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Bridging Interpersonal and Ecological Dynamics of Cognition through a Systems Framework of Bilingualism

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M.T., D.T., and J.G. conceptualized the study, and E.K. and R.Y.F. contributed to the design of the materials. M.T., J.G., and R.Y.F. contributed to testing and data collection. M.T. performed the data analysis and all authors contributed to the interpretation of the results. M.T. and R.Y.F. created the visualizations. M.T. wrote all drafts which all authors reviewed, edited, and approved. D.T. and J.G. procured funding for this study.

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Abstract

Human cognition occurs within social contexts, and nowhere is this more evident than language behavior. Regularly using multiple languages is a globally ubiquitous, individual experience that is shaped by social environmental forces, ranging from interpersonal interactions to ambient language exposure. Here, we develop a *Systems Framework of Bilingualism*, where embedded layers of individual, interpersonal, and ecological sociolinguistic factors jointly predict people's language behavior. Of note, we quantify interpersonal and ecological language dynamics through the novel applications of language-tagged social network analysis and geospatial demographic analysis among 106 English-French bilingual adults in Montréal, Canada. Consistent with a Systems view, we found that people's individual language behavior, on a global level (i.e., overall language use), was jointly predicted by the language characteristics of their interpersonal social networks and the ambient linguistic patterns of their residential neighborhood environments, whereas more granular aspects of language behavior (i.e., word-level proficiency) was mainly driven by local, interpersonal social networks. Together, this work offers a novel theoretical framework, bolstered by innovative analytic techniques to quantify complex social information and empower more holistic assessments of multifaceted human behaviors and cognition, like language.

Keywords: Bilingualism, Cognition, Social Network Analysis, Demographic Analysis, Social Systems, Social Context

When a botanist discovers a new species of plant in the forest, they observe the plant's behavior alongside its surrounding flora and fauna. They also observe the ecology it inhabits, for example, the soil, light availability, and other geobiological properties, to holistically and systemically obtain a nuanced theoretical and empirical understanding of the plant. As a consequence, the ensuing theories the scientist develops about the plant are informed by rich information about the ecological forces acting upon its individual characteristics. Counterintuitively, scientific domains that observe the cognitive and neural determinants of *human* behavior, and that develop theories based on these observations, often deemphasize or miss altogether a holistic, systems-level appreciation of behavior, despite the fact that human neurocognition predominantly occurs within *social* contexts (Giles et al., 1973; Green et al., 2003; López et al., 2021; Maguire et al., 2000; Richard et al., 2003; Titone & Tiv, under review; Tiv, Kutlu, et al., 2021; Todorov et al., 2006; Werchan & Amso, 2017).

The turn of the century spurred an ideological pivot from traditional conceptualizations of particular aspects of cognition as being highly modular, generative, black-box systems (e.g., Chomsky, 1965; Fodor, 1983) to more emergentist, usage-based processes that are dynamically influenced by external aspects of social context, environment, and experience (e.g., Bates et al., 1998; Bybee, 2010; Bybee & Beckner, 2015; Christiansen et al., 2016; Ellis, 1998; Goldberg, 2006; Lupyan & Dale, 2010; Raviv et al., 2020; Tomasello, 2000). Language was central to this ideological shift. This stands to reason given that language is a primary vehicle through which cognitive representations are formed, communicated, and changed (Charlesworth et al., 2021; M. Lewis & Lupyan, 2020). In turn, effective production and comprehension of language appears to be dependent on the coordination of basic and higher-order cognitive mechanisms (Andresen & Carter, 2016; Titone & Tiv, under review; Tomasello, 2000). Language is thus central to almost all aspects of cognitive processing. At the same time, language is inherently social, enabling communication between people. Therefore, a socially-contextualized theoretical understanding of cognition is ideally realized within in the domain of language, though it is certainly not exclusive to language.

In this paper, we specifically address a socially contextualized understanding of a particular set of language behaviors, referred to as bilingualism, which collectively describes how people acquire, maintain, and deploy their knowledge of multiple languages in real-world social settings. Bilingualism is well-suited as a case study for how human cognition is shaped by systemic social influences for several reasons: the vast number of people globally who are bilingual; the great diversity of people's bilingual language experiences; the interpersonal nuance associated with using multiple languages in particular social settings; the variation in regional policies and attitudes regarding bilingualism and particular languages at a sociological level; and finally, the systematic ways that language can change over time arising from all of the above (Beatty-Martínez & Titone, under review; Grosjean, 1982; Gullifer & Titone, 2019, in press; Leon Guerrero & Luk, in press; López et al., 2021; Luk & Bialystok, 2013; Titone & Tiv, under review; Tiv et al., 2020; Tiv, Kutlu, et al., 2021).

Past research on bilingualism has shown that language phenomena are unlikely to be exempt from social forces at a cognitive level. For example, healthy bilingual adults with greater contextual diversity of language use opportunistically engaged greater proactive control than bilinguals who compartmentally used each language (Gullifer & Titone, 2020; Gullifer et al., 2018). Similarly, bilingual adults' word productions were constrained by the linguistic profile of where they lived (Beatty-Martínez et al., 2019), which in another study, further impacted language learning among monolinguals (Bice & Kroll, 2019). Related work has shown that mere exposure to diverse linguistic environments can shape social cognitive behavior among children and infants (Fan et al., 2015; Liberman et al., 2017), while greater social diversity in one's own language use promotes social cognition among adults (Tiv, O'Regan, et al., 2021). Such efforts honor the potential role of social context and history in shaping language use (Ortega, 2020), and highlight how bilingual experience can offer a unique window into broader theoretical questions about the interplay of cognitive and social processes. However, to date, these efforts have focused on single levels of social influence at a time (e.g., questionnaires to probe individual differences or cross-regional comparisons to assess ambient ecology), which has led to a siloed literature on the role of social context.

Thus, to systematically operationalize and quantitatively characterize the role of social context on language, particularly bilingualism, and cognition more broadly, we develop a socially-situated theoretical approach, which we refer to as a *Systems Framework of Bilingualism*. This approach capitalizes on analytic tools from the language sciences, network science, and geospatial demographic analysis. It is informed by Bronfenbrenner's social-ecological theory of human development (Bronfenbrenner, 1977), ecolinguistic traditions (Finke, 2001; Grosjean, 1982; Labov, 1972; Steffensen & Fill, 2014; Van Lier, 2002), and other ecological theories of language (de Bot et al., 2007; Douglas Fir Group, 2016). However, unlike some existing domain-specific approaches (e.g., language learning), our framework adopts a domain-general view of language use as an ever-evolving and multifaceted cognitive experience, which focused at this time on how bilingual adults – the majority of the world's population – are holistically shaped by sociocultural forces (Grosjean, 1982, 2015; Siegel, 2018; Wigdorowitz et al., 2020). Critically, this framework will allow researchers to more systematically operationalize and quantify unique sources of social information on bilingual language use, as one type of cognitive experience, and also probe meaningful relationships between these sources of social information on other aspects of neurocognition.

According to this *Systems Framework* (Figure 1), an individual (or ego, following network science convention), is nested within a hierarchical system of contexts that exert influence on each other, and on the individual. The first layer of influence, *interpersonal language dynamics*, involves person-to-person interactions. The second, *ecological language dynamics,* comprises of the contextual influence of their residential neighborhood, their school or workplace, and any semiotic exposure to language. The third, *societal language dynamics,* involves higher-order characteristics of the society, including attitudes, beliefs, status, and policy. Together, this system of local and ambient social influences changes over time and is shaped by historical and developmental context.

< FIGURE 1 ABOUT HERE >

In our framework, *interpersonal language dynamics* comprise the direct person-to-person interactions of daily life. For example, we can examine how a bilingual person with two bilingual parents may use French with one parent and Spanish with the other. We can also examine how the two parents communicate with each other in English, consequently informing how the child statistically tracks language choice across contexts (Tiv et al., 2020). To quantify these dynamics, we measure social network attributes from the language(s) used in person-to-person interactions. Past work has revealed that social networks are influential in shaping behavior (Paluck & Shepherd, 2012), but few studies have related social networks to language or bilingualism. These have been limited to analyzing bilingual Twitter users (Eleta & Golbeck, 2014; Kim et al., 2014), understanding identity-construction among bilingual immigrants (Doucerain et al., 2015; Lanza & Svendsen, 2007), and characterizing socially-driven learning in bilingual immersive instruction (Paradowski et al., 2021). Social network analysis has been less widely deployed as a systematic tool to evaluate the full spectrum of language diversity among speakers of multiple languages.

