Précis of Towards an Ecologically Valid Neurobiology of Bilingualism

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Introduction:

Understanding how our brains process language is one of the fundamental problems in cognitive science — one that goes to the core of what it means to be human, and to have a human mind. In order to reach such understanding, it is critical to cover the full spectrum of manners in which humans acquire and experience language. However, due to the natural inclination of individuals to take their own experience as the norm, and the historical hegemony of Anglo-Americans in the high echelons of academia and society in the US, the majority of investigations on the neurobiology of language have taken the monolingual English speaker as the representative of universal language processing. As it turns out though, this linguistic experience is far from being the norm. In reality, less than half of the world's population is monolingual, and even in the US, it is expected that monolingual English speakers will be less than half of the population by 2040 (US Census, 2013). In other words, our understanding of human language processing has been heavily determined by our understanding of how the most powerful subset of the population processes language, rendering an incomplete portrait of how humans process language in general.

In my dissertation, I addressed the lack of diversity in this field of research by placing the focus of my investigation on an understudied population; multilingual individuals, and combining insights from individuals who do not process language through sound but sign, to inform a theory of the neurobiology of language that is more inclusive and comprehensive than the accounts that had been developed to date. To obtain an extensive profile of these experiences, I combined insights from linguistics, psychology and neuroscience with a range of methodological approaches, including neuroimaging, univariate and multivariate statistics, and natural speech tagging paradigms. Further, I took the most naturalistic approach possible to inform a theory that can not only account for laboratory based experiments but rather aims to capture the multifaceted and socially influenced experience of what it means to communicate in the real world. The findings of this dissertation uncover fundamental knowledge about the neural bases of natural, multilingual communication that transcend articulator limitations, and are thus relevant to a broad audience of researchers in cognitive science, cognitive development, clinical psychology, linguistics and education.

Chapter 1: Bilingual language switching in the lab vs. in the wild: The spatio-temporal dynamics of adaptive language control

Blanco-Elorrieta & Pylkkänen (2017) *Journal of Neuroscience*

In trying to develop a neurobiology of language that includes the multilingual experience, a fundamental issue to uncover is what the mechanisms are that allow bilinguals to successfully communicate in two languages. How must different linguistic systems interact and integrate such that people can, depending on the context, either mix languages or stick to just one? To answer this question, researchers focused on analyzing the process by which bilinguals switch from one language to another. Specifically, they developed experiments in which bilinguals were asked to switch from one language to another following a color cue (e.g., Meuter & Allport, 1999). Researchers very reliably found that switching languages was effortful; i.e., bilinguals were slower, they made more mistakes, and they required increased engagement from prefrontal areas associated with cognitive control whenever they were required to switch languages as compared to when they remained in the same language. The theoretical inference from the fact that switching languages was effortful was that bilingual individuals' language architecture is composed of two independent linguistic systems, and the cost emerges from having to go from one to the other. This inference seemed to follow since, if one were to believe that there is a single unified system for both languages, there should be no difference between staying in the same language or going from one to another, since all elements are part of the same system.

But is switching languages really costly? Because a common observation when bilingual individuals talk to each other is that in fact they switch languages very frequently, and it would seem extremely counterintuitive that people would engage in this process that frequently if it were in fact so effortful for them. Thus, there seemed to be a tension between the cost researchers had found in the lab and what seems to be the intuitive experience of bilingual individuals. This divergence led me to question whether the cost that researchers had previously identified was truly inherent to the process of language switching, or whether the observed switching cost may instead arise from the task request to switch languages on demand.

I investigated this issue in production and comprehension by developing a series of experiments that modeled language switching in multiple contexts ranging from i) a completely artificial color-cued context, ii) a context where participants switched languages based on which monolingual interlocutor they were communicating with, iii) a context where switching occurred freely on participants' volition while communicating with another bilingual individual, and iv) the comprehension of a fully natural bilingual conversation recorded "in the wild." (Fig. 1A). I convincingly replicated the behavioral and neural costs associated with language switching in an artificial setting, when participants switched languages following color-cues, but found that these costs decreased in more naturalistic environments and in fact, voluntary switching was absolutely effortless (Fig. 1C and 1D).

