Sign Languages

As part of the Language Archive (Max Planck Institute for Psycholinguistics in Nijmegen, The Netherlands)
https://www.mpi.nl/resources/data

Telephone conversations

Switchboard: a collection of about 2,400 two-sided telephone conversations among 543 speakers (302 male, 241 female) from all areas of the United States.
https://catalog.ldc.upenn.edu/LDC97S62

Translation

Multilingual Student Translation Corpus (MUST)
https://uclouvain.be/en/research-institutes/ilc/cecl/must.html

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53. Psycholinguistic methods in the study of bilingualism

1. Introduction

In this chapter, we provide an overview of frequently used research methods in the psycholinguistic study of (individual) bilingualism. The study of individual bilingualism primarily examines the cognitive and neural mechanisms, processes, and knowledge structures involved in the acquisition and use of two (or more) languages. It also covers topics such as translation ability and the consequences of mastering two languages for other aspects of cognition (e.g. executive control and theory of mind).

The research methods employed in the study of bilingualism are largely similar to those used in more conventional psycholinguistics. Though by no means exhaustive − if only because researchers can be very creative in pursuing their goals − the collection of research methods presented in this chapter can be used to address questions concerning

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the three main areas of study in bilingual psycholinguistics (i.e. language acquisition, comprehension, and production) and questions concerning several linguistic domains (e.g. the lexicon, syntax, and semantics).

Because most of the selected methods can be used to address several research questions, ordering of the methods based on research topics was not possible. Instead, we primarily ordered the methods according to the dependent variables and tasks involved, with each section title reflecting the dependent variable or task of interest. The section titles thus provide a way for scholars in the field to quickly find methods suitable for their purposes.

Space limits only allowed a succinct description of the presented methods. To enable readers to obtain further details about each method and to illustrate how it can be applied in bilingualism research, we have briefly described in each section a bilingual study that used the method in question. These brief descriptions of exemplary studies will likely provide readers with a clear sense of the content of the study of individual bilingualism as well as of the role(s) played by a set of major variables in this research area.

2. Measuring changes in attention to reveal the initial stages of language acquisition

2.1. Habituation-dishabituation paradigm

The habituation-dishabituation paradigm is a procedure to assess whether very young babies can discriminate between different stimuli, for example, between speech sounds from two languages. It is based on the well-known facts that babies and young children tend to scrutinize a new stimulus but lose interest when it is no longer new, for example, after it has been presented multiple times in a row. Babies' interest can be measured in various ways, for example, by measuring time spent looking at a stimulus (Weikum et al. 2007) or sucking rate on a pacifier (high amplitude sucking procedure; see Byers-Heinlein, Burns, and Werker 2010). Loss of interest, a reflection of habituation to a stimulus, is evident from a decrease in looking time or sucking rate. Once habituation is established, a new stimulus is presented to the baby. Only if the baby notices the difference will dishabituation occur, and as a result, looking times or sucking rates will increase. Using this method, the development of perception of speech sounds can be investigated with very young babies as participants (Christophe and Morton 1998). In a closely related paradigm, slightly older babies were rewarded for turning their heads upon detecting a difference between presented speech sounds (Werker and Tees 1999). Here, a head turn indicated that the babies could notice the difference between the sounds.

2.2. Preference procedures

Another way to assess language development in young children is the preferential looking procedure. This method does not rely on novelty detection, but rather establishes whether young children understand (parts of) the linguistic material they hear. Young children are presented with two different visual stimuli (pictures, videos, or life materials) at two adjacent locations, and hear linguistic material that is congruent with one of these stimuli. If the child looks at the congruent-stimulus location more than at the other location, it can be inferred that the child has understood that the linguistic material referred to the congruent stimulus (Bobb et al. 2016).

In a related procedure, known as the disambiguation task, young children are given the choice to look at two screens presented next to each other, each displaying an object. The child knows the name of one of the objects, but the name of the other object is unfamiliar. When an (unknown) new object name is presented, and the child looks longer at the object with the unfamiliar name than at the one with the known name, researchers infer that the child is able to disambiguate the new word. By using this procedure, it has been shown that bilingual children aged 16−18 months exhibit different behaviors as compared to monolingual controls (Byers-Heinlein and Werker 2009).

