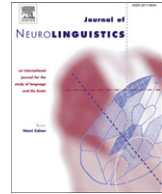




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Review

Brain activity during translation: A review of the neuroimaging evidence as a testing ground for clinically-based hypotheses



Adolfo M. García^{a,b,*}

^a Facultad de Lenguas, Universidad Nacional de Córdoba (UNC), Avenida Valparaíso s/n, 5000 Córdoba, Argentina

^b Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, C1033AAJ Ciudad Autónoma de Buenos Aires, Argentina

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ABSTRACT

The ability to translate is a concomitant of bilingualism. Since bilinguals outnumber unilinguals around the globe, studying the neurological underpinnings of translation may have far-reaching theoretical and clinical implications. This paper reviews nine imaging studies on translation employing EEG, ERP, fMRI, fNIR_{CWS}, PET, and direct electrostimulation. The evidence is analyzed in the light of six clinically-based hypotheses on the neurofunctional organization and neuroanatomical location of translation routes. Although the imaging data is inconclusive and contradictory in certain aspects, it indicates that (i) which specific neural substrates are involved in translation seems to depend on the type of source unit – words, sentences, supra-sentential texts – and the direction of translation; (ii) the left hemisphere is either predominantly or exclusively involved in the translation of all three types of units; (iii) Broca's area seems to play a role in all translation tasks; and (iv) no specific regions have been identified which are exclusive to translation processes.

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1. Introduction

As linguistic and cultural diversity expands in societies the world over, translation asserts itself as a burgeoning activity and an increasingly significant research topic. Professional translation requires the development of specialized competencies through task-specific training (Hurtado Albir, 1999;

* Falucho 1830 4A (Segundo cuerpo), 7600 Mar del Plata, Argentina. Tel.: +54 223 493 7702, +54 223 155190568 (mobile).
E-mail address: adolfofomartingarcia@gmail.com.

PACTE, 2000). Instead, the ability to translate –i.e., reformulating input in a source language (SL) by means of a target language (TL)– is a concomitant of bilingualism (Harris & Sherwood, 1978; Malakoff, 1992). Given that bilinguals outnumber unilinguals around the globe (Grosjean, 1994; Hartsuiker, Costa, & Finkbeiner, 2008; Walraff, 2000), studying the neurological underpinnings of translation may have far-reaching theoretical and clinical implications for neurolinguistics at large.

Using the native language (L1) or the non-native language (L2) in different settings during monolingual communication is not the same as translating (cf. Grosjean, 1985; Hurtado Albir, 1999; Obler, 1983). It follows that translation-specific processes cannot be directly inferred from research on, or models of, the bilingual brain. In several behavioral studies, translation training has been shown to modulate accuracy and response times (RTs) in a variety of linguistic and non-linguistic tasks. Bajo, Padilla, and Padilla (2000) found that professional interpreters perform better than interpretation students and bilinguals without translation experience in a semantic categorization task when non-typical exemplars are involved. Christoffels, De Groot, and Kroll (2006) showed that professional interpreters respond faster and more precisely than bilingual university students in both language and working memory tasks, and that they also outperform foreign language teachers in the latter. Also, a comparison of stress-induced physiological responses between interpretation students and professional interpreters revealed that the latter tend to maintain a lower and more constant pulse rate during simultaneous interpreting sessions (Kurz, 2003). Linguistic processing differences between interpreters and non-interpreters seem to develop during the early stages of formal translation training (Fabbro & Darò, 1995).

There is also behavioral (Fabbro, Gran, Basso, & Bava, 1990; Fabbro, Gran, & Gran, 1991; Gran & Fabbro, 1991; Green, Schweda Nicholson, Vaid, White, & Steiner, 1990; Proverbio & Adorni, 2011) and electrophysiological (Proverbio, Adorni, & Zani, 2009; Proverbio, Leoni, & Zani, 2004) evidence suggesting a reduced left lateralization of linguistic processes in simultaneous interpreters relative to monolinguals and even non-interpreting bilinguals. However, greater right-hemisphere (RH) involvement does not necessarily mean that the RH is more crucially involved in language representation or processing either in bilinguals or in translators/interpreters. Instead, such laterality differences in these populations may be due to greater reliance on attentional and pragmatic strategies – subserved by the RH – during verbal communication (Fabbro & Gran, 1997; Paradis, 1992, 1995, 2003, 2009).

Translation into L1 has also been shown to be performed unconsciously and automatically during L2 lexical processing (Thierry & Wu, 2007). This conclusion, derived from an evoked response potentials (ERP) experiment, is consistent with the one advanced by Klein et al. (2006) in a functional magnetic resonance adaptation (fMRA) study. However, previous results obtained by Chee, Hon, Lee, and Soon (2001) suggest that L2 processing may also take place without unconscious translation into L1. The level of coactivation of both languages may be determined by the goal of the reading task (e.g., monolingual reading vs. reading for translation) (Ruiz, Paredes, Macizo, & Bajo, 2008).