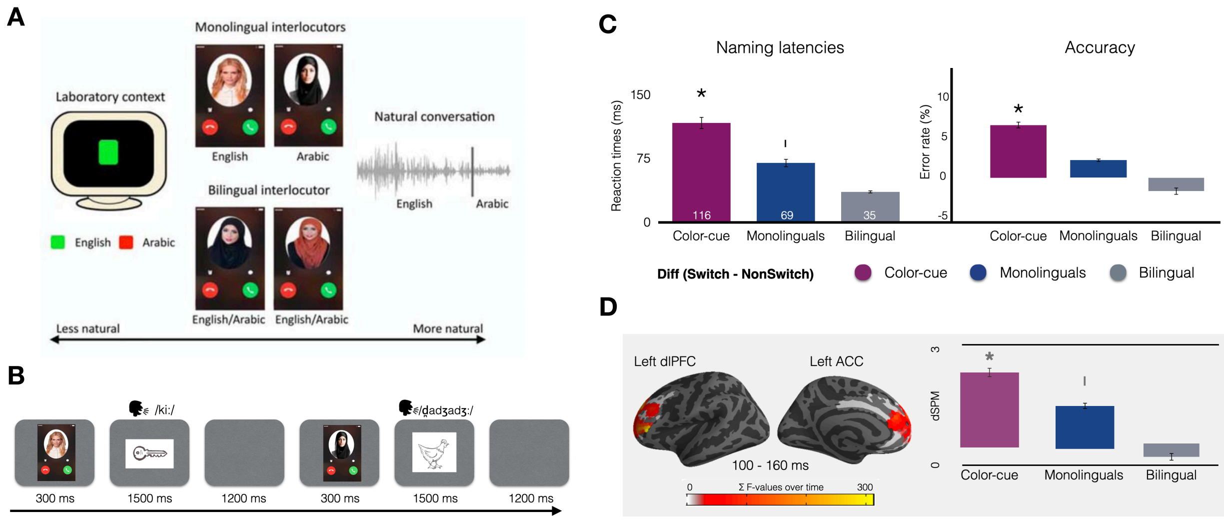

Fig. 1. A) Experimental conditions varying from less natural to more natural contexts. **B)** Example of a production trial **C)** Mean reaction times and error rates as a function of the conversational context and performed switching condition within production tasks. Bars show switch-cost amplitude. **D)** Analysis of the MEG activity time-locked to the stimulus picture to be named. The freeSurfer average brains on the left represent the spatial distribution of the reliable cluster (every source that was part of the cluster at some point in time is color-coded with the sum F or t statistic). Significance was determined using a nonparametric permutation test (Maris and Oostenveld, 2007) performed from 100 to 300 ms (10,000 permutations). Bar graphs represent the average activity per condition for the sources and time points that constitute the cluster. $^*p < .05$ $^{\text{I}}$ $p < .1$

In comprehension, while single-word switches anticipated by artificial cues recruited executive control areas (Fig. 2B), fully natural switching within a conversation did not require any such engagement (Fig. 2C), only auditory cortices showed increased activation during a language switch (Fig. 2D).

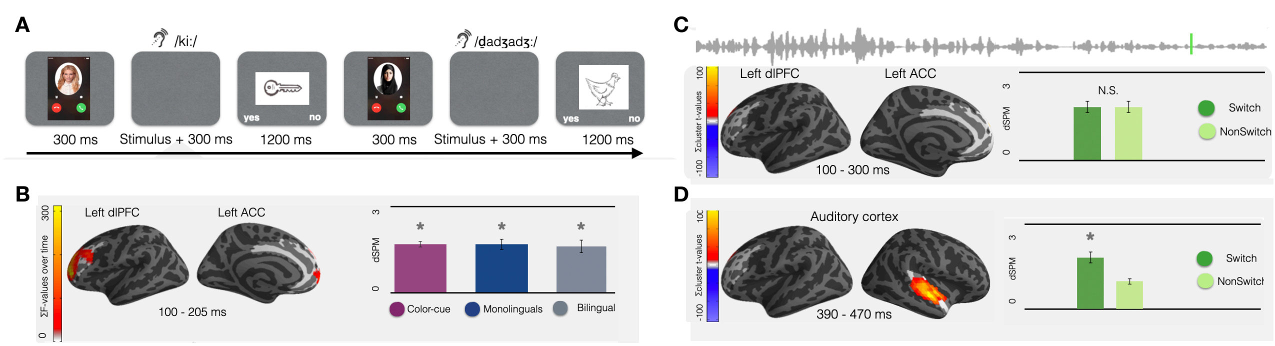

Fig. 2. A) Example of a comprehension trial. **B)** MEG activity time-locked to the onset of the stimulus word showing a cost associated with comprehending an isolated language switch to be comprehended **C)** Null MEG results in executive control areas while participants processed switches contained within a natural conversation **D)** Auditory cortex showing differential activation when it detected a switch in the language of the conversation. In B, C and D, the freeSurfer average brains represent the spatial distribution of the reliable cluster. Significance was determined using a nonparametric permutation test (Maris and Oostenveld, 2007) performed from 100 to 300 ms (10,000 permutations). Bar graphs represent the average activity per condition for the sources and time points that constitute the cluster. $^*p < .05$ $^{\text{I}}$ $p < .1$ (corrected).