3. Methods involving judgments: two methods for examining sentence processing

3.1. Thematic role assignment

Readers and listeners assign semantic roles to the words and phrases they read or hear. For example, upon reading the sentence *John kicked the dog*, the word *John* plays the actor (or agent) role, while the noun phrase *the dog* plays a recipient (or patient) role. One line of research using the thematic role-assignment method aims at investigating possible differences between monolingual speakers of different languages in preferred role assignments, and if such differences exist, between the particular role-assignment strategies bilinguals use. The question then becomes whether bilinguals always use the strategies associated with their L1, their L2, or a mixture thereof. In a study by Vaid and Chengappa (1988), for example, listeners heard three-word sentences, each consisting of two nouns and one verb, in various word orders. After hearing each sentence, they were asked to indicate which noun performed the action (reaction times were not measured). Under one condition, the words were taken from English, under the other, they were taken from Kannada (a language used primarily in the south of India). The participants could use noun animacy cues (i.e. whether the noun referred to an animate or inanimate entity), word order cues, and noun-verb agreement cues (in which one or both nouns agreed with the verb in number). The performance of a group of adult bilingual Kannada-English speakers was compared to that of a group of monolingual Kannada speakers. Under both the English and the Kannada condition, bilinguals showed a pattern of role assignment that was very similar to that of monolingual Kannada speakers (and very different from monolingual English speakers), indicating a transfer of role assignment strategies from Kannada to English.

3.2. Grammaticality judgments

When using this method, sentences are presented to participants and they are asked to indicate whether or not each sentence is grammatically correct in a particular language.

The method has been, for example, a useful tool in testing the idea that the learning of both the native and a foreign language might be different (and less successful) after a critical (or sensitive) period has ended rather than before such a period ends. In Birdsong and Molis (2001) learners of English heard sentences which were grammatically correct (e.g. *The horse jumped over the fence yesterday*) or incorrect (e.g. *The horse jumped the fence over yesterday*), and then circled a *yes* or *no* response about the grammatical correctness of each sentence on an answer sheet. The study replicated a study by Johnson and Newport (1989), who investigated speakers of L1 Korean and L1 Chinese learning English (whereas Birdsong and Molis [2001] tested a group of speakers of L1 Spanish learning English). The results showed, among others, that the total number of correct grammaticality judgments of participants who arrived in the United States after the closure of the putative critical (or sensitive) period correlated negatively with their age of arrival in the United States. This result, they argued, was not in line with the critical (or sensitive) period hypothesis.

Aside from response accuracy, response speed can also be measured using this task. Lago, Garcia, and Felser (2018) studied bilinguals who acquired German as an additional language. Participants read German sentences in which a pronoun and possessor either agreed or disagreed in gender, and indicated whether each sentence was acceptable or not. L1 Spanish-L2 English participants showed a smaller effect of pronoun-possessor agreement violation on response times than L1 English-L2 Spanish participants. In addition, although the overall accuracy of the judgments was the same for both groups, proficiency in English played a role within the L1 Spanish-L2 English group: participants with high proficiency in English performed better on this task than participants with low proficiency. These results were attributed to the fact that, unlike the English and German grammars, the Spanish grammar lacks pronoun-possessor agreement; still, knowledge of L2 English grammar increased sensitivity to pronoun-possessor agreement violations in the additional language (German).

4. Methods involving eye-movement recording

The recording of eye movements has proved a very useful technique in studying both visual and auditory language comprehension. In the visual domain, participants are presented with sentences or other text units, and recordings of eye movements reveal where and how long participants look while processing the presented text. From these measurements, the cognitive processes concerning word and sentence processing can be inferred (using the eye-mind assumption, which states that the mind processes the text fragment on which the eyes are currently fixated). The technique also allows researchers to study potential processing problems that cause participants to look back at previously read text, for example, because an initial interpretation of the meaning of a word or sentence proved to be wrong. For an example of the application of this technique in the study of bilingualism, see Frenck-Mestre and Pynte (1997), who studied how bilinguals resolved syntactic ambiguities.