Furthermore, the ERP study conducted by Elmer, Meyer, and Jancke (2010) offers compelling evidence that translation-specific training brings about neuronal adaptations in the bilingual brain. Eleven professional interpreters specifically trained in L2–L1 translation –i.e., backward translation (BT)– and 11 non-interpreting controls were shown pairs of disyllabic nouns in four conditions: (i) both in L1, (ii) both in L2, (iii) the first in L1 and the second in L2, (iv) the first in L2 and the second in L1. Some of the pairs in each condition were semantically congruent, and some others were incongruent. ERP measurements revealed enlarged N400 responses in the interpreters upon detection of incongruent trials within both L1 and L2. The same results were obtained when the pairs were presented in the opposite direction as specifically trained –i.e., L1–L2 translation, or forward translation (FT). The authors concluded that such enlarged N400 responses in conditions (i), (ii), and (iii) relative to (iv) suggest that translation-specific training induces changes in sensitivity to lexico-semantic processing within and across L1 and L2.

The evidence above strongly suggests that translation expertise brings about neurophysiological adaptations altering monolingual processing in bilinguals –i.e., processing in all-L1 or all-L2 tasks. However, these studies do not tap translation-specific processes or routes. Most of the available data on the functional organization of the translating brain comes from lesion studies. In particular, the documentation of four translation-related neuropathologies has led to the postulation of several hypotheses regarding the neurofunctional systems and neuroanatomical areas involved in translation proper (see Section 2 below). On the assumption that lesion studies alone are insufficient to reveal the critical brain

areas subserving a given function, this paper aims at reviewing the available neuroimaging studies on translation-specific processes and using their findings to test relevant clinically-based hypotheses.

2. Translation-specific neuropathologies and relevant clinically-based hypotheses

The study of interlingual reformulation skills subsequent to brain damage has led to the identification of four distinct neuropathologies compromising translation abilities in bilinguals (Fabbro, 1999, 2001; Paradis, 1989). First, *spontaneous translation* consists in the involuntary, unsolicited, and immediate translation of utterances. This disorder may be accompanied by an inability to translate willingly. Also, there are reports of spontaneous translation into a language unavailable for monolingual production (cf. De Vreese, Motta, & Toschi, 1988; Eviatar, Leikin, & Ibrahim, 1999; García-Caballero et al., 2007; Jakobson, 1964; Kauders, 1929; Lebrun, 1991; Perecman, 1984; Schulze, 1968; Stengel & Zelmanowitz, 1933; Veyrac, 1931; Weisenberg & McBride, 1935). Second, patients have been diagnosed with an *inability to translate* upon the observation that they are unable to translate utterances voluntarily in either one or both directions. This syndrome may occur even when monolingual production skills are (relatively) spared in one or both languages (cf. Aglioti, Beltramello, Girardi, & Fabbro, 1996; Aglioti & Fabbro, 1993; Byng, Coltheart, Masterson, Prior, & Riddoch, 1984; Eviatar et al., 1999; Fabbro & Paradis, 1995; Gastaldi, 1951; Nilipour & Ashayeri, 1989; Perecman, 1984; Weekes & Raman, 2008). Third, *paradoxical translation behavior* is a rare pathology in which patients are capable of translating into a language unavailable for monolingual production, but incapable of translating into a language which is available for monolingual production (cf. De Vreese et al., 1988; Paradis, Goldblum, & Abidi, 1982). Finally, cases have been reported of *translation without comprehension*, a pathology in which patients are able to translate words or utterances correctly and unhesitatingly although they are unaware of the meaning of the SL expressions (cf. De Vreese et al., 1988; Paradis et al., 1982; Veyrac, 1931).

The analyses and meta-analyses of the case reports referenced above have led to the postulation of three neurofunctional and three neuroanatomical hypotheses on the organization of translation routes in the bilingual brain. These are summarized in Tables 1 and 2, respectively.

In the last twenty years, a number of neuroimaging studies have been conducted to measure brain activity patterns during translation. However, the evidence thus obtained has not been hitherto systematically reviewed, nor has it been analyzed in the light of the above hypotheses. Both endeavors are pursued in the following sections. The studies are organized in terms of the type of translation unit employed in each case, namely: single words, isolated sentences, and supra-sentential texts –i.e., texts longer than one sentence.

3. Neuroimaging evidence on translation processes

Nine neuroimaging experiments are presently reviewed offering evidence on brain activity patterns during translation proper. The techniques used include electroencephalography (EEG), evoked-response potentials (ERPs), functional magnetic resonance imaging (fMRI), functional near-infrared continuous

Table 1
Three neurofunctional hypotheses on the organization of translation routes in the bilingual brain.

Hypothesis	Empirical basis	References
1. Translation routes are neurofunctionally independent from those implicated in all-L1 or all-L2 processing.	Patients with paradoxical translation behavior or inability to translate are not necessarily impaired in all-L1 or all-L2 processing tasks.	Paradis (1984, 1994), Fabbro (2001).
2. There are neurofunctionally independent routes for backward (L2–L1) and forward (L1–L2) translation.	Patients with paradoxical translation behavior or inability to translate may be selectively impaired in either backward or forward translation tasks.	Paradis (1984, 1994), Fabbro and Paradis (1995).
3. There are neurofunctionally independent systems for structural (form-based) and conceptual (meaning-based) translation.	In translation without comprehension, patients are able to perform accurate translations in the absence of conceptual processing.	Paradis (1994).