Ecological language dynamics comprise broader, ambient sources of language exposure. For example, a bilingual person may live in a linguistically diverse neighborhood, where they engage more languages during everyday activities, or they may live in a predominantly English-speaking neighborhood, where the opportunities to use other languages are limited. To quantify these dynamics, we mine population-level linguistic demographic data from the Canadian Census to quantify ambient language exposure. While researchers of bilingualism have leveraged census data to examine the distribution of bilingual speakers across the United States (Nagano, 2015) and Canada (Gullifer & Titone, 2019), our geospatial approach extracts census demographic statistics as precise indicators of language use in neighborhoods of residence for our sample.

Societal language dynamics derive from overarching features of the society, which for us, is Montréal, Québec, Canada (e.g., Kircher, 2014; Leimgruber, 2020). While the Canadian federal government recognizes both English and French as official languages, the only official language in the province of Québec is French, where the majority of French speakers in Canada reside (~94% in 2017, Statistics Canada, 2016). Given that all participants reside in this single locale, we can situate our conclusions about societal context on individuals.

Together, we predict these layers of social influence will jointly constrain linguistic, cognitive, and neurocognitive processes within an individual across time. As discussed in other ecological frameworks (Douglas Fir Group, 2016), whether or not each layer of social influence is directly examined in a given study does not discount its constant influence (i.e., people are always embedded in a social context). However, the extent to which each layer exerts unique social force on a given linguistic or cognitive process likely depends on a variety of factors, including the precise linguistic and cognitive processes in question, the sensitivity of the experimental measure, and the relative influence of other layers. For instance, it is possible that more general or global linguistic and cognitive behaviors (e.g., overall language use) are predicted by more ambient sources of social influence, such as ecological language dynamics, whereas those same dynamics are less impactful on more granular linguistic behaviors (e.g., word-level knowledge).

Present Study

Guided by a *Systems Framework of Bilingualism*, we assess the impact of a multi-level, hierarchical system of local and ambient sociolinguistic contexts on individual language behavior. To pursue this goal, we combined methods from network science and geospatial demographic analysis, ideally suited to this purpose (Borgatti, 2009). We first extracted characteristics of language use within personal social networks. We then computed indices of ambient language exposure across their neighborhoods of residence. We next probed the relationships between these interpersonal and ecological systems of linguistic context. Lastly, we assessed whether these inter-related systems constrain individual-level bilingual behavior that is global or more granular in nature. To foreshadow our results, consistent with a *Systems Framework of Bilingualism*, interpersonal and ecological dynamics of the sociolinguistic context related to one another, and also predicted individuals' real-world language behavior.

Methods

Participants

One hundred and six bilingual adults (Mean age = 21.2 years) living in Montréal, Canada participated. This sample size was selected based on past work assessing aspects of language use across personal social networks (Doucerain et al., 2015). Recruitment occurred on-campus at McGill University and off-campus in the Greater Montréal community, thus, the sample had a mix of students and non-students. Gender identity of our sample consisted of 84% female, 15% male, and 1% queer. Racial and ethnic identity consisted of 69% white, 16% bi/multiracial, 6% Black, 4% Middle Eastern, 2% East Asian, 2% other, 1% Pacific Islander, and 1% Southeast Asian. Participants self-reported knowing at least English and French, Canada's two official languages, and some reported knowledge of additional languages. Participants' first language, as defined by the language(s) they were exposed to in their first year of life, was English (n = 38), French (n = 40), or both English and French (n = 28). Any additional languages were acquired after the first year of life. The average age of acquisition of each language was as follows: English: 2.64 years old, French: 2.12 years old, other languages: 10.88 years old. Similarly, the average overall daily use of each language was as follows: English: 67.32%, French: 30.94%, other: 1.90%. Additional background information, including socioeconomic status, education, and place of birth, is provided in Supplementary Materials. All participants provided written consent prior to starting the experiment, and the study was in accordance with McGill University's Research Ethics Board guidelines.

Materials

The Social Network Survey

We used Egocentric Social Network Analysis (Borgatti, 2009) to quantify aspects of interpersonal language dynamics. Social Network Analysis is a specialized form of Network Analysis in which the nodes represent people (alters), who may be graphically connected to one another with a tie (edges), reflecting some relationship or shared experience. The nature of the ties is highly flexible and may be weighted based on some aspect of the alter-alter connection, such as closeness.

In this Egocentric Social Network Survey, participants (egos) were asked to nominate eight to twelve alters with whom they regularly interacted over the past six months. These respondents were instructed to draw across all contexts of their daily life, including work, school, home, social, and virtual spheres, in selecting their alters. To encourage a diverse nomination pool, experimenters recommended alternating between alters who did and who did not know each other (e.g., Alter 1 may not know Alter 2 but they may know Alter 3, etc.). Participants received no instructions to consider alters' language backgrounds during this name generation phase.

Next, participants provided some demographic information on each alter, including gender identity, age group, education, race or ethnic origin, and their city and country of residence. Subsequently, participants answered questions pertaining to their own relationship with the alter, such as their relationship type (e.g., close family, friend, classmate, etc.), the context and frequency of their interaction (e.g., daily, weekly, monthly, etc.), their perceived closeness (7-point Likert scale: Not close at all to Extremely close), and the language(s) they use together.

Lastly, participants indicated whether each alter pair communicates with each other in any way (e.g., talk, text, call, email). In cases where two alters communicated with each other (undirected), participants were asked to rate the perceived closeness of the alters (7-point Likert scale: Not close at all to Extremely close). While other alter-alter information was gathered (e.g., language), it was not analyzed due to potential limitations in the participant's knowledge of the details of these alter-alter relationships. The Social Network Survey was administered with the Network Canvas software (Complex Data Collective, 2016).

From each respondent's full, personal network, we created three language-tagged subnetworks based on the language(s) they reported using with each alter (English, French, Bilingual). Then, we extracted eleven basic network measures from the full network and the three language-tagged subnetworks (for full description of each measure, see Scott, 2017). Some measures reflected compositional aspects of the network and the alters within it, whereas others represented structural characteristics of the overall network.

Network size, or the total number of nodes or alters, indicates the number of people in the network or subnetwork. For example, someone who listed ten alters in total (overall network size = 10) may have listed three people with whom they use English (English subnetwork size = 3), three people with whom they use French (French subnetwork size = 3), and four people with whom they use both English and French (Bilingual subnetwork size = 4). This value indicates overall exposure to each language (or language mode) on an interpersonal level.

Number of ties, or the number of connections between alters within each network or subnetwork, indicates the number of relationships between the alters independent of the respondent (e.g., one tie means that only a pair of alters know each other directly).

Density, or the total number of ties divided by the total number of possible ties, reflects the overall interconnectedness of the alters. Density ranges from zero to one where zero reflects no ties among the alters (i.e., none of the alters directly know each other) and one means that all alters know all other alters. Both number of ties and density reflect how connected the alters are to each other and they may provide insight on the participant's potential in bridging diverse perspectives. For instance, in low density networks, the participant may be the only connection between the listed alters, but in high density networks, there are many alternate points of connection between alters.

Number of components, or the number of clusters that form when alters that are connected to each other but to no additional alters are counted, can reflect the number of unique communities of information. For example, if all alters know at least one other alter in the network, there would only be one component, the full network. However, imagine a social network of a participant's family and their co-workers without any crosstalk between these groups. The resulting social network would comprise of at least two components reflecting these two groups, reflecting two unique sources of information.

Conversely, the **number of isolates** is defined as the number of alters who are only connected to the respondent but to no other alter. If a network has a density of zero, then the total network size would equal the number of isolates. These individuals may present additional potential for access to unique information, as they reflect key, underrepresented aspects of the social space.

Lastly, we were interested in capturing the overall closeness of the network. Thus, we extracted the overall **strength** of the network or subnetwork weighted by the reported closeness between alters. This measure was based on the sum of all adjacent tie weights (i.e., alter-alter closeness), which was reported by the respondent. We expected this measure to reflect subjective interconnectedness of the network and each language-specific subnetwork.

We also extracted several measures of **network centrality**, which generally refers to one or more ways that single alters can be structurally influential in a network based on the quantity or quality of their social connections. For each alter, a relatively high centrality score indicates greater influence, or a more ‘central’ role, in the network, whereas a relatively low centrality scores indicates some extent of peripherality or exclusion (Scott, 2017).

One way to measure centrality is to count the total number of direct ties that each alter has to other alters (**degree centrality**). Alters with high degree centrality have connections to many other alters, indicating potential for high social influence.

