to match the context. Participants in the integrated and varied contexts had higher error rates on reactive control trials than on proactive control trials, but no difference was found for separated context bilinguals. Additionally, relative to control trials, separated and integrated context bilinguals made more errors on proactive control trials, but there was no difference in these conditions for varied context bilinguals.

Participants in the varied and integrated contexts, both of which are dual language contexts, showed greater reliance on proactive cognitive control strategies than did those in the separated context, a single language context, where participants relied more on reactive control. For overall performance, the contexts were ordered with the best outcomes for varied contexts, followed by integrated contexts, and finally separated contexts. In general, as the diversity of language use increased, bilinguals showed greater reliance on proactive control strategies.

Language entropy and interactional context from the ACH both impact cognitive outcomes, and in both cases, performance has been assessed using the AX-CPT. The main results are summarized in Table 1. The studies used different populations, different versions of the task, and were conducted in different contextual environments, so simple patterns are elusive. Although there is no one-to-one relation between entropy and ACH, there is likely some relation between them. Entropy focuses on individual variation in language use and ACH focuses on features of the context, but the cognitive outcomes rely on both. Gullifer and Titone (2021) propose that entropy offers a way to test the ACH by comparing bilinguals who immerse themselves in dual language contexts relative to single language contexts. Therefore, investigating entropy in a different interactional context could shed light on how both contextual factors function to modify cognitive outcomes.

The formulation of entropy was developed in Montréal, a unique linguistic context. The present study examined the extent to which the construct also applies to Toronto where language use patterns are different. Montréal is a highly bilingual city (Gullifer & Titone, 2020). French is the official language (CQLR, 2021) and is the dominant language used despite substantial language diversity in the city. All businesses in Quebec are required by law to function in French. Therefore, even in areas of Montréal where English is predominant, public interactions will be in both English and French. In terms of the ACH, Montréal is a dual language (or possibly dense code switching) context. In Toronto, by contrast, the dominant language for public interactions is English despite an enormously diverse population. Unlike Montréal, there is a clear separation between the language used in public spaces and the language used at home. In this sense, Toronto is largely a single language context.

These differences are evident in demographic data from the Canadian census (StatisticsCanada, 2017). Because English and French are both official languages in Canada, official records,

Table 1. Summary of previous studies investigating bilingual performance on the AX-CPT.

Study[1]	N	Language Groups	AX-CPT task	Main Results
1	44	Monolingual Bilingual	Distractor version	Reactive accuracy: Bilingual > Monolingual
2	52	Monolingual Bilingual	No distractors	Target accuracy, Reactive accuracy, and Proactive accuracy: Bilingual > Monolingual
3	27	Bilinguals vary in age of L2 acquisition, entropy No Monolinguals	"B" cue is letter B	Reactive RT: Faster with earlier AoA Proactive RT: Faster with higher entropy
4	200	Bilinguals: a. Italian-English, late, high proficiency b. Italian-Sardinian, early, high proficiency c. Italian-Sardinian early, low proficiency d. Italian-Sardinian, late, low proficiency No Monolinguals	Distractor version	Reactive accuracy: High proficiency BL > low proficiency BL
5	96	Bilinguals: a. Separated context (SBL) b. Integrated context (IBL) c. Varied context (VBL) No Monolinguals	Distractor version	Reactive RT: SBL > VBL Reactive accuracy: Integrated and varied context BL more prone to reactive errors than proactive errors. Magnitude of proactive vs reactive accuracy difference greater for varied BLs than separated BLs.
6	459	Bilinguals vary in entropy No Monolinguals	"B" cue is letter B	Social entropy → more reliance on proactive control. Work entropy → decreased reliance on proactive control.

[1]Studies: 1. Morales et al., 2013; 2. Morales et al., 2015; 3. Gullifer et al., 2018; 4. Bonfieni et al., 2019; 5. Beatty-Martinez et al., 2020; 6. Gullifer & Titone, 2021

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such as the census, obtain information separately for these two languages while combining all others into a category of non-official languages. In Montréal, 50.0% of the population reported French as their first language, 12.4% reported English, and 33.3% reported a non-official language. More importantly, 57.4% of the population reported knowledge of both English and French. In Toronto only 1.3% reported French as their first language, 50.9% reported English, and 43.9% reported a non-official language. This last category included over 150 other languages. In contrast to Montréal, only 9.1% of individuals in Toronto reported knowledge of both English and French. Therefore, despite both cities having extensive degrees of bilingualism, Montréal is characterized by a mixture of English and French in public spaces whereas Toronto is characterized by English in public spaces and another language in the home. These data support the notion that Montréal is largely a dual language context and Toronto is a single language context.