Table 2

Three neuroanatomical hypotheses on the organization of translation routes in the bilingual brain.

Hypothesis	Empirical basis	References
4. Translation routes are strongly left-lateralized.	A revision of 21 cases of the four translation neuropathologies indicates that 19 resulted from damage to the language-dominant hemisphere, 1 from bilateral damage, and only 1 from RH damage.	García (2012).
5. Word translation is critically subserved by posterior (temporo-parietal) areas implicated in declarative memory functions.	Patients with damage to frontobasal regions evidence either mild or no impairments in single-word translation tasks, but severe deficits in sentence translation tasks. The average results of four such patients (Fabbro & Paradis, 1995) were 60.9% in single-word translation and 46.7% in sentence translation. Moreover, whereas some patients with frontobasal damage were completely incapable of translating sentences in either one or both directions, none of them completely lost the ability to translate single words. Also, reports of patients with posterior lesions include records of word-translation dysfunctions, but document no impairments in spontaneous (non-rotely-learned) sentences.	
6. Sentence translation is critically subserved by frontobasal areas implicated in procedural memory functions.		

wave spectroscopy (fNIR_{CWS}), positron emission tomography (PET), and direct cortical electro-stimulation. Excluded from this review are those studies in which bilingual subjects –including translators/interpreters– perform monolingual or non-linguistic tasks requiring no deliberate interlingual reformulation (e.g., Klein et al., 2006; Proverbio et al., 2004, 2009; Thierry & Wu, 2007).

3.1. Neuroimaging evidence on single-word translation

Three imaging studies have been conducted to explore brain activity during single-word translation.

3.1.1. Klein, Milner, Zatorre, Meyer, and Evans (1995): A PET study

Klein et al. (1995) conducted a PET study with 12 right-handed native speakers of English who were also fluent in French. Their average age of acquisition (AoA) was 7 years. The experiment involved various tasks, namely: (i) word repetition in L1, (ii) word repetition in L2, (iii) synonym generation in L1, (iv) synonym generation in L2, (v) rhyme generation in L1, (vi) rhyme generation in L2, and (vii) two translation tasks. In the first translation task, participants were asked to translate 22 orally-presented words out loud from L1 into L2 (FT); in the second one, the same task was done from L2 into L1 (BT). The stimuli included nouns, adjectives, and verbs.

In both translation conditions, participants were highly accurate (FT = 87.2%; BT = 89.5%) and had similar response latencies (FT = 1608 ms; BT = 1560 ms). Thus, there were no significant behavioral differences between the two conditions.

No cortical right-hemisphere (RH) involvement was observed in either condition, both FT and BT causing significant activity increases in Brodmann Areas (BAs) 47, 46, 45, 8, and 9 of the left hemisphere (LH). Such inferior and dorsolateral frontal and prefrontal regions were also active to a similar degree in the synonym generation and rhyme generation tasks. This led the authors to conclude that the left inferior frontal gyrus is implicated in phonological and semantic processing in all lexical access tasks, and that the prefrontal cortex would be critical for working memory processes.

Besides, both translation conditions also yielded moderate activity in the inferior temporal region (BA 37/20), and weak activations in the superior parietal cortex (BA 7) and the cerebellum. An additional activation increase was observed in the left putamen for FT, but not for BT. Other areas are assumed to have been implicated in both FT and BT, although these did not figure distinctively in the

translation conditions because they were also involved in the monolingual repetition tasks used as a baseline for subtraction.

3.1.2. Price, Green, and von Studnitz (1999): A PET study

In another PET study, Price et al. (1999) recruited 6 right-handed native speakers of German who had begun learning English at an average age of 8.8 years. At the time of the study, the participants had been highly fluent in English for roughly 10 years. Two tasks were administered: (i) reading in L1 and L2, with alternate stimuli; and (ii) silent translation of visually presented words, in both directions. Each condition included 20 different items.

Behaviorally, there were no significant differences between FT and BT. In both conditions, high-frequency words were translated more accurately than low-frequency words (97.5% vs. 69.2%).

As compared to the reading tasks, translation tasks produced increased bilateral activation in the anterior cingulate, putamen, and head of the caudate, as well as left-sided activations in the anterior insula, the cerebellum, and the supplementary motor cortex. These patterns were similar for both FT and BT. No significant prefrontal activity was observed in any condition. Interestingly, relative to the reading tasks, both translation conditions yielded diminished activation in the medial superior frontal gyrus (BA 10), left medial temporal cortex (BA 39), and posterior cingulate (BA 39) –all implicated in semantic processing–, as well as the middle and inferior temporal cortices (BA 21, BA 20) of the RH.