In studying auditory language comprehension, eye-movement recordings have, for instance, been used to study whether words from both languages are simultaneously activated when bilinguals hear a word in one of their languages. In an application of the technique known as the *visual world paradigm* (for a review, see Huettig, Rommers, and Meyer 2011) participants' eye movements are recorded while they see various pictures of objects and simultaneously hear a word. One of the pictures (the target picture) depicts the heard word. The crux of the method involves the manipulation of various aspects of the depicted non-target objects. For example, in Spivey and Marian (1999), one of the non-target pictures sometimes showed an object whose name in the bilingual participants' other language was phonetically related to the word spoken in the language of the experiment. Participants looked more at these non-target objects than at non-target objects with totally unrelated names, indicating that, during word recognition, words in both languages known by a bilingual are activated. Another recent example is a study by Morales et al. (2016), in which Italian-Spanish bilingual participants saw two pictures whose names always had congruent gender in Spanish, but either congruent or incongruent gender in Italian. Participants received Spanish-language auditory instructions that indicated a target object by using its article and its noun. Recordings of eye movement showed that participants looked less at target objects with incongruent Italian gender names than at target objects with congruent Italian gender names. The authors explained this effect as a result of the interaction of the bilingual's languages at the gender level.

5. Methods involving response speed and accuracy measurements

5.1. Lexical decision

On each trial in the lexical decision task, participants see a letter string and are asked to indicate whether it forms a word or not. Reaction times (RTs) and accuracy measures of the responses are the dependent variables. RTs are assumed to include the time required for lexical access, the component in which researchers are specifically interested. However, RTs also include the time involved in making (and executing) the decision. Many studies have shown that the decision-making process can be influenced by a diverse set of factors, including the percentage of *yes* responses and the composition of the letter strings that do not form a word.

In bilingualism research, participants can be instructed to produce a *yes* response if the letter string is a word in either of their two languages (*generalized* or *language-neutral* lexical decision), or in just one of them (*language-specific* lexical decision). Many studies using the lexical decision task have been devoted to examining the processing of *interlexical homographs* (an interlexical homograph is a written word that has different meanings in a bilingual's two languages) and *interlexical homophones* (an interlexical homophone is a spoken word that has different meanings in a bilingual's two languages). The results of such studies may help to answer questions regarding the activation of a language currently not in use in a bilingual lexicon, but the interpretation of the results is not always straightforward. For example, interlexical homographs may cause either longer, shorter, or similar reaction times compared to words that exist in the target language only, depending on the specifics of the task instruction (i.e. to perform a language-neutral or a language-specific lexical decision task) or the stimulus materials used (Dijkstra, van Jaarsveld, and ten Brinke 1998). For a recent example of a study using this task, see Brysbaert, Lagrou, and Stevens (2017).

5.2. Identification

Methods involving identification most often use accuracy measures as the dependent variable. The method consists of the presentation of hard-to-identify word stimuli, and the task of the participant is to try to identify what was presented. Words may be made hard to identify by using visual masks and brief presentation of the words themselves, or by presenting only parts of them auditorily. As with the lexical decision task, identification tasks not only encompass processes devoted to the component of interest (lexical access), but also a decision process about what was perceived. In addition, visual or auditory processing itself may play an important role in these tasks.

In studying bilingual visual word recognition, Dijkstra, Grainger, and van Heuven (1999) used a *progressive demasking* technique in which they presented a masking stimulus with a presentation duration of 300 ms followed by a word stimulus with a presentation duration of 15 ms. Next, this presentation sequence was repeated but the mask presentation duration was decreased by 15 ms and the word presentation duration was increased by 15 ms. The adjustment of the durations was repeated until the participant indicated recognition of the stimulus word. Participants then typed the stimulus word at the computer. Mean RTs and error percentages were thus available for further analyses. The authors used English target words that could be related in meaning, orthography, or phonology to Dutch words. In comparison with unrelated control words, Dutch-English bilinguals were faster at recognizing the target words when they were related in meaning or orthography, but slower when they were related in phonology. The authors presented interpretations of these findings based on the structural characteristics of the bilingual processing system as well as the strategic use of this system.