In all, this study not only confirmed that switching is easier in more naturalistic environments (see also Blanco-Elorrieta & Pylkkänen, 2015 *Front Human Neurosci*) but showed for the first time that the switch cost that had been previously regarded as intrinsic to the process of switching languages was in fact only caused by the artificial constraint requiring participants to switch languages based on external demands.

Chapter 2: Language switching decomposed through MEG and evidence from bimodal bilinguals

Blanco-Elorrieta, Emmorey, & Pylkkänen (2018) *Proceedings of the National Academy of Sciences*

These findings raised the question: what exactly is it that causes a cost when switching is constrained by external demands? While switching had been previously discussed as a monolithic process, upon scrutiny it becomes apparent that it is minimally composed of two sub-processes, both of which need to be successfully executed for a language switch to occur. First, a person needs to disengage from the language they were producing up until that point (i.e., they need to turn a language "off"). Second, they need to activate the language they intend to produce from that moment onward (i.e., they need to turn a language "on"). This chapter explored which of these two processes was the source of the costs associated with switching languages on demand.

Dissociating these processes with bilingual individuals who know two spoken languages is not possible, as in order to engage a new language or turn a language "on", a person has to necessarily stop producing the other one first. Thus, I turned to bimodal bilinguals, who are bilinguals who know a spoken and a sign language. These individuals have the unique ability to simultaneously produce a word and a sign (a code-blend), which allowed me to separate these two processes by asking these individuals to go from single-language production into a code-blend (thereby turning a language "on") or from a code-blend to producing a single language (thereby turning a language "off").

Analyses of the MEG data of our twenty-one American Sign Language – English bilinguals revealed that having to disengage from the previous language (i.e., turning a language "off") required the involvement of prefrontal regions and was behaviorally costly; while activating a new language came for free (Fig. 3A and B). This result was additionally supported by Granger causality analyses showing that turning a language off required additional connections between key prefrontal regions (Fig. 3D-F).