The purpose of the present study was to evaluate entropy as a description of language use in Toronto and to determine if there was a relationship between entropy scores and performance on the AX-CPT task for bilinguals in this single language context. There were two hypotheses. First, because Toronto is a single language context, measures of entropy will be lower than has been reported for Montréal. Second, because of the reduced uncertainty in language selection, these measures will not impact cognitive performance on the AX-CPT.

Method

Participants

Participants were young adult bilinguals who had been involved in previous studies conducted between 2018 and 2021. These studies administered a variety of cognitive tasks as well as the Language and Social Background Questionnaire (LSBQ; Anderson et al., 2018). Data were obtained from 523 participants (283 female, 240 male) who ranged in age from 17 to 44 years. The non-English languages of the bilingual participants included: Albanian, Amharic, Arabic, Bangala, Bengali, Bini, Cantonese, Chaldean, Chinese, Croatian, Dari, Dutch, Fanti, Farsi, Filipino, French, Greek, Hebrew, Hindi, Hokkien, Hungarian, Italian, Japanese, Korean, Kweyol, Luganda, Malayalam, Mandarin, Mizo, Oromo, Patois, Polish, Portuguese, Punjabi, Russian, Somali, Spanish, Tagalog, Tamil, Thai, Turkish, Turkmen, Twi, Urdu, and Vietnamese. The participants acquired either English or their non-English language at different points, ranging from birth to early adulthood. Socioeconomic status (SES) was determined by parents' education on a scale from 1 to 5, where 1 indicates some high school; 2 indicates high school diploma; 3 indicates post-secondary education; 4 indicates post-secondary degree or diploma; and 5 indicates graduate or professional degree. A subsample of participants ($n = 323$; 232 female, 91 male) completed an online version of the AX version of the Continuous Performance Task, described below (Rosvold, Mirsky, Sarason, Bransome & Beck, 1956; Servan-Schreiber, Cohen & Steingard, 1996). Sample demographics are shown in Table 2.

Table 2. Mean (Standard Deviation) Participant Demographics

	Whole Sample	AX-CPT Subsample
	Mean (standard deviation)	
N	523	323
Age (years)	20.3 (2.8)	20.7 (2.2)
SES (parents' education)	3.5 (1.2)	3.6 (1.1)
English Proficiency (%)		
Speaking	92.4 (11.5)	92.1 (11.8)
Understanding	94.3 (10.4)	93.9 (10.4)
Non-English Proficiency (%)		
Speaking	77.3 (23.2)	71.5 (28.3)
Understanding	83.2 (20.8)	79.4 (24.3)

Materials

Language and Social Background Questionnaire (LSBQ) and Language Entropy

The LSBQ (Anderson et al., 2018), which was used to collect language history data, contains three sections. The first, Social Background, gathers demographic information such as age, education, country of birth, and parents' education as a proxy for SES. The second section, Language Background, assesses which language(s) the participant can understand and/or speak, where they learned the language(s), and age of acquisition. There are questions assessing self-rated proficiency for speaking, understanding, reading, and writing in each indicated language, where 0 indicates no ability and 100 indicates complete or native-level fluency. The third section, Community Language Use Behavior, assesses language use in different life stages and in specific contexts, such as with different interlocutors (parents, siblings, neighbors, and friends), in different situations (home, school, work), and for different activities (reading, social media, watching TV). The LSBQ yields a continuous measure of degree of bilingualism by computing scores based on the factor analysis created by Anderson et al. (2018).

For the purposes of computing language entropy, the LSBQ data yields 25 potential micro-contexts to evaluate the diversity of language use – namely, Parents, Siblings, Grandparents, Relatives, Partner, Roommates, Neighbors, Friends, Home, School, Work, Social Activities, Religious Activities, Extracurricular Activities, Shopping/Restaurants, Healthcare, Email, Texting, Social Media, Writing lists, TV, Movies, Internet, and Praying. For each context, Shannon entropy (H; Shannon, 1948) was computed using the following equation $H = -\sum_{i=1}^{n} P_i log_2(P_i)$, where n represents the total number of possible languages within a given context, and Pi is the proportion a language is used within the context. The entropy distribution has a minimum value of 0 and a maximum value of log n (i.e., 1.00 for two languages). Lower entropy values represent compartmentalized language usage in which one language is dominantly used in each context, and higher entropy values represent integrated language usage in which two or more languages are used actively. A fully documented languageEntropy R package is provided by Gullifer and Titone (2020) that computes language entropy. It can be found at: https://github.com/jasongullifer/languageEntropy.