Conversely, one could consider the extent to which a given alter resides on a critical path between other alters, thus demonstrating importance in the flow of information between other alters (**betweenness centrality**), or potential to bridge otherwise unconnected people. For both degree and betweenness centrality, we extracted the mean and the maximum centrality scores from each network which indicate the range of social influence the network may have on the respondent.

The third centrality measure we extracted was **Eigenvector centrality**. Some consider this score the most important measure of centrality because it captures the extent to which well-connected alters are well connected with each other (Borgatti, 2005). In essence, Eigenvector centrality reflects the overall quality of the connections between nodes in the network. For this measure, we extracted the single eigenvector value for the network.

Altogether, we expect the centrality measures will map onto the quality of input the respondent is getting from the full network as a whole, as well as from language-specific subnetworks. For instance, a respondent with high centrality in their French vs. English network may be generally more influenced by French-speaking alters than English-speaking alters.

The Brief Language & Social History Questionnaire

Here, participants provided self-report responses on various aspects of their own language and social history. These questions probed basic demographic variables about the participant, such as their age, gender identity, race or ethnic origin, current educational level, place of birth, and their duration of living in Canada, in Québec, and in Montréal. Participants were also asked to provide the postal code of their current residence, which was used for the census analysis.

Participants then answered some basic questions regarding their language history and current usage. First, participants self-reported the language(s) they were exposed to in their first year of life. This language or languages informed our classification of their first language (L1). Next, participants self-reported all other languages they knew, in terms of listening, speaking, reading, writing, or some combination of these. For each of these reported languages, we assessed the age at which they were acquired and whether the participant currently uses the language. Lastly, we asked the percent of daily life that participants perceived using each of their languages, which is the dimension we predicted in the final part of this study. This brief questionnaire was administered with Qualtrics (Qualtrics, 2020).

Canadian Federal Census

We used Statistic Canada's 2016 Canadian Census Profile (catalogue number: 98-401-X2016046) (Statistics Canada, 2016) to examine language use in neighborhoods inhabited by our participant sample. This demographic survey method is described by Statistics Canada as being distributed to all Canadian households every five years, approximately 25% of which receive a long-form questionnaire, and the remaining receive a short-form questionnaire. This question was marked as containing 100% data, which Statistics Canada describes as meaning that "data was collected for all unites (dwellings) of the target population, therefore no sampling is done." Statistics Canada also notes that institutional residents, or "a person, other than a staff member and his or her family, who lives in an institution, such as a hospital, a nursing home, or jail," were excluded from the population. Census respondents had the choice of a single response to this question or multiple responses. Single responses were divided by Statistics Canada into official languages (English, French) and non-official languages. They then divided non-official languages into “Aboriginal” vs. “non-Aboriginal languages”, both of which were further narrowed to reflect language families and their subsidiaries. In total, we counted 182 possible languages using this categorization. In contrast, multiple responses were reported in the following four categories: (1) English and French, (2) English and non-official language, (3) French and non-official language, (4) English, French, and non-official language.

All census responses are tagged with the respondent’s residential Forward Sortation Area (the first three digits of the postal code which take the form of [a-z][0-9][a-z].). The first letter of the Forward Sortation Area reflects the province or sub-provincial region. For example, Forward Sortation Areas starting with “J” represents areas in Western Québec, such as Gatineau and mainland suburbs of Montréal, whereas “H” reflects the Island of Montréal and its neighboring islands (e.g., Laval). As will be discussed in greater detail below, we limit our analysis to Forward Sortation Areas beginning with “J” or “H”, in order to capture the full geographic region surrounding the Island of Montréal (i.e., the Greater Montréal Area) where the study took place (see Figure 3).

For each of the 419 Forward Sortation Areas, we computed three key measures from the results of the 2016 Census Profile: English Index, French Index, and Language Diversity. **English Index** was calculated by totaling the number of respondents who reported that English was their only mother tongue, or it was among one of their mother tongues. To account for population density differences across Forward Sortation Areas, we divided this number by the total number of respondents in each Forward Sortation Area. This resulted in a proportion (0-1) where a higher number reflected more people in the neighborhood with English as their mother tongue, and a lower number reflected fewer people in the neighborhood with English as their mother tongue. This calculation was repeated for the **French Index**. For this score, we totaled the number of respondents who reported that French was their only mother tongue, or it was among one of their mother tongues. We divided this number by the total respondents in the Forward Sortation Area. With this approach, certain respondents – specifically individuals who reported both English and French, or English, French, and a non-official language as their mother tongues – were factored into both indices.

Lastly, we calculated the **Language Diversity** of each Forward Sortation Area using Wilcox's *Index of Qualitative Variation* (IQV) (Wilcox, 1973) as measured through the Deviation from the Mode. Generally, this class of indices is a quantification of heterogeneity, variability, dispersion, or diversity across categorical variables. We used Wilcox's basic DM (Deviation from the Mode) method, which is based on the Variation Ratio and is formalized below (Agresti & Agresti, 1978; K. Lewis et al., 2008):

$$1 - \frac{\sum_{i=1}^{k}(f_m - f_i)}{N(K-1)}$$

where f_i is the frequency of the i^{th} category, f_m is the frequency of the modal category, N is the number of cases, and K is the number of categories.

This index, ranging from 0-1, indicates the extent to which there is uniform distribution across the nominal categories, comparing the observed differences between categories to the maximal differences between categories. For example, if there are six observations across three categorical variables, an even distribution of (2, 2, 2) would result in maximal diversity (IQV = 1), whereas a skewed distribution of (6, 0, 0) would result in no diversity (IQV = 0).

This formula was applied to the number of respondents for each of the 182 languages from the 2016 Canadian Census Profile for each Forward Sortation Area. As a result, Forward Sortation Areas that were heavily dominant in one language as the mother tongue were given low language diversity scores, whereas Forward Sortation Areas with multiple pervasive mother tongues were given high language diversity scores.

LexTALE

We administered two behavioral language tasks to assess granular English and French language proficiency. LexTALE (Lexical Test for Advanced Learners of English) consists of a computerized un-speeded lexical decision task (Lemhöfer & Broersma, 2012). In the English version, sixty single-word trials (40 real English words, 20 English-looking nonwords) are shown one-by-one, and participants are instructed to judge whether each presented letter string is a real English word or not. This validated test has been shown to be an effective measure of English vocabulary knowledge and general English proficiency. A French adaptation of LexTALE was created to similarly assess French proficiency (Brysbaert, 2013). This task consisted of a similar un-speeded lexical decision task structure as the English version but varied in the number of trials (56 real French words, 28 French-looking nonwords).

Across both tasks, we calculated percent accuracy according to the scoring guidelines of LexTALE (Lemhöfer & Broersma, 2012), which corrects for the unequal proportion of real words to non-words. Given the English and French versions of this task were developed by different groups, we standardized each participant’s accuracy score to the English and French versions by computing a z-score.

Results

Interpersonal Language Dynamics

From each respondent's full personal network, we created three language-tagged subnetworks based on which language they reported using with each of their 8-12 alters, as illustrated in Figure 2 (Csardi & Nepusz, 2006; Krenz et al., 2020; R Development Core Team, 2019). Given federal and provincial language distinctions between English and French in Canada, and that participants were recruited on the basis of minimally knowing these two languages, we grouped the ego-alter languages into the following three categories: (1) English Subnetwork = English, or English and other languages besides French; (2) French Subnetwork = French, or French and other languages besides English; (3) Bilingual Subnetwork = English and French, or English, French, and other languages. For each subnetwork, we drew unweighted and undirected ties between alters who were reported to interact with one another. We then extracted eleven commonly used structural network measures from the full network and each subnetwork (listed in Table 1 and Methods).

The language-tagged subnetworks revealed several patterns of social language use (see Table 1 for summary statistics; see Supplementary Materials for the full results of the one-way ANOVA test and follow-up paired tests on each network measure). First, Tukey Honest Significant Difference tests, which followed up our one-way ANOVAs, indicated that language network effects were larger for English subnetworks than French subnetworks on all measures, except density (Size: t = -2.27, *adj.* p < .001; Ties: t = -1.27, *adj.* p = .01; Components: t = -1.30, *adj.* p < .001; Isolates: t = -0.78, *adj.* p < .001; Eigencentrality: t = -0.49, *adj.* p = .001; Mean Degree Centrality: t = -0.30, *adj.* p = .02; Max Degree Centrality: t = -0.61, *adj.* p = .003; Mean Betweenness Centrality: t = -0.17, *adj.* p = 0.02; Max Betweenness Centrality: t = -0.70, *adj.* p = .04; Strength: t = -1.34, *adj.* p = .02). Similarly, language network effects were larger for Bilingual subnetworks than French subnetworks on all measures, except mean and maximum betweenness centrality (Size: t = 1.82, adj. p < .001; Ties: t = 1.13, *adj.* p = .02; Density: t = 0.10, *adj.* p = .003; Components: t = 1.05, *adj.* p < .001; Isolates: t = 0.65, *adj.* p = .001; Eigencentrality: t = 0.55, *adj.* p < .001; Mean Degree Centrality: t = 0.41, *adj.* p < .001; Max Degree Centrality: t = 0.67, *adj.* p < .001; Strength: t = 1.53, *adj.* p = .01). Lastly, Bilingual subnetwork density was larger than English subnetwork density (Density: t = 0.08, *adj.* p = .04), however, no other statistical differences were detected between these two subnetworks.