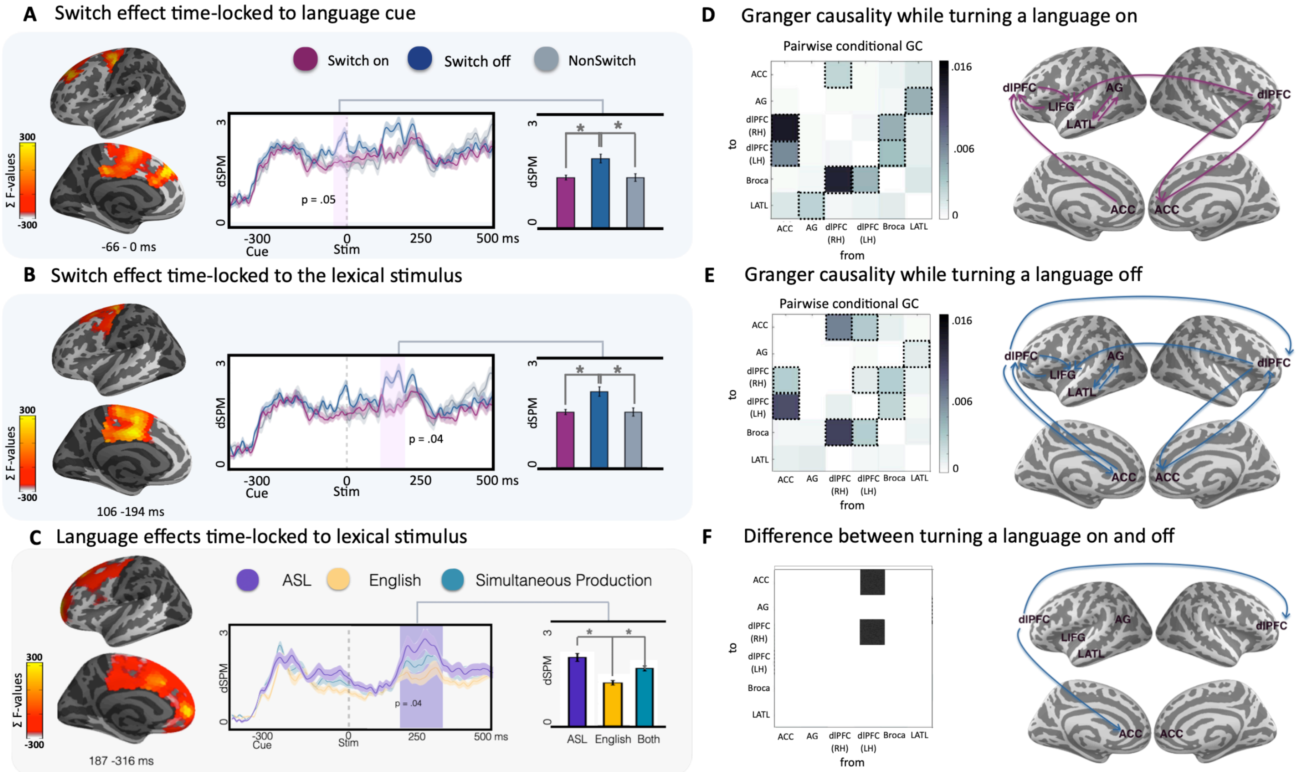

Fig. 3. A-C) Analysis of the MEG activity time-locked to the onset of the stimulus word to be comprehended. The freeSurfer average brains represent the spatial distribution of the reliable cluster. Significance was determined using a nonparametric permutation test (Maris and Oostenveld, 2007) performed from 100 to 300 ms (10,000 permutations). Bar graphs represent the average activity per condition for the sources and time points that constitute the cluster. *$p < .05$ $^{|}$ $p < .1$ (corrected). **C)** Null MEG results in executive control areas while participants processed switches contained within a natural conversation **D)** Auditory cortex showing differential activation when it detected a switch in the language of the conversation.

I further replicated these results and showed that they generalize to the purely spoken domain in a subsequent EEG study with Chinese, Japanese and English trilinguals, where participants were asked to either switch out of a given language (thus turning that language "off") or to specifically switch into a certain language (turning the target language "on"; Liu, Zhang, Blanco-Elorrieta, Hea, & Chen, 2019).

In all, through the combination of univariate and connectivity analyses, and by testing a variety of spoken languages and a sign language, I found that the cost that had been previously ascribed to switching languages generally was instead the consequence of being externally required to hold back and stop producing a language that would otherwise be produced.

Chapter 3: Bilingual Language Control in Perception versus Action: MEG Reveals Comprehension Control Mechanisms in Anterior Cingulate Cortex and Domain-General Control of Production in Dorsolateral Prefrontal Cortex

Blanco-Elorrieta & Pylkkänen (2016) *Journal of Neuroscience*

What are the mechanisms that allow bilinguals to hold a language back when the context requires them to though? Do bilinguals develop specialized language control mechanisms to deal with potential interference from their non-target language (e.g., Calabria et al., 2011), or do they instead rely on the mechanisms that are in place to control behavior generally (e.g., Craik & Bialystok, 2006)? Theoretically, for one to be able to argue that bilinguals develop specialized language control mechanisms, it would have to be the case that these networks are engaged uniquely during language switching, as otherwise the identified mechanisms could be general switching or cognitive control, and not be associated with language particularly.

Constructing an experiment that can test this premise is not straightforward. Previous research had compared language-switching tasks with established general cognitive control tasks (e.g., Stroop or Flanker tasks). However, this comparison is confounded by the differences in demands posited by each of the tasks, and does not allow the unambiguous attribution of any distinct effects emerging from the language switching task to the intrinsic properties of language. It is critical then to develop a maximally parallel experiment where the only divergence between tasks is the involvement of language.

I achieved this goal by developing an experiment that compared maximally parallel language-switching and category-switching tasks in production and comprehension. In both tasks, participants saw playing cards. In the language-switching task, participants always named the number on the card, either in English or Arabic using the color of the card as the cue (Fig. 4A). In the category-switching task, participants always named the stimuli in Arabic, but they alternated between naming the number or the suit of the card. In comprehension tasks, participants heard the stimuli, were subsequently shown a card, and had to press a button to indicate whether the card matched the auditory stimulus they just heard. Thus, across production and comprehension I kept the stimuli, the task demands, and even half of the target responses equal across conditions - the only difference was truly whether there was a language switch involved or not. This set up guaranteed that should there be any difference in neural activity associated with language-switching, it really was intrinsic to the need to control language selection and not corollary to the task differences.

I tested 19 Arabic-English bilingual individuals and I found that in production both language- and category-switching tasks elicited an equivalent spatiotemporal profile of activity in prefrontal regions, thus undermining the possibility that bilinguals develop language-specific control mechanisms. Instead, these results suggested that multilingual individuals use shared, domain-general mechanisms to control interference and select the elements they want to produce (Fig. 4B). Effects of language-switching in comprehension localized to the anterior cingulate cortex and were not shared by category-switching, which elicited no activity in executive control areas (Fig. 4C). These results fit within the broader proactive/reactive framework of cognitive control and further prove that there is no such thing as "language control regions"; rather the design of the traditional language-switching tasks in production required the kind of proactive control exercised by prefrontal regions to achieve goal-directed behavior. In all, this chapter has critical implications as it 1) disproves the second premise required to postulate specialized language control mechanisms; and 2) proves the extent to which results previously ascribed to language switching were instead a mere consequence of the cognitive operations elicited by artificial experimental manipulations.