Another identification technique is to embed a target word in a presentation sequence, in which the target is preceded by both a masking stimulus and a briefly presented prime stimulus (see Section 7.1), and followed by another masking stimulus. Using this technique, Brysbaert, van Dyck, and van de Poel (1999) presented French target words to Dutch-French bilinguals for 42 ms. The primes could be phonologically related to the target word or not (hence the name of this technique: *masked phonological priming*). Identification accuracy was the dependent variable. One of the results was that primes that were Dutch homophones of the French target words caused better recognition of those targets as compared to unrelated primes.

In an auditory word recognition study by Grosjean (1988), French-English bilingual participants heard French sentences whose presentation initially stopped at the onset of a target word. The target word was either an English guest word or a French borrowing thereof. In consecutive presentations of the sentence, more and more of the target word was revealed, in increments of 40 ms. This technique is known as *gating*. After each presentation, participants guessed the target word and indicated their confidence in the guess and their idea about the language of the target word. The results showed that phonotactic language cues and the composition of the French and English lexicons influenced the speed of word recognition.

5.3. Naming

A relatively straightforward task in the study of bilingualism is naming. Participants can be asked to read visually presented words aloud or to name pictures. In both tasks, RTs and/or accuracy measures can be recorded. Researchers use the reading aloud task primarily to measure lexical access time for the words involved. However, as with the lexical decision and identification tasks discussed above, it is well known that other variables might influence the results. For example, in languages with alphabetic scripts, participants might sometimes bypass lexical access and use grapheme-to-phoneme conversion rules to produce a response (as they do when reading non-words aloud). In addition, performance on this task also involves word production processes, the ease of which may vary independent of lexical access time. The latter processes may be identified by delaying the response until well after lexical access has taken place (a procedure known as *delayed naming*).

Using this task, de Groot et al. (2002) compared the influence of many linguistic variables (semantics, frequency, length, lexical neighborhood, word onsets, consonant clusters, sound intensity, and cognate status) in a study with Dutch-English participants. In addition to common word naming, a delayed word naming task and a lexical decision task were used; stimulus materials were derived either from Dutch or English. Onset structure turned out to be the most important variable governing naming times in Dutch, whereas frequency and length variables were particularly important in English. Comparisons of the naming and lexical decision tasks showed that, when these tasks were performed in Dutch, naming produced results that were quite different from those emerging in lexical decision (but quite similar to the results of delayed naming). When the tasks were performed in English, the results for naming and lexical decision were more similar. Overall, the authors concluded that the results of the naming and lexical decision tasks seem to reflect very different processes. In this particular experiment, words were presented in isolation, but they can also be presented in a sentence context (Schwartz and Kroll 2006). In the latter study, sentences were presented automatically word by word (by means of *rapid serial visual presentation*, or RSVP), but word presentation may also be controlled by the participant (*self-paced reading*).

Another naming task is picture naming. On each trial, participants see a picture on a screen and name the depicted object as quickly and accurately as possible. RTs are recorded by using a voice-key, and the experimenter judges whether or not the response was accurate. The picture naming task seems well suited, for example, to investigate whether words from a bilingual's not-in-use language are nevertheless activated when speaking in the other language. Costa, Caramazza, and Sebastián-Gallés (2000) investigated this issue by asking Spanish-Catalan bilingual participants to name pictures in Spanish. The names of the depicted objects shared phonology between the two languages (so-called *cognates*, e.g. Catalan *gat* and Spanish *gato*, English 'cat') or were unrelated (*noncognates*). The results were clear: pictures with cognate names were named more quickly than pictures with noncognate names, suggesting that Catalan words were nevertheless activated during naming in Spanish. In this study, the pictures were presented in isolation, but they can also be presented in a sentence context, as in Starreveld et al. (2014); this latter study employed a self-paced reading technique.