AX-CPT

The present study used archival data: therefore only a subset of participants ($n = 323$) was given an online version of the AX-CPT. The experiment was run using Inquisit 6 Player app

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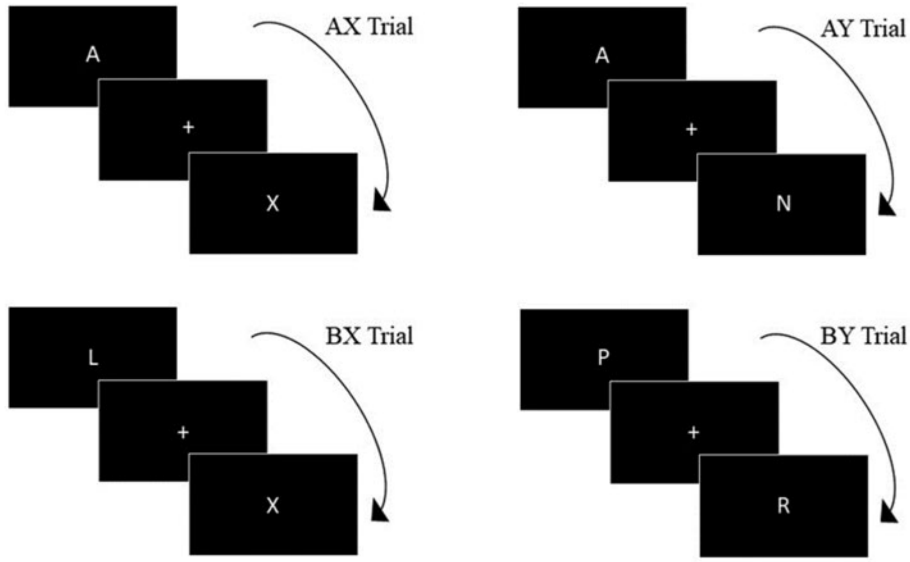

Fig. 1. AX-CPT Sequence for all Four Trial Types

(Inquisit 6, 2020) to present stimuli on participants' computers, with an average refresh rate of 60 Hz. Participants saw a continuous sequence of white sans-serif letters, each presented for 300 ms in the center of a black screen. There was an interstimulus interval of 1200 ms during which a fixation cross appeared and stayed on the screen until the participant responded.

The task began with a single practice block consisting of 40 trials, including all four experimental conditions (AX, AY, BX, BY). The practice block was followed by the experimental block consisting of 350 trials, of which 245 were AX trials (70%) and 35 each were AY, BX, and BY trials (10% each). This ratio of trial types is comparable to that used in most previous studies with the AX-CPT paradigm (Braver & Cohen, 2001; Cohen et al., 1999; Paxton et al., 2008). Although participants saw a continuous stream of letters, the sequence was interpreted in term of cue-probe pairs. Cues were all letters except "X," and "Y," and "K" due to their similarity to "X", and probes were any letters except "A," "K," and "Y". The four relevant trial types were those for which the cue was A or B, and the probe was X or Y. A target was defined as cue "A" followed by probe "X". For these trials, participants were instructed to respond "yes" to the "X" by pressing the "J" key. For all other letters, participants were instructed to respond "no" by pressing on the "F" key. Participants were directed to respond as quickly and accurately as possible. The task was divided into three phases each consisting of approximately 117 trials to offer participants a break. Participants were given pseudo scores at the end of phases 1 and 2 to encourage them to keep going. The four trial types are shown in Figure 1.