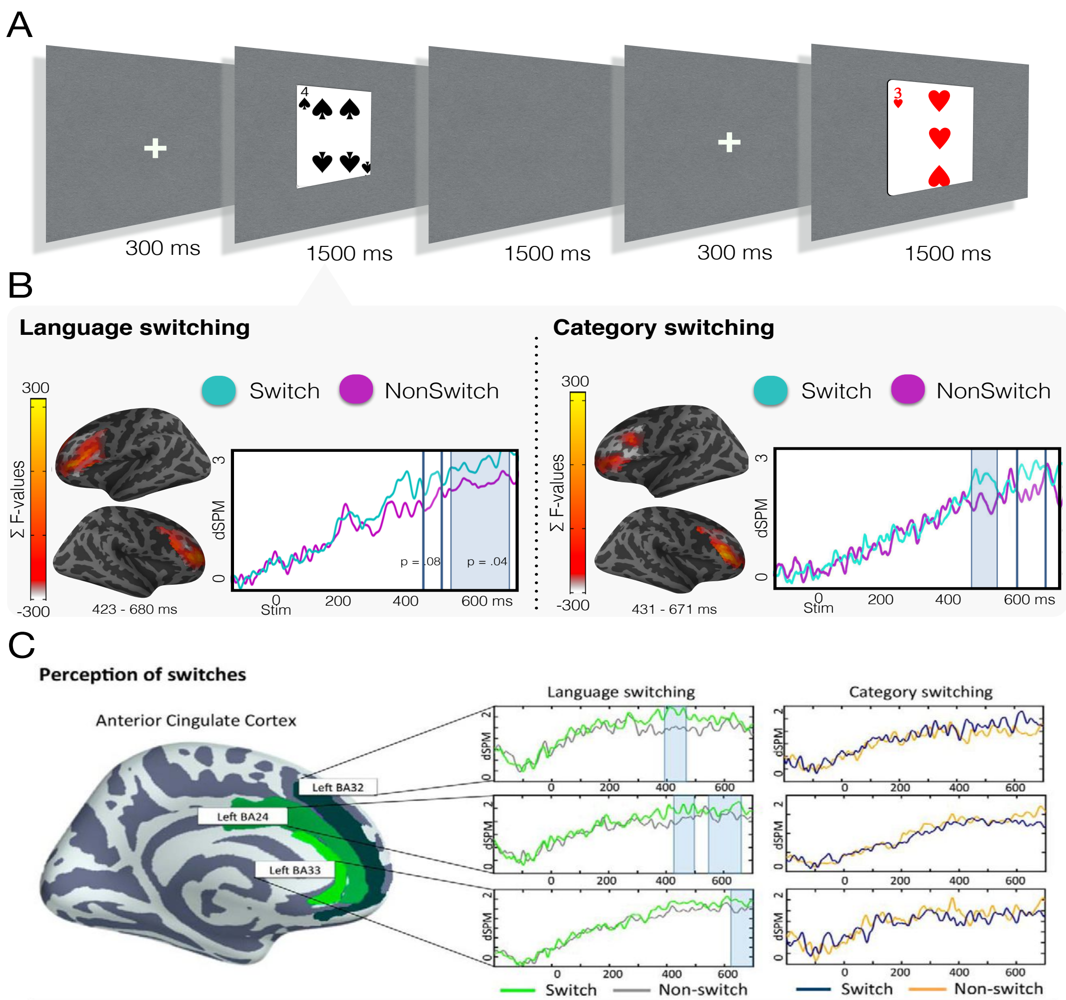

Fig. 4. A) Example of the trial structure. In the 'Language-switching' tasks, the color of the card indicated whether participants had to name the number displayed on the card either in English or in Arabic. In the 'category-switching' task, the color indicated whether they had to name the number or the suit of the card, always in Arabic. **B)** MEG results for the language-switching and the category switching tasks in production; showing parallel prefrontal increases for switching on both tasks. **C)** Results for the comprehension tasks, showing ACC engagement for the language but not the category-switching task. For B and C, MEG activity was time-locked to the presentation of the stimulus. The freeSurfer average brains represent the spatial distribution of the reliable cluster; waveforms show the unfolding of activity over time. Vertical lines indicate $p < .1$; shading indicates $p < .05$. Significance was determined using a nonparametric permutation test (Maris and Oostenveld, 2007) performed from 100 to 650 ms (10,000 permutations).