Taken together, the French subnetwork emerged as the smallest across all network characteristics, except for network density, which was statistically comparable to the English subnetwork. This includes network measures related to overall size (e.g., number of alters), interconnectedness among alters (e.g., number of ties, strength), and alter influence or positionality (e.g., eigenvector centrality, degree centrality). The English and Bilingual subnetworks were comparable across most of these same network characteristics, again except for network density. Here, the density of the Bilingual subnetwork was greater than both the English and French monolingual subnetworks. This distinguishes the Bilingual subnetwork by indicating that the alters with whom egos use both English and French are more likely to know each other compared to alters with whom only English or French is used.

To summarize thus far, we applied social network analysis to quantify patterns of bilingual language use in everyday, person-to-person interactions. We identified three language-tagged subnetworks and computed eleven commonly used network measures from each, relating to aspects of the network size, interconnectedness, and alter influence. Critically, we will next use these quantifications of interpersonal language experience to examine whether this layer of sociolinguistic context relates to individuals' everyday language behaviors

< FIGURE 2 ABOUT HERE >

< TABLE 1 ABOUT HERE >

Ecological Language Dynamics

We used the 2016 Canadian Census Profile (Statistics Canada, 2016), freely available through Statistics Canada, to characterize ambient, ecological language patterns in the residential neighborhoods of our sample, focusing on respondents' self-reported mother tongue(s). We aggregated the results by Forward Sortation Area (i.e., the first three characters of the six-character residential postal code of each responding household).

We computed three key measures from the 2016 Census using mother tongue(s) of residents in each Forward Sortation Area: English Index, French Index, and Language Diversity (Table 2, see also Methods). We did this across all postal codes in the Greater Montréal Area (i.e., Island of Montréal, adjacent islands, and mainland West Québec) and merged them with the specific residential postal codes of our sample. As expected, the overall salience of French as at least one of the mother tongues substantially exceeded the salience of English, as can be surmised from both the mean and maximum values of these indices. We also observed that the overall English Index, French Index, and Language Diversity of our sample was broadly representative of population dynamics across the Island of Montréal, but not more rural parts of Québec. In those latter regions, the salience of English was lower, the salience of French was higher, and overall language diversity was also lower.

< TABLE 2 ABOUT HERE >

< FIGURE 3 ABOUT HERE >

We illustrated the geographic distribution of these ecological language dynamics in Figure 3. This geographic information system-generated figure visualizes the linguistic disparities between the neighborhoods within the Island of Montréal (includes Laval) compared to mainland Québec, with the urban islands depicting greater language diversity and a greater English Index than the suburban and rural areas. Moreover, this figure highlighted subtle linguistic patterns within the Island of Montréal, where the west side of the island exemplified greater language diversity, a greater English Index, and more simultaneous English/French mother tongue speakers than the East side.

This section assessed census language demographic statistics to compute three indices of ecological language patterns across the residential neighborhoods of our sample in Montréal: English Index, French Index, and Language Diversity. Next, we examine whether this layer of sociolinguistic context can be statistically dissociated from the social network interpersonal language dynamics and predict individuals' real-world language behavior.

Extracting the Systems Structure through EFA

Here, we tested the relationship between these two layers of interpersonal and ecological linguistic influence. To statistically determine this system structure, we applied Exploratory Factor Analysis. We included eighteen, normalized variables in the analysis: five previously-mentioned Social Network variables that captured unique aspects of the network structure and demonstrated distributional variance (network size, density, number of components, Eigencentrality, and strength) for each of the three subnetworks (English, French, Bilingual) and the three census indices (English Index, French Index, Language Diversity). The Kaiser, Meyer, and Olkin (KMO) measure of sampling adequacy (KMO = 0.66) and Bartlett's test of sphericity

($\chi 2(153) = 2457.01$, $p < .001$) indicated that our data were suitable for Exploratory Factor Analysis (Lüdecke et al., 2020).

To determine an appropriate number of latent factors to extract, we used the 'n_factors' function from the parameters package in R (Lüdecke et al., 2020; R Development Core Team, 2019) with an oblimin rotation to suit the correlated nature of our variables. This consensus-based function implements multiple existing procedures to determine the number of factors to retain during exploratory factor analysis. In our case, eighteen methods, including parallel analysis, optimal coordinates, and acceleration factor, were assessed and exhibited support for a range of one to fifteen factors. The choice of four factors was the smallest, non-singular number of factors that was supported by multiple metrics (beta method from the multiple regression family and optimal coordinates and acceleration factor methods from the scree family).

We extracted four factors with an oblimin rotation and a multiple regression factor method, which accounted for 71.33% of the total variance of the original data. As can be seen in Figure 4, all personal French language network measures (i.e., Eigencentrality, strength, network size, and density) positively loaded on Factor 1, which accounted for 19.9% of the overall variance. Next, all network measures from the English personal language subnetwork positively loaded on Factor 2, which accounted for 19.6% of the overall variance. Here, network size and number of components from the personal Bilingual subnetwork negatively loaded on Factor 2. All personal Bilingual subnetwork measures positively loaded on Factor 3, which accounted for 17.3% of the overall variance. Lastly, the three census measures loaded on Factor 4, which accounted for 14.5% of the overall variance. Language diversity and English Index positively loaded on Factor 4, and French Index negatively loaded on this factor.

Moreover, we tested whether the three factors comprising of interpersonal language network dynamics correlated with Factor 4 on ecological language dynamics from the Canadian Census (full correlation table available in Supplementary Materials). Indeed, the personal French network factor (Factor 1) negatively correlated (r = -0.30) with the Ecological factor (Factor 4), whereas the personal English network factor (Factor 2) positively correlated (r = 0.18) with the Ecological factor (Factor 4). Given that greater ambient English use loaded positively on the Ecological factor, these results highlight a contextual alignment between greater English use in interpersonal interactions and greater ambient exposure to English in one's neighborhood of residence. We did not find evidence supporting a correlation between the personal Bilingual network factor (Factor 3) and the Ecological factor (Factor 4) (r = -0.03). A correlational analysis of all the raw network measures and the ecological language indices confirmed that the relationship between the interpersonal and ecological layers of linguistic context did not stem from general network properties (e.g., overall network size), but instead were specific to language-based characteristics of the social network (Supplementary Materials, Figure 1). From here, we will assess whether these latent variables comprising our Systems Framework predict individuals' bilingual language behavior.

< FIGURE 4 ABOUT HERE >

Predicting Individuals' Cognitive & Linguistic Processes

Lastly, we examined how interpersonal and ecological linguistic influences, quantified through the four-factor latent structure of our Systems Framework, in turn influenced real-world bilingual language use for the individuals in our sample. In particular, we generated separate robust multiple linear regressions to model a global aspect of language use, self-reported percent of daily conversations that were engaged in English vs. in French, and a granular aspect of language proficiency, performance on the LexTale task in English vs. in French.

Robust regressions minimize the weight of single data points with large residuals on the regression slope. In this case, this analytic approach is effective in capturing the diversity of linguistic experiences (see panel A in Figure 5) while preventing single points from exerting undue influence on the model (Maechler, 2021; Venables & Ripley, 2002). In other words, robust regression coefficients are less likely to be determined by single, extreme values than regular regression. Across all models, we computed partial eta-squared (η^2), which conveys the variance explained by the effects in the model.