Results

LSBQ to Entropy

The LSBQ yielded 25 potential micro-contexts from which entropy values could be calculated. However, because language entropy was developed using a different questionnaire from the one in this study, several changes were needed before calculating entropy. The scales on the LSBQ measure language use for both languages on a single scale but the scales used to measure language entropy assessed the use of each language individually. Therefore, the LSBQ scales were duplicated to generate information for each language in every context. For example, on one scale participants indicate their language use with parents from "Always English" (0) to "Always Non-English" (100). A response of 75 means that the participant uses a non-English language 75% of the time in that context. To calculate the use of English in that context, the reported usage in the non-English language was subtracted from 100 to determine the value for English use (25%). These figures were then converted to proportions – specifically, .75 and .25 to provide a score for each language on that scale. The entropy package in R Studio (Gullifer & Titone, 2018) was used to calculate language entropy for each micro-context producing an entropy score for each that varies on a scale from 0 to 1. The mean entropy values ranged from 0.09 to 0.62. By comparison, the reported mean entropy values across contexts in Montréal ranged from 0.60 to 0.94. The complete list of values for all the micro-contexts in the present study is shown in Table S1 (see Appendix).

Factor analysis and correlations

To reduce the complexity of the data, a principal component analysis (PCA) using the *FactoMineR* package for R was conducted (Husson, Josse & Le, 2008). First, the entropy values were inspected to examine the amount of missing data for each micro-context. This revealed that there were significant missing data (24-63%) for four contexts – Roommates, Partner, Religious Activities, and Praying – as many participants either did not have a partner, take part in religious activities or praying, or did not live with a roommate. These micro-contexts were excluded from the PCA. All other contexts were imputed using multiple imputation by chained equations (van Buuren & Groothuis-Oudshoorn, 2011). The correlations between the remaining micro-contexts are shown in Table S2 and S3 (see Appendix).

Two components were extracted from the PCA, as determined from the scree plot. Variables related to language use in various social settings loaded onto one component and explained 28% of the variance, so Factor 1 is called "Social Language Use." Variables related to home use of language loaded onto the second component and explained 12.5% of the variance, so Factor 2 is

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called "Home Language Use." Cross-loading between the two components suggests that these factors are not entirely distinct. Values for these two factor scores were calculated for each participant and used to explore the associations between entropy, proficiency, and AX-CPT performance.

Correlations were conducted to determine the association between entropy and self-rated assessments of proficiency in English and the non-English language. The expectation was that higher entropy will be associated with higher self-ratings of proficiency, as more proficiency will be associated with greater probability of using that language. The social entropy factor was negatively correlated with English speaking $r = -.15$, and understanding $r = -.12$, and positively correlated with non-English proficiency for speaking $r = .18$ and understanding $r = .09$, $ps < .05$. Therefore, more use of the non-English home language in social contexts is associated with self assessments of poor English but strong non-English proficiency. In contrast, the home entropy factor entropy was positively related to English proficiency assessments for both speaking $r = .12$, and understanding $r = .14$, $ps < .05$, but there was no correlation with non-English assessments, $rs < .08$. This makes sense if the non-English language is the language of the home and proficiency is assumed to be high.

AX-CPT

Accuracy and RT of correctly identified targets across trial type are shown in Table 3. A one-way ANOVA to examine task effects for accuracy showed a significant effect of trial type, $F(3, 966) = 272.44$, $p < 0.001$, with significant differences between BY and AX, AX and BX, and BX and BY, $ps < 0.001$. Similarly, a one-way ANOVA on RT also indicated a significant effect of trial type, $F(3, 966) = 334.01$, $p < 0.001$. There were significant differences between AX and BY and BX and AY, $ps < 0.001$, but no difference between BY and BX, $p = 0.27$.

Correlations were conducted to examine the association between the two entropy factors and performance on the AX-CPT. No significant correlations were found between either social or home entropy factors and accuracy or reaction time for any of the trial types, $rs < .1$, $ps > .07$.

Discussion

The possibility that bilingual experience impacts cognitive performance remains controversial, with studies continuing to produce both positive supporting evidence and null results. One promising approach to resolving the contradictions in the literature is by considering the nature of the bilingual experience in more detail. To this end, two such frameworks have been proposed: Language Entropy (Gullifer et al., 2018) and the Adaptive Control Hypothesis (Green & Abutalebi, 2013). Both frameworks have been used to investigate the effect of contextual variation in bilingual experience on cognitive outcomes, and both have reported reliable relations with performance on the AX-CPT task. However, as shown in Table 1, the effects do not appear to be consistent.