5.4. Word translation

One of the skills bilinguals possess is to translate between languages, that is, to transpose a language unit from one language (in translation studies, typically called the 'source' language) into another (the 'target' language). In a substantial number of translation studies, the language unit to translate is the individual word. Other translation research deals with translating larger linguistic segments in one form or another (e.g. from text to text; from speech to speech, as in simultaneous interpreting; see Section 6). Unlike the latter type of studies, word translation studies typically use RTs and accuracy measures as the dependent variables. One main goal of these studies has been to chart the factors affecting word translation (e.g. word characteristics such as concreteness and frequency; L2 proficiency) and explain the reasons why. Another goal is to reveal the architecture of the memory structures representing word knowledge in bilingual memory. In pursuing these goals, RTs obtained for translation from the stronger language (most often the L1) to the weaker L2 ('forward' translation) is often compared with RTs in 'backward' translation (from L2 to L1). In combination with a variable that can reveal whether word meaning is accessed in memory during the translation process, this translation-direction variable is thought to reveal the structure of lexical representations in bilingual memory, and the processing routes through these structures (i.e. circumventing or accessing meaning representations; Kroll and Stewart 1994).

5.5. Language switching

An important issue in bilingual research concerns bilinguals' ability to control which language to use, depending on the demands of the current communicative setting. One way researchers have examined this issue is by using language-switching methods. In most such studies, the switches are imposed by the experimenter. For example, Costa, Santesteban, and Ivanova (2006) used a picture naming task (see Section 5.3) in which bilingual participants named pictures in one or the other language, depending on the color in which the picture was displayed. Sometimes the color changed between successive trials (switch trials), while sometimes it did not (non-switch trials). Reaction times to switch and non-switch trials were then compared in order to assess the so-called switch costs (the RT difference between responses following a response in the same language versus one in the other language). The authors indeed found switch costs, but also showed that these costs were asymmetrical for unbalanced bilinguals: switching to the dominant native language resulted in greater switch costs than switching to the weaker second language. However, this asymmetry might be linked to the fact that switching was imposed by the experimenters, as the results stand in contrast to findings from Gollan and Ferreira (2009: 643), who instructed bilingual participants to "just say whichever name comes to mind most quickly" and obtained symmetrical switch costs for unbalanced and balanced bilinguals. Results such as these inform theories on language control in bilinguals.

6. Methods for studying simultaneous interpreting

A special case of language control concerns simultaneous interpreting, wherein most of the time, both languages must be used concurrently by the interpreter. Simultaneous interpreting encompasses multiple components, including source-language comprehension, target-language production, and memorizing portions of the input before they can be expressed in the target language. An oft-used approach to studying this complex task is to compare the performance of professional interpreters and 'ordinary' bilinguals on one or more of these components. For example, Christoffels, de Groot, and Kroll (2006) compared three groups of native Dutch speakers proficient in L2 English (trained interpreters, university students, and highly proficient English teachers) on two indices of working memory capacity (reading and speaking span) and two measures of word-retrieval efficiency (word-translation speed and picture-naming speed). They found that the interpreters had a larger working memory capacity than both the English teachers and the students, but were only faster than the students in word translation and picture naming in English. The authors concluded that fast word retrieval in an L2 emerges from extensive practice in the L2, and is thus concomitant with proficient bilingualism, but that a large working memory capacity results from specific on-the-job interpreting practice.

A common method for studying the various components of simultaneous interpreting in interaction with one another is by measuring the ear-voice-span (EVS; Goldman-Eisler 1972), the time between the start of a fragment in the source language and the moment the target-language equivalent of this fragment is rendered by the interpreter. The EVS is a sensitive measure of momentary processing load, with increases in processing demands lengthening the EVS. Other ways to assess interpreting performance are the use of various quality-of-performance measures, including the assessment of interpreting errors and durations of pauses.

7. Methods involving the manipulation of target processing by another stimulus

7.1. Priming of target processing by another stimulus

Priming is a method which can be combined with many other methods. The idea is simple: a target stimulus is preceded by another stimulus (the prime). Whenever responses to the target are influenced by prime presentation, processing of the target must have been facilitated by (or interfered with) as a consequence of processing of the prime.

Many variations on the procedure exist: the prime can be presented at various intervals before target presentation; the duration of the prime presentation can be varied; and the prime can be presented in full view or can be masked. In bilingual research, cross-language priming effects are often examined. In such research, the prime and the target are taken from a bilingual participant's different languages. We give a few examples. When a lexical decision task (see Section 5.1) is performed on the target and if the prime and the target share a semantic relationship, cross-language semantic priming can be obtained (Frenck and Pynte 1987); when the prime and the target are translation equivalents, translation (or cross-language repetition) priming effects can be obtained (Altarriba

1992). When a perceptual identification task (see Section 5.2) is performed on the target and if the prime and the target share a phonological relationship, cross-language phonological priming can be obtained (Brysbaert, van Dyck, and van de Poel 1999). Such effects indicate that language representations and/or processing operations are shared between bilinguals' two languages.