Daily Conversations. Participants reported the average percent of each day they spent using English and French. Our first model revealed that percent of daily conversations in English was significantly predicted by the three interpersonal language factors and the ecological language factor (FA1-French: B = -11.18, SE = 2.00, t = -5.59, p < 0.001, 95% CI [-15.10, -7.26]; FA2-English: B = 4.89, SE = 1.99, t = 2.46, p = 0.02, 95% CI [0.99, 8.79]; FA3-Bilingual: B = -4.05, SE = 1.89, t = -2.14, p = 0.03, 95% CI [-7.75, -0.35]; FA4-Ecology: B = 7.72, SE = 1.90, t = 4.07, p < 0.001, 95% CI [4.00, 11.40]). As shown in Figure 5, higher French and Bilingual factor scores patterned with lower use of English in daily conversations, but higher English and Ecology factor scores patterned with greater use of English in daily conversations. Effect size, measured by partial eta-squared, is as follows: FA1-French = 0.38, FA2-English = 0.11, FA3-Bilingual = 0.06, FA4-Ecology = 0.15.

Our second model revealed that percent of daily conversations in French was significantly predicted by the French and English personal language networks as well as the Ecological factor, but not the Bilingual personal language network (FA1-French: B = 11.43, SE

= 2.06, t = 5.56, p < 0.001, 95% CI [7.39, 15.50]; FA2-English: *B* = -4.96, SE = 2.04, t = -2.43, p = 0.02, 95% CI [-8.96, -0.96]; FA3-Bilingual: *B* = 3.66, SE = 1.95, t = 1.88, p = 0.06, 95% CI [-0.16, 7.48]; FA4-Ecology: *B* = -6.29, SE = 1.95, t = -3.22, p = 0.002, 95% CI [-10.10, -2.47]). Here, higher French factor scores patterned with greater use of French in daily conversations, but higher English and Ecology factor scores patterned with lower use of French in daily conversations (Figure 5). Effect size, measured by partial eta-squared, is as follows: FA1-French = 0.38, FA2-English = 0.11, FA3-Bilingual = 0.05, FA4-Ecology = 0.11.

Across both models, the French personal language network had the largest standardized coefficient and partial μ^2 effect size (0.38) on current usage followed by the Ecological factor (0.15 English usage, 0.11 French usage). Thus, both models detected converging evidence that interpersonal and ecological characteristics of bilingual language behavior jointly predicted how individuals use their languages in everyday conversations (see Figure 5).

LexTALE. Participants also completed a lexical proficiency task in English and French. To model performance on the English and French LexTale tasks we simply replaced the dependent variable of the previous two models (i.e., percent English/French use) with standardized percent accuracy on the English and French LexTale tasks, respectively.

Our first model revealed that performance on the English LexTale task (z-scored) was significantly predicted by the French personal language network (FA1-French: *B* = -0.40, SE = 0.14, t = -2.93, p < 0.01, 95% CI [-0.67, -0.13]), but no other variables (FA2-English: *B* = -0.06, SE = 0.15, t = -0.39, p = 0.70, 95% CI [-0.36, 0.23]; FA3-Bilingual: *B* = -0.22, SE = 0.13, t = -1.72, p = 0.09, 95% CI [-0.48, 0.03]; FA4-Ecology: *B* = 0.14, SE = 0.14, t = 0.99, p = 0.33, 95% CI [-0.13, 0.42]). Here, as French personal language network score decreased, English LexTale accuracy increased (Figure 6). Effect size, measured by partial eta-squared, is as follows: FA1-French = 0.17, FA2-English = 0.00, FA3-Bilingual = 0.06, FA4-Ecology = 0.02.

Our second model revealed that performance on the French LexTale task (z-scored) was significantly predicted by both the English and French personal language networks (FA1-French: *B* = 0.33, SE = 0.12, t = 2.68, p < 0.01, 95% CI [0.07, 0.58]; FA2-English: *B* = -0.33, SE = 0.13, t = -2.49, p = 0.01, 95% CI [-0.59, -0.08]), but not the Bilingual language network nor the Ecological factor (FA3-Bilingual: *B* = 0.03, SE = 0.12, t = 0.24, p = 0.81, 95% CI [-0.21, 0.27]; FA4-Ecology: *B* = -0.10, SE = 0.12, t = -0.83, p = 0.41, 95% CI [-0.34, 0.14]). These results indicate that as English personal language network scores decreased and French personal language network scores increased, French LexTale accuracy increased (Figure 6). Effect size, measured by partial eta-squared, is as follows: FA1-French = 0.23, FA2-English = 0.13, FA3-Bilingual = 0.00, FA4-Ecology = 0.01.

Across self-reported usage patterns and performance on LexTALE, it is worth noting that while all participants were recruited on the basis of their proficiency in both English and French, testing was conducted in an English-dominant environment (i.e., McGill University) with English speaking experimenters.

< FIGURE 5 ABOUT HERE >

< FIGURE 6 ABOUT HERE >

Discussion

In this paper, we both developed and offered evidence for a novel *Systems Framework of Bilingualism* to holistically model the hierarchical layers of sociolinguistic context that constrain people's cognitive and linguistic processes. Specifically, we merged methods from social network analysis and geospatial demographic analysis to quantify local and ambient influences of social context, respectively. We conducted latent variable analysis and found that each linguistic social network grouping loaded on independent factors (English, French, Bilingual), and all ecological variables loaded on one factor (English Index and Language Diversity loaded positively, French Index loaded negatively), despite scaling variables prior to analysis. Correlations within this oblique-rotated factor structure highlighted a *contextual alignment* between interpersonal and ecological language dynamics: having a large, interconnected, and influential English-speaking personal network was associated with living in neighborhoods with more English speakers and linguistic diversity, whereas these same characteristics among the French-speaking personal network were associated with living in French-dominant neighborhoods. Lastly, but of greatest importance, latent factors underlying local and ambient layers of social context *jointly* predicted general, global aspects of language behavior (daily usage) whereas only local, interpersonal dynamics predicted specific, granular language behavior (lexical proficiency).

We had anticipated that local (i.e., interpersonal social networks) and ambient (i.e., ecological, neighborhood characteristics) dynamics would predict different aspects of language and cognition depending on the granularity of the process under question. The results from this study support this idea. When examining global aspects of language use, both interpersonal and ecological factors were predictive. Interestingly, standardized model coefficients revealed that the linguistic composition of one's residential neighborhood was associated with an approximately 6-7% change in daily language use, which exceeded the effect of some of our language-specific social networks. A supplementary stepwise model also indicated that the addition of the Ecological factor led to the largest decrease in residual standard error than any other factor (Supplementary Materials, Table S1). In contrast, only some local, interpersonal social network characteristics predicted performance on the LexTALE, which we understand as a more nuanced assessment of language behavior which targets language experience at the lexical level. It is possible that the people with whom languages are directly used (i.e., the alters in a social network) are more consequential on specific word-level knowledge than ambient exposure to one or more languages, such as one might overhear when walking down the street. However, it is possible that probing language behavior at another level of analysis (e.g., phonological recognition) would reveal a more active role of ambient linguistic experiences. Such questions open the door to future innovative investigations of which precise levels of language are impacted by which socioecological forces and highlight the theoretical productivity of a Systems Framework of Bilingualism.

We were especially intrigued by the variable impacts of the Bilingual subnetwork on daily English vs. French use, which also did not relate to the Ecological factor. In other words, while there was contextual alignment in how English and French are used within social networks and across neighborhoods, we did not find that bilingual language use within social networks mapped onto our neighborhood language indices. While this may reveal meaningful differences stemming from English's status as a global *lingua franca*, it is also possible that the network *structure* of the Bilingual subnetwork exerted weaker influence on real-world linguistic behavior than the two monolingual network structures. We found greater density within the Bilingual subnetwork than both the English and French monolingual subnetworks, and a follow-up revealed that respondents also felt closer to alters in the Bilingual subnetwork than to alters in either monolingual subnetwork (Supplementary Materials), implicating strong affiliation with bilingual alters, perhaps resulting from homophilic linguistic identity (Blackledge & Pavlenko, 2001; Rogers & Kincaid, 1981). These patterns align with past findings that linguistic innovation is spurred by weak ties in a social network structure (i.e., the strength of weak ties) (Granovetter, 1973), and may in part reflect why simplified operationalizations of bilingualism fail to predict behavioral results in other domains of cognition (e.g., executive control). It may be that such relationships are better characterized by pooled sets of weakly predictive variables, as we find here through the network structure, or through other budding methods like machine learning (Gullifer & Titone, 2020).

Additionally, these results must be contextualized within the broader social environment of Montréal, Canada, where the status of English, French, and bilingualism intersect with politics and many other aspects of identity. With this in mind, it is possible that the role of the bilingual social network (which was operationally defined as English-French bilingualism) may meaningfully differ in other linguistic milieus. This may include regions where the social status of two languages is asymmetrical (e.g., English and Spanish in many parts of the United States), linguistic experiences are mode-specific (e.g., heritage language knowledge within second generation immigrant communities), or social networks are relatively homogenous (e.g., rural areas).