3.1.3. Janyan, Popivanov, and Andonova (2009): An ERP study

Janyan et al. (2009) studied the RTs and ERP topography of 18 Bulgarian subjects who had learned English as L2 after age 9, on average. All were very fluent in English. Participants were asked to orally translate visually-presented words, only in backward direction. Stimuli were organized in four conditions, each combining a semantic variable (concreteness) with a structural variable (cognate status): (i) concrete cognates, (ii) abstract cognates, (iii) concrete non-cognates, and (iv) abstract non-cognates.

Electrodes were placed symmetrically in frontal, centro-temporal, and parietal regions in both hemispheres. Response-time records showed no concreteness effect in any of the cognate conditions –i.e., conditions (i) and (ii). However, ERP measurements revealed a topographical concreteness effect for cognates only. Cognate translation produced N400-like deflections which were maximal in centro-temporal sites, moderate in frontal sites, and negligible in parietal sites. The concreteness effect observed in cognates was more pronounced in the RH than in the LH –the greater the level of concreteness, the greater the involvement of the RH. No concreteness-based differences were observed for non-cognates.

3.1.4. Discussion

Price et al.'s (1999) study failed to replicate the Klein et al.'s (1995) finding that word translation generates activation increases in the dorsolateral prefrontal cortex. Price and colleagues attribute this difference to their subjects' being more proficient in L2, on the assumption that prefrontal involvement decreases as expertise increases (Raichle et al., 1994). Unlike Klein et al. (1995), Price et al. (1999) observed no differential patterns in the left inferior temporal lobe for translation tasks relative to the baseline conditions –repetition, in the former; and reading, in the latter. Since reading itself engages left temporal lobe structures, these may have been active during Price et al.'s (1999) translation tasks and still be absent upon subtraction of the baseline from the experimental condition.

However, in both studies, word translation tasks elicited activation exclusively in the LH. Based on a technique with poor spatial resolution, Janyan et al.'s (2009) study does not directly support this finding, but it does not necessarily contradict it. ERP recordings indicated that the LH was implicated in all translation conditions, whereas the RH was involved in only two of them. In these two, what was observed was that the N400-like deflections evoked during the concrete-word translation tasks reached their highest amplitude in the RH. Nevertheless, such deflections may have actually been generated in the LH –negative deflections associated to semantic effects, such as concreteness, have been correlated to left temporal lobe structures (Kiehl, Laurens, & Liddle, 2002; Olivares, Bobes, Aubert, & Valdes-Sosa, 1994). Furthermore, in Janyan et al.'s (2009) study, word translation elicited more activity in centro-temporal than frontal areas. LH posterior –especially inferior and superior temporal– regions were implicated in all three experiments.

Frontal activations in these studies may have been produced by motor-articulatory rather than translation-specific processes. Specifically, the frontal and prefrontal activations obtained in Klein et al.'s (1995) experiment were not identified after subtraction from the baseline condition; rather, they were the same as the ones detected during the other two oral production tasks. Finally, cerebellar activity in the two PET studies may reflect lexical retrieval demands (cf. Ullman, 2004).

3.2. Neuroimaging evidence on sentence translation

The three studies reviewed below used full sentences as stimuli, involving syntactic processing demands not present in the previous experiments.

3.2.1. Quaresima, Ferrari, van der Sluijs, Menssen, and Colier (2002): An fNIR_{CWS} study

In Quaresima et al.'s (2002) experiment, 8 right-handed early bilinguals, speakers of Dutch (L1) and English (L2), were asked to sight-translate 7 short sentences in each direction –e.g., 'I'm eating fish and chips,' 'She writes with a pencil.' The control condition consisted in reading simple sentences out loud. The study was based on the fNIR_{CWS} technique, which allows monitoring changes in the levels of activation of predefined brain areas without the invasiveness and interferences proper to PET and fMRI. The region of interest in this experiment was Broca's area and adjacent LH regions.

Similar activity patterns were observed in both translation directions. Activation increases were more pronounced in the inferior frontal cortex, including Broca's area. Relative to the control conditions, both translation tasks engaged wider frontal regions. However, the sites adjacent to Broca's area were not uniformly activated in BT and FT, suggesting a directionality effect. No recordings were obtained of posterior or subcortical areas.

3.2.2. Lehtonen et al.'s (2005): An fMRI study

In their fMRI experiment on translation, Lehtonen et al. (2005) recruited 11 native speakers of Finnish who had been exposed to Norwegian (L2) for roughly 5 years (AoA = 26.7 years). 10 participants were right-handed; the remaining one was ambidextrous. The subjects were asked to silently translate 54 visually-presented sentences, only in forward direction. After each trial, they had to decide whether another L2 sentence presented immediately afterward was an acceptable translation of the stimulus sentence. In the control task, subjects were briefly shown a sentence in L1, which they had to retain in their minds in order to decide whether it was identical to the immediately following sentence. Half the sentences in each task were syntactically complex and required a word-order change for translation. The other half were syntactically simple and required no word-order change.