7.2. Interference of target processing by another stimulus

An important method that has been used to investigate (bilingual) language production is to deliberately induce interaction between production and perception processes. Both processes are important in the picture-word interference task. In this task, the main component is picture naming (see Section 5.3), but now a picture is accompanied by a distractor (often a word). Participants are asked to name the pictures and to ignore the distractors. Despite this instruction, effects of various relationships between the distractor and the target (i.e. the depicted object's name) can be obtained. Again, several variants of the task exist. For example, the distractors can be presented visually or auditorily. Often, the distractors are presented slightly before, concurrently with, or slightly after picture presentation. In this way, a time course of the effect under investigation can be obtained. An example of the use of this method is presented in Costa, Miozzo, and Caramazza (1999). Catalan-Spanish bilinguals named pictures in Catalan. Both Spanish and Catalan distractors were used, which could be semantically related to the target, unrelated to it, or its translation equivalent. The authors found, among other results, cross-language interference effects of semantically related distractors, as well as cross-language facilitation effects of translation equivalents (both effects were relative to a baseline obtained using unrelated distractors). They explained their results by assuming that representations of words from both languages were activated during task performance, but that lexical selection was restricted to representations of words from the response language only.

Instead of a target picture, a to-be-named or to-be-translated target word can also be used (see Sections 5.3. and 5.4). The difference between target and distractor may then be indicated by a difference in color, position, or time of presentation.

8. Methods involving (functional) neuroimaging

Functional neuroimaging methods are different from all methods mentioned above because they do not measure overt behavior, but rather brain activity that occurs during stimulus processing. Though this is the quintessential feature of these methods, one should always bear in mind that brain activity and stimulus processing are not necessarily causally related. In addition, although heightened activity in a given brain region is often interpreted as showing evidence of stimulus processing by that region, absence of increased brain activity in a given region does not necessarily mean the stimulus is not processed by that region, especially when stimulus processing is (largely) automatic. Still, the methods described in this section have proved very useful in many research areas, including bilingual studies. Although other neuroimaging methods exist (e.g. magnetoencephalography, or MEG; near-infrared spectroscopy, or NIRS; positron emission tomography, or PET), we discuss below only the more frequently used methods.

8.1. Using electrical signals

Using electrodes that are placed at the scalp, it is possible to record electrical brain activity directly and continuously. Neural communication in the brain involves the transfer of ions, and the movement of large amounts of ions can be detected as they cause very slight changes in voltage. The detection process, and the graphical representation thereof, is called electroencephalography (EEG). A derivative of the EEG signal (not the signal itself), the *event-related potential* (ERP), is particularly informative to researchers interested in language processing (and other aspects of cognition). This derivative involves combining and averaging the EEG signals following, and time locked to, the repeated presentation of a certain type of stimulus event.

For language scholars, the most important effects (i.e. peaks in the ERP signal, typically called 'components') that have emerged from this field are the N400 and the P600. The N400 is a negative peak in the ERP waveform that occurs 400 ms after a semantic abnormality in the stimulus is presented (Kutas and Hillyard 1980; for a broader interpretation of the N400 effect, see Lau, Phillips, and Poeppel 2008). The P600 is a positive peak in the ERP signal that occurs 600 ms after the presentation of a syntactic abnormality in the stimulus (Osterhout and Holcomb 1992). Both peaks are relative to the averaged waves produced by stimuli that do not show semantic or syntactic abnormalities. The temporal resolution of the EEG method is high, whereas its spatial resolution is rather low.