This work builds on knowledge from sociological research to extend our understanding of the power of social context in shaping a myriad of mental processes within human psychology (Giles et al., 1973; Grosjean, 1982; Todorov et al., 2006). For example, frameworks like Lewin's Field Theory contextualized individuals within their socialized environment (Lewin, 1951). Payne and colleagues (2019) found that modern-day, individual-level anti-Black bias across the southern United States was predicted by the regional proportion of enslaved African people there in 1860, implicating historical, systemic actions in determining contemporary psychology. Ofosu and colleagues (2019) demonstrated that collective norms are dictated by policies, components of the societal-level layer of social influence that we did not alter in the present study. The current study adds to this burgeoning literature by exploring how a hierarchical, social system of linguistic experiences constrains linguistic and cognitive processes. We suggest that focusing on language to highlight the socially-contextualized nature of cognition is a practical starting point for many reasons, including the fact that language use at a population level is measured through federal census data and most interpersonal relationships engage linguistic communication in some way. This offers a unique and concrete opportunity to operationalize and quantitatively characterize such socioecological dynamics on cognition that may otherwise seem amorphous. Our ongoing work extends this theoretical framework to other aspects of cognition, including language attitudes (Feng et al., under review), implicit bias (Kutlu et al., in press, under review), and cognitive perspective-taking or mentalizing (Tiv, O'Regan, et al., 2021).

Accordingly, the Systems Framework of Bilingualism developed here can guide research on emergent questions in related psychological domains, particularly given the growing interest in analytic tools like social network analysis across areas such as cognitive science (Vitevitch, 2019). Indeed, a Systems perspective may enrich our understanding of other cognitive processes. For example, Vlasceanu and colleagues (2018) discuss the implications of social network and societal experiences on memory consolidation. As such, the framework introduced in this paper can be flexibly applied to many other cognitive processes, such as memory, attention, and decision-making, that like language are situated in social contexts. One extension of this work may be the interaction among layers of social influence, which may further constrain language and cognition, as well as related psychological experiences including identity formation, sense of belonging, and well-being (Doucerain et al., 2015). Another valuable inquiry is how these dynamics change over time, which was held constant in this study. Such questions would engage historical perspectives through use of longitudinal data and developmental perspectives by examining changes across the lifespan. Finally, this model can be broadly applied to examine linguistic and cognitive dynamics among historically marginalized groups, including neurodiverse populations and racialized communities. Accounting for the diversity in these social experiences can cultivate a richer, more multidimensional, and more representative understanding of their lived experiences.

We acknowledge several limitations of this study, including the correlational nature of our analyses which precludes causal links between interpersonal and ecological sociolinguistic constraints on language behavior (see Supplementary Materials, Tables S2 & S3, for an additional analysis addressing the flow of sociolinguistic influence). Additionally, our sample was mostly composed of bilingual-raised, English-dominant speakers, presumably due to the study taking place at a primarily English-speaking institution. However, this constraint allowed us to characterize a globally ubiquitous group who grew up with multiple languages and use English in professional contexts. Our ongoing work examines diverse, global populations of bilinguals, to assess how their rich experiences manifest through behavior.

To conclude, we found evidence that *multi-layered* social-contextual dynamics jointly predict how an individual uses their languages. This insight is crucial for developing a comprehensive study of the role of language in human experience that bridges psychological subdisciplines. Much of our understanding of language and cognition, has been internally directed through assessments of individual-level attributes. We present evidence that a reorienting towards external constraints is needed for inherently social neurocognitive processes, like language. Such an undertaking is challenging. Here, we offer theoretical and methodological tools, alongside an analytic pipeline to facilitate holistic assessments of language and cognition that we hope will empower more realistic examinations of diverse social experiences, including those of minority, heritage, and racialized language speakers. We also hope that the approach taken here serves as a theoretical, methodological, and analytic model for how other behavioral and cognitive phenomena can be framed in a more holistic, socioecological manner.

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Figure 1

A Systems Framework of Bilingualism

*A Systems Framework of Bilingualism, which comprises of three interrelated layers of sociolinguistic context: interpersonal, ecological and societal. Across all contexts, time exerts subtle influences on the system, depicted by the phases of the moon. An individual (ego), shown by the brain icon, is situated within this interactive constellation, or system, of social influence. Consequently, this system holds implications for their cognition, language, and neural activity. *

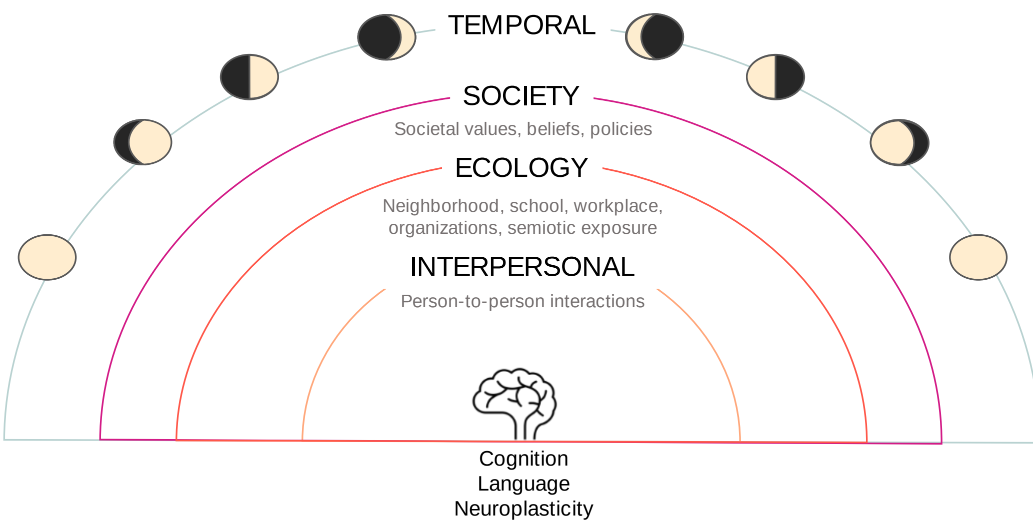

Figure 2

Full networks of six people (i.e., egos)

The linguistic and structural diversity of the personal social networks of six respondents. The top row of this figure illustrates highly interconnected networks, where alters are reported to know and interact with one another, and the bottom row of this figure illustrates disconnected networks, where the respondent is sometimes the sole connection between otherwise non-communicating alters. The left-most panel illustrates English-dominant networks, the middle panel illustrates French-dominant and networks, and the right-most panel illustrates English-French linguistically mixed networks. Across all panels, node color indicates language(s) between the respondent and each alter and node size indicates perceived closeness between the respondent and each alter (bigger = closer). Respondents (egos) are not represented in these networks.

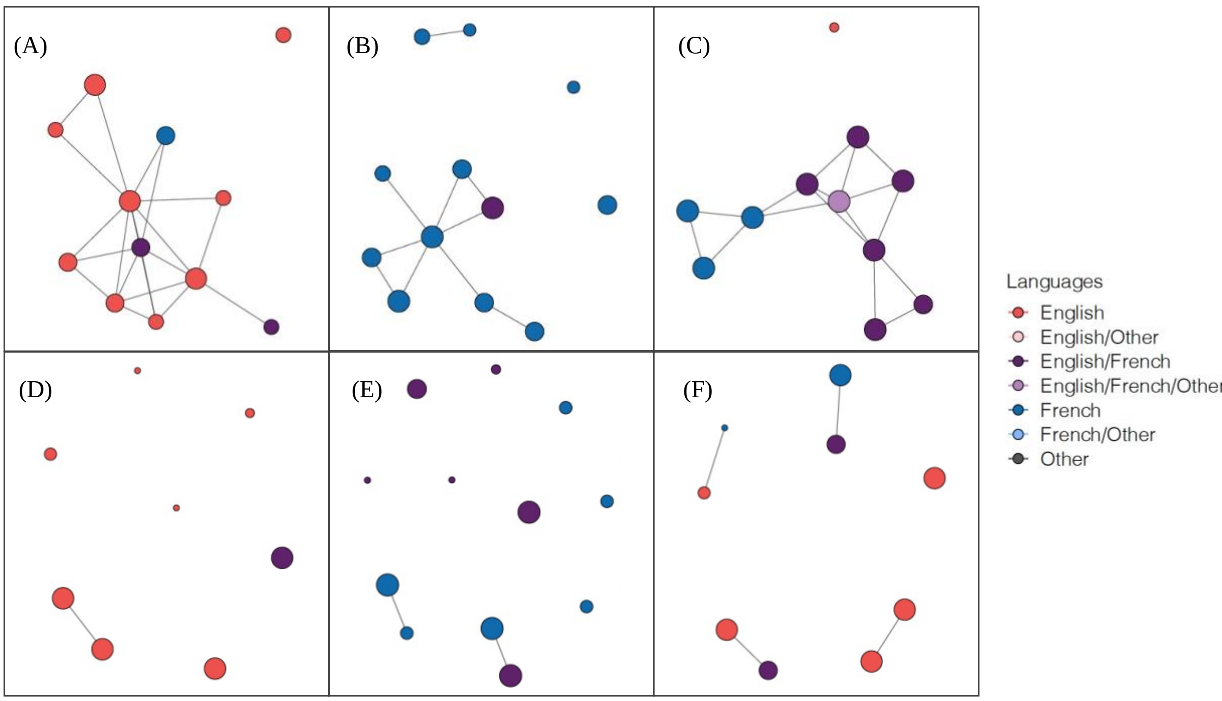

Table 1

Summary Statistics for Eleven Network Measures of Personal Social Networks

Summary statistics regarding the full network and each of the three, language-tagged subnetworks. While the full network, which was not tagged with any language specific information, is provided here for context, we only statistically tested for differences between the three, language-tagged subnetworks.