Behaviorally, no significant accuracy differences were found between the two types of sentences. An unexpected finding was that RTs were longer for simple than complex sentences. According to the authors, this may be due to the fact that the former included double adjectives before the head noun, resulting in increased working-memory demands.

fMRI scans revealed that all active areas belonged to the LH only. Upon subtraction of the control condition, the only differential activation increases for translation occurred in the ventrolateral prefrontal cortex (AB 47, within Broca's area) and the globus pallidus. Activation patterns were similar for simple and complex sentences.

3.2.3. Hervais-Adelman, Moser-Mercer, Michel, and Golestani (2011): An fMRI study

Another fMRI experiment on sentence translation was conducted by Hervais-Adelman et al. (2011). Twenty-three students of simultaneous interpretation (L1 = French, L2 = English) were asked to simultaneously interpret thirteen blocks of simple sentences in backward direction. The control condition consisted in a shadowing task, that is, simultaneous repetition of stimuli in the same language.

As compared to the shadowing task, BT caused activation increases in left prefrontal and subcortical areas, namely: Broca's area (BA 45, 47), supplementary motor cortex, caudate nucleus, and premotor cortex. Separate analysis of the interpreting task also revealed significant activity in the left anterior prefrontal cortex (BA 10), and bilateral activations in the putamen and superior temporal gyrus.

3.2.4. Discussion

The first two studies suggest that task-specific neural activity during sentence translation occurs exclusively in frontobasal structures of the LH. Quaresima et al.'s (2002) experiment, in which only frontal areas were monitored, is also compatible with such a hypothesis. This was corroborated for both FT (Lehtonen et al., 2005) and BT (Hervais-Adelman et al., 2011). Directionality-based differences were observed in Quaresima et al.'s (2002) study, suggesting that FT and BT may involve different micro-anatomical substrates. However, the authors consider that the different levels of activity around Broca's area for each direction may be due to the anatomical particularities of the subjects' brains.

Lehtonen et al. (2005) propose that the activation of BA 47, within Broca's area, may be associated to conscious and controlled retrieval of verbal and semantic information represented in posterior regions. Broca's area was also implicated in sentence translation in Hervais-Adelman et al.'s (2011). According to the authors, this may be due to the crucial role of BA 45 and BA 47 in semantic and syntactic processing, respectively. The premotor and supplementary motor cortices were activated in Hervais-Adelman et al.'s (2011) experiment but not in Lehtonen et al.'s (2005) study, probably because motor processing was involved only in the former's experimental task.

3.3. Neuroimaging evidence on the translation of supra-sentential texts

Other experiments have explored translation processes without restricting SL stimuli to the word or sentence levels. It must be noted that, cognitively speaking, supra-sentential text translation is radically different from sentence translation and, more particularly, from word translation. While supra-sentential text translation involves the ongoing creation of a progressively richer verbal context guiding translation decisions, word translation tasks are decontextualized and can be successfully carried out by resorting only to lexical declarative memory.

3.3.1. Kurz (1994, 1995): An EEG study

The EEG study reported by Kurz (1994, 1995) investigated broad neural activity changes in 4 conference interpreters during silent simultaneous interpretation sessions. Three participants were right-handed; the third was left-handed, and his language-dominant hemisphere was the RH. The language combinations of the participants were German (L1) and English (L2) for participants 1 and 2; English (L1), French (L2), and German (L3) for participant 3; and German (L1), English (L2), and Russian (L3) for participant 4. The experimental task consisted in alternating 4-min periods of simultaneous interpreting and 1-min rest periods. All participants performed the task in both forward and backward direction.

Relative to rest periods, interpreting periods yielded activation increases in the LH, especially in temporal –and less notably in frontal– areas. Left temporal activation increases as well as RH involvement were more prominent in FT than BT. These results were replicated in a follow-up study including 10 professional interpreters (Petsche & Etlinger, 1998).

3.3.2. Rinne et al. (2000): A PET study

Based on the PET technique, the experiment conducted by Rinne et al. (2000) brought together 8 right-handed professional interpreters, between 32 and 56 years of age, who spoke Finnish as L1 and English as L2. The subjects had between 5 and 20 years of experience in the profession, and were proficient in both BT and FT. The study comprised five conditions, namely: (i) rest, (ii) L1 shadowing, (iii) L2 shadowing, (iv) backward simultaneous interpreting, and (v) forward simultaneous interpreting. Stimuli consisted in eight speeches recorded by native speakers of each language, ranging from 3.5 to 4 min in length and delivered at an average rate of 98 words per minute. Each task was performed twice, each time with a different source text.

Qualitative analysis of the TTs produced by the subjects revealed greater propositional accuracy in FT than BT. According to the authors, this may be indicative of a better comprehension of the L1 source texts than the L2 source texts.

Relative to condition (i), shadowing in both languages resulted in pronounced bilateral activation in the cerebellum as well as temporal and frontal regions implicated in linguistic comprehension and production. Activation was greater in the LH, and, within it, more extended in condition (iii) –L2 shadowing. A comparison of BT with L2 shadowing showed that the former differentially involves the left supplementary motor cortex (BA 6) and a site anterior to Broca's area (BA 46). On the other hand,

relative to L1 shadowing, FT resulted in more extended left frontal activations in the same areas, and additional activations in the left inferior temporal lobe (BA 20 and 28). A direct contrast between L2 shadowing minus BT, on the one hand, and L1 shadowing minus FT, on the other, revealed greater activity in Broca's area in FT relative to BT. Neither interpreting task yielded distinctive RH activations.