Ardal et al. (1990) and Weber-Fox and Neville (1996) were among the first to adopt the EEG/ERP methodology in bilingual studies. Ardal and colleagues (1990) compared the N400 in English monolinguals and English-French bilinguals. Participants saw sentences which were semantically normal (e.g. *It is raining and I forgot my umbrella*) and anomalous (e.g. *I generally like menthol bottles*). The words of each sentence were presented one at a time, and ERP measurement started upon presentation of the final word, which was either semantically normal or anomalous. The authors found that the N400 occurred earlier in monolingual than in bilingual participants, especially for bilinguals tested in their second language. They attributed these results to a higher degree of automaticity of language processing in monolinguals than in bilinguals, and in bilinguals' processing of their L1 as compared to their L2. In addition to semantic anomalies, Weber-Fox and Neville's (1996) study also included syntactic anomalies. The participants were presented with grammatically incorrect sentences (e.g. *The scientist criticized Max's of proof the theorem*). Monolingual English speakers showed a P600 peak following the grammatical violation. For Chinese late learners of English, the amplitude of the P600 peak was reduced, suggesting that such learners either did not attempt to repair the meaning of the sentence, or did so later. For a review of ERP research in bilingual language processing, see Moreno, Rodríguez-Fornells, and Laine (2008); for a recent example, see Martin et al. (2016).

8.2. Using hemodynamic magnetic signals

Another way to measure brain activity is to register the amount of blood flow in particular areas of the brain. The technique exploits the fact that increased neuronal activity in the brain is followed by an increased oxygen-rich blood flow beginning around 2 s later and peaking around 4−6 s later, after which blood flow falls back to − and typically undershoots − the original level. In functional magnetic resonance imaging (fMRI), blood oxygen level dependent (BOLD) contrast is measured by studying changes in the magnetic fields induced by the MRI scanner. The BOLD contrast is rooted in the fact that oxygenated blood is not magnetic, whereas deoxygenated blood is. When a change in the oxygen concentration of blood flow occurs, a difference in the resultant magnetic fields can be detected, which researchers then attribute to neural activity at a specific location in the brain. Researchers usually measure brain activity for a time duration of around 20 to 30 s, during which participants perform a certain task. In a variation on this method, measuring of the BOLD response is time-locked to the presentation of a single stimulus, and the results of several measurements are then averaged. This variant is known as event-related fMRI. In general, in comparison with ERP, fMRI has low temporal resolution (because the blood flow needs time to build up), but high spatial resolution: brain structures of a few mm^3 can be differentiated.

One of the issues addressed in bilingual research using fMRI is whether the two languages of bilinguals are processed by the same or different brain areas. In such studies, participants perform various language tasks (e.g. word-production, covert sentence generation, covert word-stem completion, semantic categorization, listening, or silent reading). Comparisons can then be made between imaging results for various tasks used in the study, often including a condition in which participants do not actively process linguistic material (e.g. the participant looks at a fixation stimulus). The results of such studies diverge, but a review of the literature by Indefrey (2006) showed that, in general, bilinguals' L1 and L2 are not processed by different brain areas. However, a number of the areas involved (15 out of a total of 114, that together cover the entire brain) did show differences in the level of activation between L1 and L2, with L2 processing causing greater activation than L1 processing in most cases (13 out of 15 areas).

Another research area in the study of bilingualism concerns the control processes that allow a bilingual to selectively use one language, or to switch between languages if needed. Many such studies indicate that the dorsolateral prefrontal cortex, the anterior cingulate cortex, and the caudate are involved in language control, in both production (Abutalebi et al. 2007) and comprehension (van Heuven et al. 2008) tasks.

8.3. Diffusion tensor imaging

Finally, we describe an example of a neuroimaging method that allows mapping of (changes in) structural connectivity between language areas of the brain. Water molecules diffuse more easily parallel to a white matter tract than perpendicular to it. The direction of diffusion of water molecules can be measured with a technique derived from magnetic resonance imaging called diffusion tensor imaging (DTI). From DTI measurements, the precise location and mass of white matter in the brain can be reconstructed. Xiang et al. (2015) used DTI to investigate the changes in white matter in language-related areas of the brain during acquisition of a second language. German participants took an intensive 6-week Dutch language learning course, and possible pathways between the left parietal lobe and four subregions of Broca's complex were mapped both before and after the course, and in both the left and the right hemisphere. Dutch proficiency was measured with a cloze test. The results showed that during second language learning, lateralization dominance of a pathway mainly along the arcuate fasciculus shifted from the left to the right, and back again, with increasing proficiency.

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