Network Measure	Full Network				English Subnetwork				French Subnetwork				Bilingual Subnetwork (English & French)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Size	9.76	1.68	8.00	14.00	4.15	3.14	0.00	10.00	1.88	2.64	0.00	11.00	3.70	2.52	0.00	11.00
Ties	8.17	4.47	1.00	29.00	2.26	3.40	0.00	16.00	0.98	2.23	0.00	11.00	2.11	3.16	0.00	16.00
Density	0.19	0.09	0.03	0.68	0.13	0.17	0.00	1.00	0.11	0.25	0.00	1.00	0.21	0.27	0.00	1.00
Components Number	4.12	1.67	1.00	10.00	2.44	1.78	0.00	7.00	1.14	1.43	0.00	7.00	2.19	1.44	0.00	6.00
Isolates	1.96	1.64	0.0	8.00	1.53	1.48	0.00	7.00	0.75	1.13	0.00	7.00	1.40	1.27	0.00	6.00
Eigenvector Centrality	2.55	0.90	1.00	5.41	0.95	1.09	0.00	4.75	0.46	0.89	0.00	4.00	1.01	1.11	0.00	4.61
Mean Degree Centrality	1.64	0.77	0.25	4.75	0.65	0.84	0.00	4.57	0.34	0.69	0.00	3.33	0.75	0.92	0.00	4.57
Max Degree Centrality	3.46	1.62	1.00	9.00	1.17	1.46	0.00	7.00	0.55	1.13	0.00	5.00	1.23	1.43	0.00	5.00
Mean Between Centrality	0.84	1.23	0.00	5.70	0.22	0.70	0.00	4.78	0.05	0.19	0.00	1.64	0.13	0.29	0.00	1.71
Max Between Centrality	4.87	6.65	0.00	31.08	1.00	3.00	0.00	16.50	0.30	1.40	0.00	13.00	0.59	1.42	0.00	8.33
Strength	6.99	3.58	0.25	19.23	2.86	3.92	0.00	21.25	1.52	3.13	0.00	14.50	3.05	4.04	0.00	17.00

Table 2

Summary Statistics for key Census Measures

104 participants provided their postal code information from which we were able to extract census-level linguistic information (2 participants did not report their postal code). The majority of our sample (n = 87) reported living on the Islands of Montréal and Laval (i.e., their postal code began with "H"). A handful of participants (n = 17) reported living on the mainland of Québec directly adjacent to the rivers surrounding the Island of Montréal, which is officially recognized as West Québec (i.e., their postal code began with "J"), though we refer to it as the Greater Montréal Area. However, it is important to note that whereas some of our participants reported living in neighborhoods that are highly proximal to the Island of Montréal and urban life, there are many other neighborhoods in West Québec that reach far into the rural expanses of mainland Québec. Given the range of possible linguistic differences across these regions, this table illustrates both the census statistics from only the Island of Montréal (postal code beginning with "H") as well as the Island of Montréal plus West Québec (postal codes beginning with "H" or "J"). These regions are illustrated in Figure 3.

	Sample (N=104)				Population: Island of Montreal				Population: Greater Montréal Area			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
English Index of Mother Tongue	0.22	0.12	0.02	0.58	0.12	0.16	0.03	0.76	0.13	0.14	0.009	0.76
French Index of Mother Tongue	0.50	0.21	0.19	0.96	0.50	0.20	0.00	0.88	0.71	0.25	0.00	0.99
Language Diversity (IQV)	0.49	0.19	0.04	0.84	0.47	0.18	0.12	0.84	0.28	0.23	0.01	0.84

Figure 3

Montréal's Ecological Language Dynamics

Panel A depicts Forward Sortation Areas within the Island of Montréal (dark grey, as defined by beginning with "H", which also includes the island of Laval) and the Greater Montréal Area (light grey, beginning with "J"). Panel B illustrates language diversity, as calculated by the Index of Qualitative Variation. Panel C illustrates English Index. Panel D illustrates French Index. Across panels B-D, darker colors indicate larger values whereas lighter colors indicate smaller values. Note differences in color scales across panels B-D. All data are based on the 2016 Canadian Census Profile.

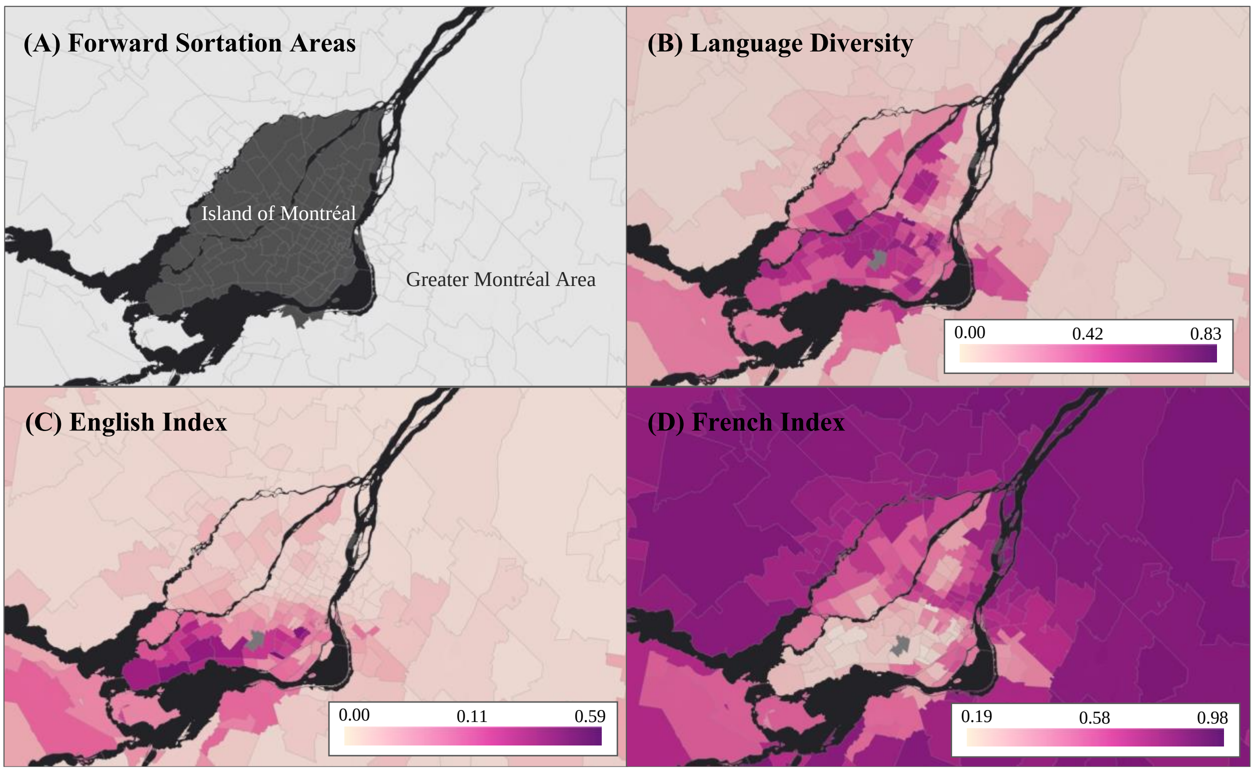

Figure 4

Factor Loadings for Exploratory Factor Analysis

Factor loading structure of 18 network variables and census indices that were inputted to Exploratory Factor Analysis. Total variance captured by all four factors is 71.33%. Solid black lines indicate 0.4 factor loading score.