3.3.3. *Borius, Giussani, Draper, and Roux (2012): A direct electrostimulation study*

More recently, *Borius et al. (2012)* published the results of a study conducted with 7 highly proficient bilinguals during presurgical direct cortical electrostimulation. Patients ranged from ages 26 to 45, and all had at least 14 years of sustained exposure to their L2s. None of them presented linguistic deficits at the time of the study, and all possessed considerable experience in translation and/or interpreting. The language pairs of the patients included various combinations of French, English, Arabic, German, Italian, and Kinyarwanda. Two of the patients were left-handed. Only the remaining five (right-handed) subjects are presently considered.

Among the several language tasks administered was a translation task. Patients were asked to sight-translate paragraphs from newspapers written in the respective L2s. Electrical stimulations were applied intermittently throughout the tasks to determine which functions –monolingual reading, confrontation naming, translation– were inhibited each time. Overall, 147 different cortical sites were studied. In the 5 right-handed patients, LH stimulation interfered with linguistic processing in 26 sites, most notably in supramarginal, superior temporal, and inferior frontal gyri. Only 3 of these sites resulted in interferences during translation upon stimulation, but none was implicated exclusively in translation tasks. Therefore, no translation-specific region was identified. One of such three sites interfered with translation not because it inhibited language processing but because it impaired visual processing –in fact, its stimulation also caused an ocular deviation.

Thus, the linguistic areas involved in translating processes in the right-handed patients were two: Broca's area in patient 3, and the posterior part of the superior frontal gyrus in patient 4. Another interesting finding is that, in the remaining three right-handed patients, no areas were detected which interfered with translation –not even those sites interfering with monolingual processing. In other words, translation processes were not impaired upon stimulation of the same sites whose stimulation interfered with all-L1 or all-L2 processing.

3.3.4. *Discussion*

The results of these studies coincide in various ways. First, they are consistent with the hypothesis that the LH is dominant for translation processes. In fact, in the two studies monitoring both hemispheres, RH activations were either null (*Rinne et al., 2000*) or comparatively milder (*Kurz, 1994, 1995*) for both translation directions. LH implication in translation is further corroborated by *Borius et al. (2012)*. Second, all three studies show that frontal areas –especially Broca's area– are involved in the translation of oral and written supra-sentential texts. Third, the two studies exploring both BT and FT showed that the latter generates more extensive activations than the former. This suggests that directionality modulates cerebral activity patterns.

In *Rinne et al.'s (2000)* study, FT caused activity increases only in the LH. On the contrary, *Kurz (1994, 1995)* reported that FT also generated activity increases in the RH, although the technique used in this experiment (EEG) is of questionable spatial resolution. The more extensive patterns provoked by FT relative to BT have been attributed to the greater cognitive effort involved in FT (*Kurz, 1995; Tommola, Laine, Sunnari, & Rinne, 2000/2001*). RH involvement may also reflect a greater use of pragmatic, attentional and/or monitoring strategies (cf. *Paradis, 2009*). For their own part, *Rinne et al. (2000)* maintain that greater left frontal activity in FT relative to BT may be indicative of increased morphosyntactic processing, semantic analysis, and working memory demands.

Finally, *Borius et al. (2012: 620)* note that the stimulation of certain sites interfered with monolingual processing tasks but not with translation tasks, concluding that “[i]n such cases, the process of translation must use neurocognitive pathways spatially distinct from these sites which have been identified as involved in reading or naming.” The authors further maintain that while no translation-exclusive sites were detected in their study, these may exist subcortically. Still, these results do not suffice to refute the possibility that there may be translation-exclusive circuits even at a neocortical level, be it in different macroanatomical regions or even microanatomically within the same areas studied.

4. Comparing activation patterns along the ‘translation unit’ variable

The joint interpretation of all nine studies presently reviewed poses various challenges, since they involve different tasks (silent translation, out-loud translation), different directions (BT, FT, or both), different translation modes (simultaneous interpretation, sight translation), different baseline conditions (e.g., rest, monolingual reading), subjects with different levels of translation expertise (lay bilinguals, interpretation students, professional translators), different techniques, and different language pairs. However, by considering translation units as a key organizing variable, their integrative analysis reveals general patterns.

4.1. Word translation vis-à-vis sentence translation

Word translation differs from sentence translation in that the latter involves syntactic processing and greater semantic and conceptual analysis demands. It has been demonstrated that cognitive fatigue is more pronounced in sentence than word translation (Green et al., 1990). Also, there is evidence that sentence context modulates the level of coactivation between lexical equivalents across languages (van Hell, 2005).