The present study addressed this issue by isolating the role of interactional context –namely, single language or dual language – on measures of language entropy. The purpose was to attempt to replicate the results of a study conducted in Montréal, a dual language context, using similar procedures in Toronto, a single language context. Despite being the two largest cities in the same country, Montréal and Toronto have substantially different language profiles and interactional patterns, as confirmed by data from the Canadian Census. In both studies, participants were university students who were similar on most demographic measures; the primary difference was their language history and language use patterns.

There were two main predictions. The first was that the values for language entropy in Toronto will be lower than those previously reported for Montréal. The reason is that the predominance of a single language context reduces the degree to which languages are combined in individual contexts. In previous research, studies conducted in contexts with lower entropy produced smaller effects on behavior, so the second prediction was that variations in language entropy will not be related to performance on the AX-CPT. The reason is that in a single language context, individual differences in language use will not capture important variation across participants.

Consider first the descriptions of language entropy generated for Toronto. Overall, there were lower entropy values on average, especially in comparison to Montréal where language mixing was more common. The mean entropy values for the various contexts in Montréal ranged from 0.60 to 0.94, whereas the entropy values in Toronto ranged from 0.09 to 0.62, barely overlapping. These values confirm that individuals in Montréal are more likely to combine languages across a range of contexts than are individuals in Toronto, supporting the interpretation that these cities can be described as dual context and single context, respectively.

The factor analysis identified different patterns of language mixing for home entropy and social entropy, although in both cases, the degree of language mixing was related to perceptions of proficiency in each language. English is the language of the community, and to the extent that individuals believed their English skills to be poor, they were more likely to use the non-English language outside the home, increasing the value for social entropy. Similarly, in single language contexts the assumption is that the non-English language will be used in the home; so to the extent that individuals felt confident in their English ability, it was used more at home, increasing the value of home entropy. Therefore, social entropy was negatively related to English proficiency and home entropy was positively related to English proficiency. Two other studies have reported positive associations between entropy and second language proficiency (Gullifer et al., 2020; Kałamała et al., 2020). Like the present study, Kałamała et al. (2020) was conducted in a predominantly single-language context, but only reported a single entropy value. It may be that the two entropy factors identified in the present study were able to differentiate subtler variations in language use and their independent associations with language proficiency.

The second prediction was that if the entropy range was lower on average, it will not be related to AX-CPT performance. The results showed task effects in the expected direction – namely, slower and less accurate performance for AY and BX trials –

Table 3. Mean Accuracy and Reaction Time (Standard Deviation) by Trial Type

	Accuracy (%)	Reaction Time (ms)
AX	92.9 (8.7)	343 (78)
AY	67.4 (19.9)	507 (104)
BX	84.7 (20.1)	380 (150)
BY	95.8 (8.5)	369 (111)

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but there was no relation between these behavioral scores and individual measures of entropy. Importantly, there were no monolinguals in the present study, so these results do not address the broader question regarding the impact of bilingualism on this task; it only rules out the more nuanced possibility that variation in language mixing in this context further modulates performance.

Previous studies examining bilingualism and cognitive control using the AX-CPT have used three different versions of the task. The first and most commonly used version inserts distractor letters between cue-probe pairs to improve task sensitivity by increasing demands for goal maintenance (Morales et al., 2013). Using this distractor version, Morales et al. (2013) concluded that bilingualism modulates executive control strategies, with bilinguals better coordinating proactive and reactive control than monolinguals. Using the same version, Bonfieni et al. (2019) showed that among bilinguals, strong proficiency in two languages was associated with greater reliance on reactive control, and Beatty-Martinez et al. (2020) demonstrated that greater social use in complex language contexts evoked a stronger reliance on proactive control strategies. These studies suggest that different bilingual experiences, and possibly contexts, might be associated with reliance on different cognitive control strategies.

However, the introduction of distractors may have decreased reliance on proactive control strategies. Therefore, it is unclear if the introduction of distractors increases goal maintenance demands (i.e., makes the task more difficult) or if it reduces the effectiveness of proactive control strategies (Gonthier, Macnamara, Chow, Conway & Braver, 2016). The second version of the task does not employ distractors between cue-probe pairs. The distractor-free version has been used to compare cognitive control strategies between monolinguals and bilinguals, demonstrating that bilinguals had better target accuracy, reactive control trial accuracy, and proactive control trial accuracy than their monolingual counterparts (Morales et al., 2015). This is the version of the task used in the present study.