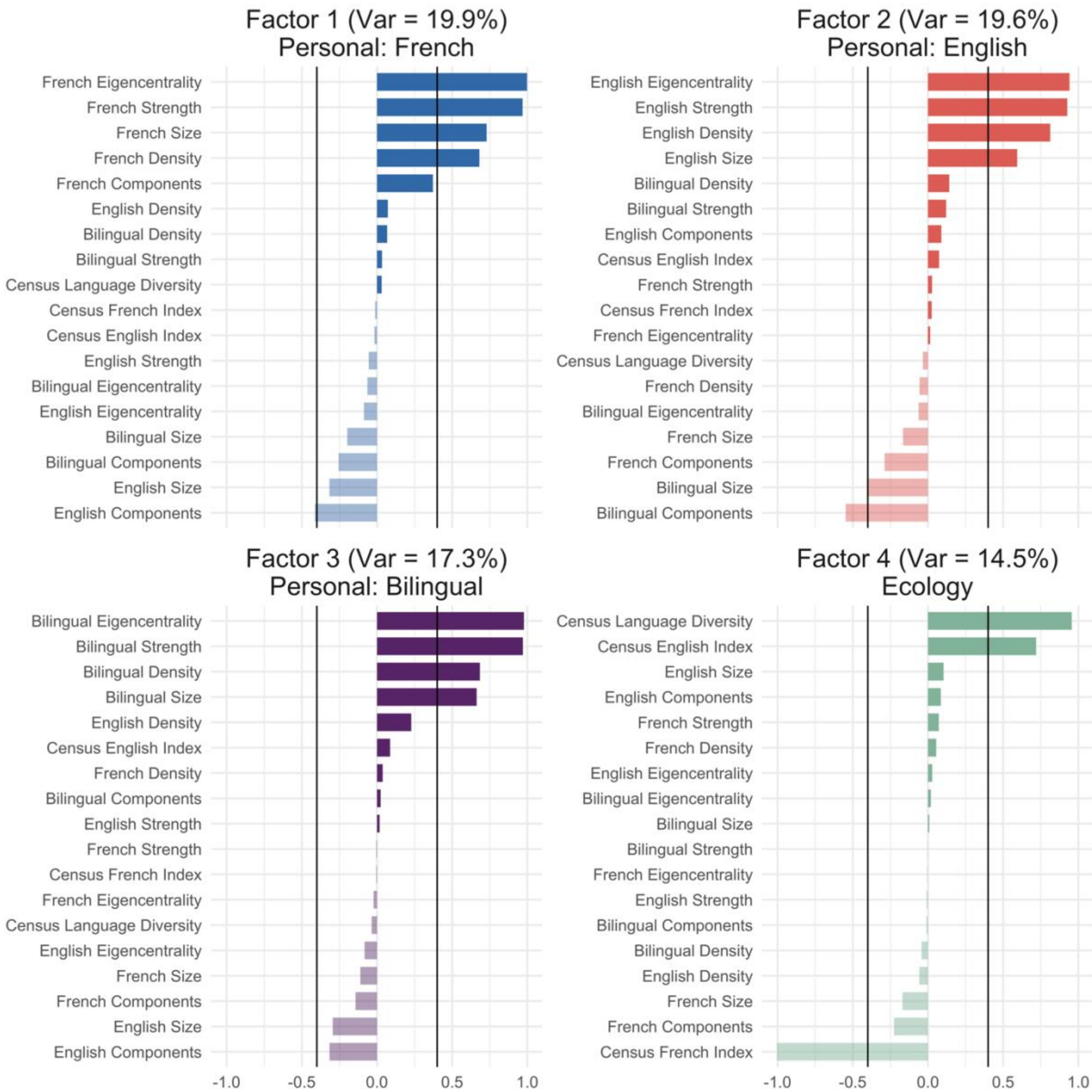

Figure 5

Predicting participants' daily percent of conversations in English and French from systems framework factor structure

(A) The distribution of each factor score. From top to bottom: French, English, Bilingual, and Ecology. To account for the diversity in factor scores across all participants, we computed robust regression models, which downweighed the global influence of scores with high residual values. (B) The distribution of percent daily conversations in English vs. French (low usage on left end of scale and high usage on right end of scale. In our sample, more people reported high usage of English and low usage of French in daily conversations. (C) The relationship between each of the four factor scores (French, English, Bilingual, and Ecology) and percent of conversations in English and French. For conversations in English, all four factors significantly predicted daily usage, and for conversations in French, the French, English, and Ecology factors significantly predicted daily usage.

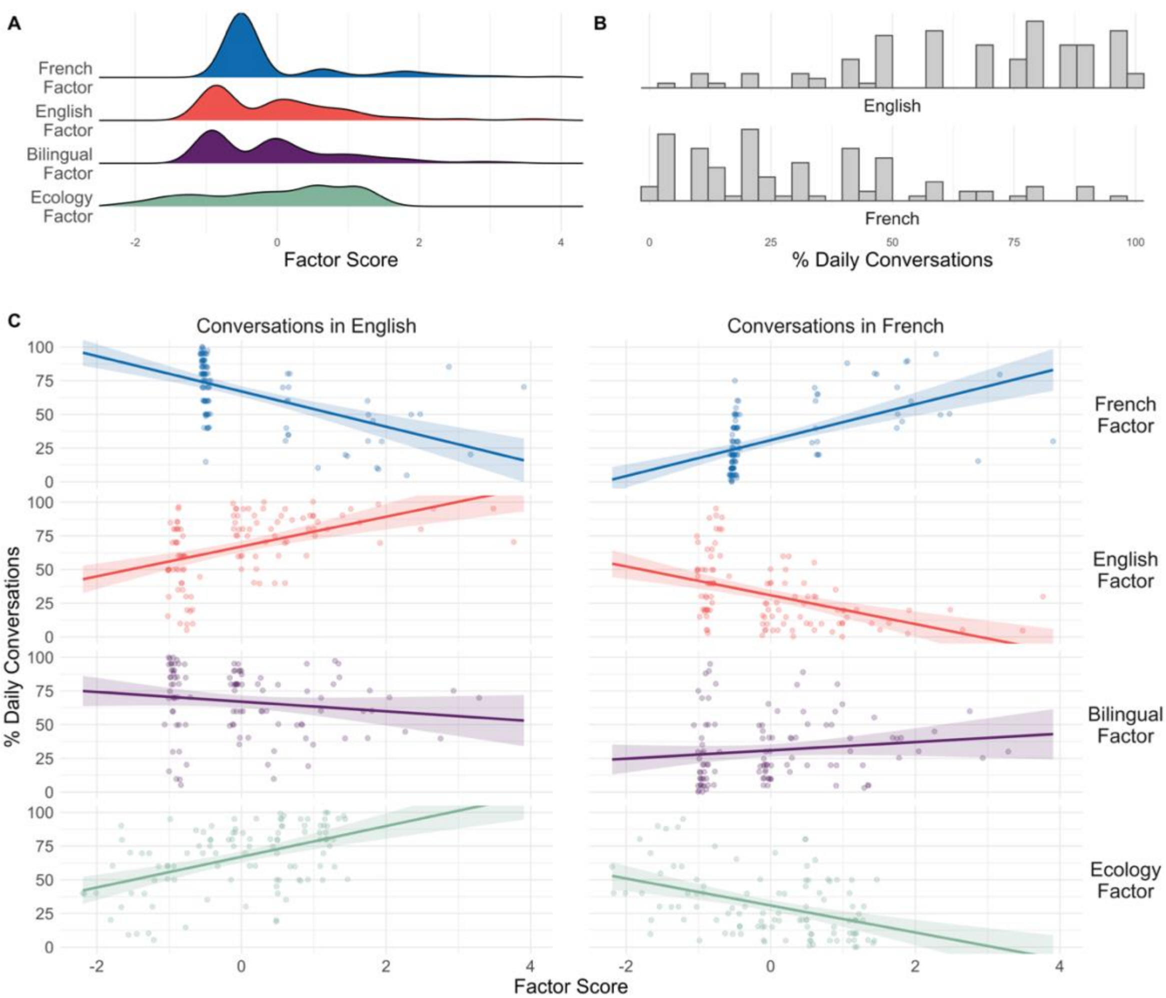

Figure 6

Predicting participants' lexical proficiency on LexTale from systems framework factor structure

Performance on LexTale English was significantly predicted by the personal French social network whereas performance on LexTale French was significantly predicted by both the French and English social networks.