The studies reviewed in Sections 3.1 and 3.2 show that both word and sentence translation engage LH structures either exclusively or predominantly. In both directions, word translation seems to generate greater activity in posterior structures than does sentence translation. In fact, no distinctive posterior activations were reported in the sentence translation studies. On the other hand, Broca’s area seems to be involved in both tasks, irrespective of direction.¹

However, word translation and sentence translation seem to involve different frontobasal circuits. The activation peaks reported by Klein et al. (1995) in the ventrolateral prefrontal cortex were 20 mm more anterolateral than the ones recorded by Lehtonen et al. (2005). Also, while both Price et al. (1999) and Lehtonen et al. (2005) observed basal ganglia activations, these were concentrated in the putamen and head of the caudate in the former, and in the globus pallidus in the latter.

4.2. Sentence translation vis-à-vis supra-sentential text translation

Left frontobasal structures –in particular, parts of Broca’s area– are differentially involved in the translation of sentences and texts beyond the sentence level, both in backward and forward direction. However, BT and FT seem to engage different frontobasal circuits both in sentence translation (Quaresima et al., 2002) and supra-sentential text translation (Kurz, 1994, 1995; Rinne et al., 2000).

The RH activations reported by Kurz (1994, 1995) in her study with supra-sentential texts were not replicated in any of the studies using sentences as stimuli. Besides, there seems to be a discrepancy between the directionality-based differences in Broca’s area reported by Rinne et al. (2000) and the absence of such differences in the same region in Quaresima et al.’s (2002) study. These differences may be due to the different translation modes (sight translation vs. simultaneous interpretation), limitations of the techniques used (fNIR vs. PET), and the level of translation expertise of each sample. Finally, Lehtonen et al. (2005) observe that while the ventrolateral prefrontal cortex –including Broca’s area– was activated in both their study and Rinne et al.’s (2000), there are millimetric differences between the sites where activation peaks occurred in each case.

4.3. Supra-sentential text translation vis-à-vis word translation

Unlike the results obtained by Kurz (1994, 1995) and Petsche and Etlinger (1998), no distinctive RH activations were observed in the studies on word translation. However, the directionality-based differences reported by Kurz (1994, 1995) and Rinne et al. (2000) in supra-sentential text translation were corroborated by Klein et al. (1995) for word translation –in this study, the left putamen was implicated only

¹ In Lehtonen et al.’s (2005) study, the only structure activated within Broca’s area was BA 47. Other sites implicated in phonological processing, such as AB 44 (Heim, Eickhoff, & Amunts, 2008; Raichle, 1994), were not activated. This is not surprising, given that the task in Lehtonen et al.’s (2005) experiment was silent translation.

in FT. Also, both Rinne et al. (2000) and Klein et al. (1995) reported left dorsolateral prefrontal activations during translation, a finding that was not replicated by Price et al.'s (1999) study on word translation. Rinne et al. (2000) maintain that the reasons for such discrepancies may lie in the use of different tasks and control conditions, as well as the varying levels of linguistic proficiency of the participants in each sample.

4.4. (Inconclusive) broad patterns based on the 'translation unit' variable

Since the nine studies presently reviewed employ different tasks, directions, modes, baselines, subjects, and techniques, it comes as no surprise that none of them exactly replicates the findings of the others. Results are inconsistent even when comparing studies using the same techniques or tasks. Furthermore, there is a fundamental cognitive difference between word translation (a context-independent recoding operation which could be emulated by machines) and discourse translation (a process that is context-bound and seems to be exclusively human). However, three broad –though inconclusive– patterns emerge upon contrasting the experiments along the 'translation unit' variable.

First, while frontobasal activations –especially in and around Broca's area– were observed for all translation units,² temporal regions were differentially activated only in word translation tasks. On the contrary, task-distinctive activations in sentence and suprasentential-text translation occurred only in frontobasal areas. These differences are compatible with the declarative/procedural model of bilingualism (Paradis, 2004, 2009; Ullman, 2001, 2005), which posits that explicit lexico-semantic information and implicit morphosyntactic representations are differentially represented and processed by declarative and procedural memory neural substrates, respectively. This suggests that at least part of the circuits involved in translation are represented in the same macroanatomical areas as those involved in L1-only or L2-only processes.

Second, except for Kurz's (1994, 1995) experiment, all studies monitoring both hemispheres show that translation processing engages the LH exclusively, irrespective of translation unit and translation direction. Also, in the case of Kurz (1994, 1995), LH activations were more prominent than RH activations. The presence of RH activations in this study may mean that only simultaneous interpreting of ongoing supra-sentential texts in real time –as opposed to decontextualized word and sentence translation– involves attentional, inferential, and otherwise pragmatic functions represented in RH regions (Fabbro & Gran, 1997; Paradis, 1992, 1995, 2003, 2009).