Chapter 4: Ecological validity in bilingualism research and the bilingual advantage

Blanco-Elorrieta & Pylkkänen (2018) *Trends in Cognitive Sciences*

The empirical findings of previous chapters have critical consequences for theoretical proposals regarding bilingual cognition. The first implication concerns the so-called bilingual advantage hypothesis, a source of heated debate in the last decade. According to this hypothesis, bilingual individuals, as a mere consequence of being bilingual develop an improved cognitive control system. Because the neural underpinnings of language control and general domain executive control were thought to overlap to some extent (Branzi et al., 2016; De Baene et al., 2015; Kang et al., 2017; Hervais-Adelman et al., 2015; Weissberger et al., 2015); this enhancement in language control mechanisms was proposed to generalize to nonlinguistic tasks, resulting in an advantage in many tasks requiring selective attention and inhibition (for comprehensive reviews see (Bialystok, 2011; Hilchey & Klein, 2011; Kroll & Bialystok, 2013). Specifically, advantages have been found for bilingual individuals over monolingual individuals in tasks that require the inhibition of distracting information (e.g., Hernández et al., 2011; Yow & Li, 2015), switching between tasks (e.g., Gold et al., 2013; Prior & Gollan, 2011), or conflict resolution (Costa et al., 2008; Hernandez et al., 2010), and these effects have been accompanied by decreased activation in executive control regions (for reviews see Adesope et al., 2010; Bialystok et al., 2012; Hilchey & Klein, 2011; Kroll & Bialystok, 2013).

The opponents of this hypothesis have failed to replicate this advantage in young adults (e.g., Paap et al., 2017; Paap & Greenberg, 2013), children (Duñabeitia, et al., 2014), and the elderly (Anton et al., 2016), and have hence suggested that such advantage may be a product of factors other than bilingualism proper (for example, small sample sizes and inconsistencies in the methods e.g., García-Pentón et al., 2016; or a result of a publication bias e.g., de Bruin et al., 2015. For a thorough review of the evidence for and against the bilingual advantage hypothesis please refer to Antoniou, 2019). If it is the case that language switching in fact is not as effortful as previously described, and does not engage cognitive control as much, then the basic premise of the bilingual advantage hypothesis disappears. However, a more nuanced version of the hypothesis could still hold, a possibility that I will elaborate in what follows.

Specifically, a version of the hypothesis that would still conform with our emerging understanding of language switching would be one in which the advantage is restricted to individuals who grow up, or are frequently immersed in contexts in which language switching is common, and further, these switches must be controlled based on outside constraints, which require frequent engagement of top-down control mechanisms. Specifically, we predict that this advantage will be most salient in individuals who frequently find themselves in contexts where there are a few individuals but each person or group of people only speaks one language, forcing bilinguals to constantly engage in goal reconfiguration and apply top-down control to select the appropriate language and fulfill the requirements imposed by different interlocutors. Contexts allowing free and rampant language switching, such as fully bilingual communities, may not offer similar exercise of targeted top-down control because every output language is valid, and hence, would not necessarily translate in the same advantage.

This proposal would allow to reconcile the two bodies of research that have emerged with seemingly opposing results in terms of whether there is a bilingual advantage in cognitive control. This is important because after a decade of well-controlled research, both sets of evidence are robust enough to deserve careful consideration. Possibly the dissonance between these results does not lie in the ultimate claim of whether or not a general bilingual advantage exists, but rather on the more subtle and specific characterization of what the source and prerequisites for this advantage may be. Given the recent findings, I proposed that only bilinguals well-versed in externally constrained language switching, that is, bilinguals who grew up or find themselves frequently in dual-language contexts, may show this advantage. Whether this hypothesis is correct only empirical research will unveil, but what seems undeniable at this point, is that the nature of the debate, and the need to categorically prove the existence or absence of the advantage in all bilinguals, may be hindering progress towards a more nuanced yet richer answer. It took over 30 years to turn the idea that bilingualism causes retardation (Goodenough, 1926) into the possibility that there may be some benefits associated with it (Peal & Lambert, 1962); and this chapter attempts to understand the specific sources of this advantage, which undeniably is observed in some bilinguals.

Chapter 5: A selection-by-activation framework of bilingual language organization

Blanco-Elorrieta & Caramazza (2021) *Cognition*

The second theoretical implication of the empirical findings presented in Chapters 1-3 pertains the fundamental organization of the bilingual lexical system. The results reported in this dissertation challenged the pillars of the status quo in the field, and forced a fundamental reformulation of the presumed bilingual language architecture. This chapter reviewed the principles under which any proposed bilingual language system could operate, and developed the theoretical tenets that follow from these empirical data into a comprehensive model of language organization. Succinctly, this framework rests on five main principles.

First, there is a single, unified language system that contains the elements and structures of both of the languages of bilingual individuals. Second, the lexical selection mechanism operates strictly on the basis of the highest levels of activation. Third, the activity levels of candidates are determined by a combination of factors including: 1) frequency of each individual element in each language, 2) language proficiency of the speaker, 3) temporal effects (recency of use or decay in activation after use of both the item proper and of the individual features that constitute the item, including e.g., language (have I been speaking English up to this point) and register, 4) intended semantic meaning, and 5) communicative context (Fig. 5).