Finally, the third version of the task modified the AX-CPT such that the “B” cue in B trial types (BX or BY) was always the letter B, which was intended to enhance the measurement of proactive control (Gullifer et al., 2018). The researchers argued that this modification increases the salience of the B cue enabling a more comparable estimation of proactive control between AY and BX conditions (Gullifer et al., 2018). To examine the association between age of second language acquisition, language entropy, and cognitive control, Gullifer and colleagues (Gullifer et al., 2018; Gullifer & Titone, 2021) used this “B is B” version of the task. They found that earlier ages of second language acquisition were associated with reliance on reactive control (Gullifer et al., 2018), again demonstrating that variations in bilingual experiences are associated with reliance on different cognitive control strategies (cf. Bonfieni et al., 2019). Additionally, participants with greater language entropy were more reliant on proactive control (Gullifer et al., 2018; Gullifer & Titone, 2021), even though the overall effect of language entropy in a young adult sample is likely small, even in Montréal (Gullifer & Titone, 2021).

The results from the present study differed from those reported from Montréal in two ways. First, the values for language entropy were substantially lower in Toronto, with almost no overlap between the range of values. This pattern reflects a largely compartmentalized use of languages in Toronto as opposed to an integrative use in Montréal, despite both cities being highly bilingual. This difference is captured by the designations from the Adaptive Control Hypothesis in terms of single language and dual language contexts, respectively. Second, individual variations in language entropy were related to performance on the AX-CPT in Montréal but not in Toronto; although again, with no monolinguals there are no implications for the general impact of bilingual experience on that task. The studies from Montréal showed that the extent to which bilinguals engage in this language mixing is related to their use of proactive control on the AX-CPT. This is not the case in a single language context in which the predominant pattern is to use one language at home and the other in the community.

Both entropy and ACH have been used to describe the nature of bilingual experiences and its effect on cognition, but in the present study designations from both entropy and ACH were different from those in the Montréal studies. Can these differences help explain the relation between the two frameworks? ACH was proposed as a means for conceptualizing language use contexts and the linguistic expectations that are associated with different environments. Language entropy, in contrast, was proposed as a means for conceptualizing individual behavior in terms of language choices. Put that way, entropy is constrained by the interactional context given by the ACH. One can only make the language selection choices that are permitted by the broader context. In the single language context of Toronto where the language choice is between English and one of approximately 150 other languages, the public domain will privilege the choice of English; in the dual language context of Montréal where the two languages are essentially English and French with high population proficiency in both, the language choice becomes an individual preference, Therefore, the notion of language entropy is less meaningful in single language contexts where there is in fact less choice for selection.

This relation between single and dual language contexts and entropy can explain why entropy values are so low in Toronto. But why does entropy in Toronto not account for variation in performance on the AX-CPT? One possibility is that higher entropy values are associated with more frequent language switching, and it is the switching that may be responsible for the larger cognitive effects. The relation between frequency of language switching and extent of cognitive outcomes has been examined in several studies (Soveri, Rodriguez-Fornells & Laine, 2011; Tao, Taft & Gollan, 2015; Timmer, Calabria & Costa, 2018; Verreyt, Woumans, Vandelanotte, Szmalec & Duyck, 2016). The results vary, but overall, there appears to be a small but reliable positive relation between language switching and cognitive performance. The calculation of entropy likely provides a more reliable estimate of degree of language switching than do the self-report questionnaires typically used in that research, but in both cases, cognitive outcomes reflect switching. In the ACH, Green and Abutalebi (2013) predicted that dual language contexts would lead to greater cognitive adaptations than single language contexts because they require more monitoring. All these descriptions are consistent with the finding that individual variations in language switching impact cognitive performance in Montréal but not in Toronto.

In summary, the present study validates the use of entropy as a measure of bilingual language use in different language contexts and shows that its impact on performance is limited by the ACH. The relationship between patterns of bilingual language use, proficiency, and cognitive control is complex but is largely supported by predictions based on previous studies of language entropy and the ACH. Importantly, the present study only examined variations in language use among bilinguals. With unclear boundaries between monolinguals and bilinguals and little attention dedicated to variations in monolingual experiences, the present study cannot draw conclusions on the effects of bilingualism generally. Finally, the present study demonstrated the importance of language context by comparing patterns of language use and subsequent associations with cognitive control between two large bilingual cities – Toronto and Montréal. Since the present study does not compare data between the two cities, it is limited in the scope of the comparisons drawn. Nevertheless, future studies investigating how bilingualism modulates cognitive performance should include descriptions of language context to allow for more accurate comparisons between results.