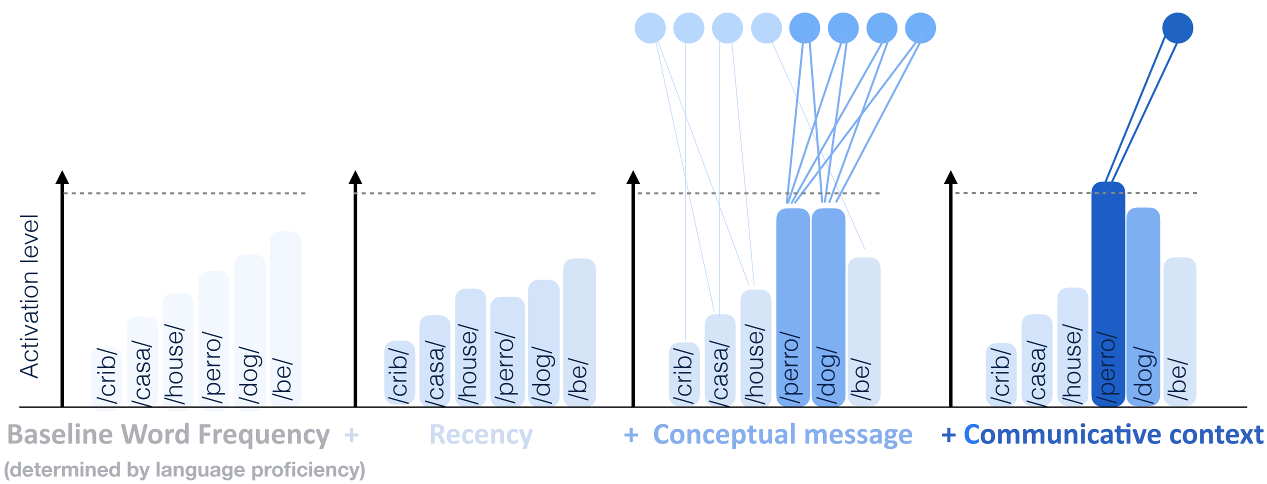

Fig. 5. Example of the selection principles applied to the lexical selection process. Node activation at any given point in time is simultaneously determined by a combination of (at least), baseline frequency, recency of use, overlap with the conceptual message to be transmitted and the communicative context of the moment.

Three, the language system's functional architecture in bilinguals is identical in all respects to that in monolinguals but for the simple addition of a Language node, which is included as part of "communicative context" and functions like other contextual features such as whether an item belongs to a given register, dialect, etc., (see Ferreira, 2019 for a similar conceptualization the audience considerations in monolinguals). This means that under this model, the Language feature operates as a node at the semantic/conceptual level, which sends activation down in parallel and in a similar manner to other semantic, conceptual or contextual features; i.e., it will send activation down to all the elements that contain that feature (similarly to the language feature described in Grainger & Dijkstra, 1992; Dijkstra & Van Heuven, 2002). This is to say that the language node *English* will spread activation down to the lexical elements "dog" and "cat" the same way that the semantic node *Animal* will spread activation down to those elements.

Four, the same selection principles are applied at every linguistic level (i.e., semantics, morphology, syntax and phonology). This means that when activation cascades down independently, and in parallel, throughout the language system (Fig. 6), selection at each level will occur based on the highest activated element at that level. This principle is key to this framework as it allows it to account for two pervasive phenomena in speech production and bilingualism. First, it can explain the tip of the tongue phenomena where a person can retrieve some of the grammatical features of a target word (e.g., grammatical gender) while failing to produce its phonology (Caramazza, & Miozzo, 1997; Miozzo and Caramazza, 1997;

Vigliocco et al., 1997), but also vice versa (Caramazza & Miozzo, 1997). Second, it can account for a ubiquitous phenomenon in fluent bilingual communication that has not been addressed by previous models of bilingual production: the application of morpho-phonological transformations of one language onto roots of the other language, leading to cross-linguistic blends such as (e.g. *los* truck*os*, derived from English *truck* + Spanish masculine gender marking "*o*" + Spanish plural marking "*s*").