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Appendix

Table S1. Micro-Context Mean (standard deviation) Entropy Values

Micro Context	Mean (SD) Entropy Value
Parents	0.56 (0.40)
Siblings	0.56 (0.40)
Grandparents	0.27 (0.41)
Relatives	0.54 (0.42)
Neighbours	0.21 (0.38)
Friends	0.54 (0.42)
Roommate(s)	0.22 (0.37)
Partner	0.35 (0.41)
Home	0.62 (0.38)
School	0.23 (0.36)
Work	0.23 (0.38)
Social Activities	0.46 (0.43)
Extra Curriculars	0.32 (0.39)
Religious Activities	0.49 (0.42)
Shopping	0.31 (0.39)
Healthcare	0.09 (0.26)
Reading	0.36 (0.40)
Email	0.12 (0.27)
Text	0.43 (0.46)
Social Media	0.37 (0.42)
Writing Lists	0.20 (0.36)
TV	0.54 (0.43)
Movies	0.52 (0.43)
Internet	0.31 (0.39)
Praying	0.47 (0.43)

Table S2. Correlations of entropy values between micro-contexts.

	Parents	Siblings	Grandparents	Relatives	Neighbours	Friends	Home	School	Work	Social Activities
Parents	1.00									
Siblings	0.50	1.00								
Grandparents	0.40	0.06	1.00							
Relatives	0.65	0.34	0.59	1.00						
Neighbours	0.13	0.20	0.07	0.12	1.00					
Friends	0.13	0.33	−0.04	0.05	0.41	1.00				
Home	0.68	0.61	0.24	0.47	0.15	0.28	1.00			
School	0.13	0.23	0.06	0.14	0.29	0.33	0.18	1.00		
Work	0.17	0.29	0.14	0.16	0.35	0.42	0.31	0.36	1.00	
Social Activities	0.15	0.32	−0.10	−0.01	0.41	0.66	0.34	0.36	0.45	1.00
Extra-curriculars	0.08	0.28	−0.02	0.01	0.52	0.57	0.19	0.46	0.52	0.58
Shopping & Restaurants	0.19	0.31	0.02	0.04	0.37	0.40	0.33	0.34	0.50	0.46
Healthcare	0.18	0.26	0.13	0.14	0.32	0.37	0.23	0.30	0.55	0.35
Reading	−0.01	0.15	−0.10	−0.22	0.28	0.53	0.15	0.22	0.26	0.49
Email	0.10	0.11	0.01	0.03	0.32	0.36	0.19	0.29	0.33	0.33
Texting	0.04	0.18	−0.11	−0.06	0.29	0.65	0.21	0.24	0.30	0.51
Social Media	−0.10	0.12	−0.16	−0.24	0.25	0.50	0.10	0.12	0.21	0.50
Writing Lists	0.03	0.15	−0.10	−0.07	0.28	0.54	0.12	0.19	0.35	0.50
Watching TV	−0.03	0.19	−0.06	−0.03	0.35	0.41	0.07	0.30	0.18	0.39
Movies	0.07	0.31	−0.09	−0.03	0.26	0.34	0.23	0.34	0.18	0.39
Internet	0.04	0.28	−0.11	−0.12	0.25	0.43	0.23	0.28	0.36	0.49

Table S3. Continuation of correlation of entropy values between micro-contexts.

	Extra-curriculars	Shopping & Restaurants	Healthcare	Reading	Email	Texting	Social Media	Writing Lists	Watching TV	Movies	Internet
Extra-curriculars	1.00										
Shopping & Restaurants	0.52	1.00									
Healthcare	0.46	0.61	1.00								
Reading	0.44	0.32	0.26	1.00							
Email	0.43	0.41	0.44	0.58	1.00						
Texting	0.46	0.25	0.33	0.77	0.50	1.00					
Social Media	0.39	0.23	0.27	0.66	0.43	0.71	1.00				
Writing Lists	0.38	0.35	0.40	0.59	0.61	0.58	0.58	1.00			
Watching TV	0.27	0.26	0.31	0.54	0.44	0.48	0.44	0.59	1.00		
Movies	0.27	0.25	0.25	0.50	0.34	0.44	0.38	0.50	0.73		
Internet	0.38	0.46	0.42	0.55	0.56	0.54	0.53	0.70	0.60	0.56	1.00

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