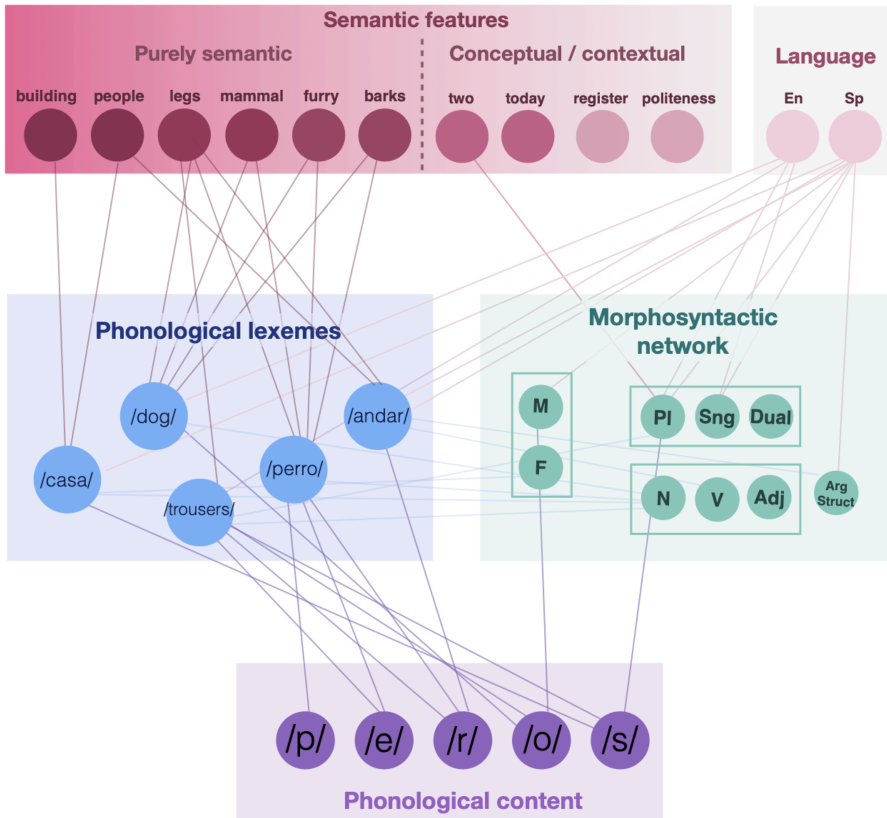

Fig. 6. Representation of the flow of activation between a fragment of the different levels of representation from semantic and language features to lexeme and morpho-syntactic networks and then on to phonological information. N=noun; V=verb; Adj=adjective; M=masculine; F=feminine; Pl=plural; Sng=singular; Dual=dual number.

Last, this framework proposes that the system does not have any built-in intelligence – once a certain input has been given, it will run through all the levels of the system, selecting the highest activated element at each level, until it reaches an output. However, it is possible that sometimes the reached output does not adjust to the environmental demands; hence, there ought to be a system in place to withhold such a response and potentially restart the search. This framework assumes that speakers can explicitly exert control at two points in the process: i) at the beginning of the process, such that based on information about the addressee/communicative situation speakers can top-down determine which specific features of meaning should be linguistically encoded, including what language/dialect/register these should be encoded in, and ii) at the output level, once the phonological form has been determined (see also Bock, 1986; Ferreira, 2019; Finkbeiner et al, 2006; Miozzo & Caramazza, 2003).

In all, this chapter reviews the principles under which any proposed bilingual architecture could operate, and presents a framework where the selection mechanism for individual elements strictly operates on the basis of the highest level of activation. I specify the conjunction of parameters and factors that jointly determine these levels of activation and develop the first theory of bilingual language organization that extends beyond the lexical level to other levels of representation (i.e., semantics, morphology, syntax and phonology). The proposed architecture assumes a common selection principle at each linguistic level to account for attested features of monolingual and bilingual speech in, but crucially also out, of experimental settings.

Conclusion and relevance

This thesis operationalized multilingual language production to a novel degree of precision and tackled the core questions about the neurobiology of multilingualism that had so far remained unaddressed. By combining conceptual and technical advances from several disciplines, and taking an approach that prices ecological validity and attempts to mirror natural language use, I acquired the empirical data necessary to challenge previous assumptions about bilingual language use; including i) the belief that language-switching is inherently costly, and ii) that language-specific networks develop to control languages in multilinguals. Further, placing the focus of experimental work on the most fundamental questions allowed me to develop a much more detailed theoretical framework than those available to date, which can account for both monolingual and bilingual language production.

In sum, the research contained in this dissertation and the conceptual implications thereof led to the first theory of language organization that successfully captures natural language use in both monolingual and bilingual populations, which has paved the way for novel avenues of research that will shift our understanding of mono- and multilingual language organization in years to come. The relevance of this work has been reflected not only in the caliber of the scientific journals that published this work, but also in the broad interest of non-specialized news outlets all over the world; including newspapers such as *The National, El Pais,* and the *American Association for the Advancement of Science,* the recording of a full episode for the major science program on Spanish national television (TVE), an invitation to deliver a TED talk, and being included on the list Forbes 30 under 30 in Science.

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