However, the role of the RH in translation is not yet well understood. Not only is the present imaging evidence insufficient, but reports of translation performance subsequent to RH damage in bilinguals are also scant and mostly uninformative. Lebrun (1991) studied a bilingual speaker of Flemish (L1) and French (L2) who had sustained a lesion to his RH causing no oral aphasia. However, after the insult the patient developed a tendency to compulsively and automatically translate written texts. During writing-to-dictation tasks in L2, the patient would first write down the word presented and then compulsively write its equivalent in L1. This behavior would also manifest with longer texts. Lebrun (1991) suggests that the RH lesion may have produced a deficit in the control of the sociolinguistic conventions governing verbal communication. Notice that the patients' ability to find the adequate equivalent to the L1 texts provided was intact. Another report of translation deficits following RH damage was offered by García-Caballero et al. (2007). However, it is not relevant to the present discussion as the patient was a crossed aphasic, so that her linguistic system was in fact entirely represented in the RH. All in all, more research is necessary to discover the contributions of the RH to translation processes involved in the reformulation of all three types of unit, especially supra-sentential texts. In this sense, evidence on the involvement of subcortical structures in translation might also prove enlightening.

Third, while the two patterns above hold irrespective of translation direction, directionality differences have been documented in the translation of all three units. Three out of four studies including both BT and FT tasks reported directionality-based differences –Klein et al. (1995) for word translation,

² The involvement of Broca's area might seem obvious since translation tasks involve language production. However, to the extent that translation-specific processes cannot be directly inferred from research on, or models of, the bilingual brain, the implication of Broca's area in the translation of all three types of units constitutes an empirical finding –albeit a minor one.

Quaresima et al. (2002) for sentence translation, Kurz (1994, 1995) for supra-sentential text translation. Only Price et al. (1999) studied both BT and FT and failed to observe any significant differences.

The above patterns, it must be emphasized, are far from conclusive. Further research is needed in order to eliminate confounding variables and validly confirm such tendencies. Experiments explicitly designed in order to explore translation-unit-based neurofunctional and neuroanatomical differences may yield firmer results. For example, the same sample may be asked to perform word, sentence, and supra-sentential text translations in both directions. The same paradigm may be then used with different samples differing in AoA, level of L2 proficiency, and level of translation expertise.

5. Discussion: neuroimaging evidence as a testing ground for clinically-based hypotheses

On account of its inconclusiveness, the neuroimaging evidence discussed above does not provide a firm ground to test the clinically-based neurofunctional hypotheses listed in Table 1. However, some of the studies seem compatible with the latter. First, the hypothesis that translation routes are neurofunctionally independent from those implicated in all-L1 or all-L2 processing (Fabbro, 2001; Paradis, 1984, 1994) is corroborated by the finding that the electrostimulation of certain cortical sites impairs monolingual processing but not translation abilities (Borius et al., 2012). Second, the postulation that there are neurofunctionally independent routes for BT and FT (Fabbro & Paradis, 1995; Paradis, 1984, 1994) is consistent with the following data: (i) in Klein et al.'s (1995) study, the left putamen was implicated in FT but not in BT, (ii) BT and FT engaged different areas adjacent to Broca's area in Quaresima et al.'s (2002) experiment; and (iii) FT involves more extensive activation patterns than BT (Kurz, 1994, 1995; Rinne et al., 2000). Third, there is indirect imaging evidence supporting the neurofunctional separation between structural (form-based) and conceptual (meaning-based) translation proposed by Paradis (1994). Relative to monolingual tasks, translation tasks elicited reduced activity in areas implicated in semantic processing in Price et al.'s (1999) study. This may mean that the subjects –all highly proficient in L2– were relying on structural associations rather than conceptual links during interlingual reformulation (cf. Kroll & Stewart, 1994). Also, Janyan et al. (2009: 28) affirm that the absence of a concreteness effect in non-cognate translation “unambiguously suggests non-accessibility of conceptual/semantic information during processing, [indicating] that the processing of cognates was conceptually mediated, and of non-cognates lexically mediated.” The absence of conceptual activations during non-cognate translation would speak to the use of the structural (form-based) route. If correct, this conclusion would also corroborate the third hypothesis.

Be that as it may, it must be acknowledged that the statistical significance of the reported results is not high enough so as to definitely confirm/disconfirm these hypotheses. At best, they may be considered compatible with the latter. Further research is needed to produce neuroimaging evidence capable of directly testing the three neurofunctional hypotheses listed in Table 1. In particular, the use of techniques offering high spatial resolution at a microanatomical level, such as fMRA (cf. Chee, 2009), might help to determine whether the bilingual brain includes circuits exclusively devoted to translation processes.

On the other hand, the evidence reviewed seems more adequate to test the neuroanatomical hypotheses presented in Table 2 (García, 2012). Hypothesis 4 (‘translation routes are left-lateralized’) is supported by the fact that the LH was either exclusively or predominantly involved in translation tasks in all of the nine imaging studies surveyed. This is an interesting finding in that it directly contradicts both behavioral (Fabbro et al., 1990, 1991; Gran & Fabbro, 1991; Green et al., 1990; Proverbio & Adorni, 2011) and electrophysiological (Proverbio et al., 2004, 2009) evidence suggesting a reduced left lateralization of linguistic processes in simultaneous interpreters relative to monolinguals and even non-interpreting bilinguals. The predominance of LH activations in the studies presently reviewed, alongside the fact that translation-specific deficits occur almost exclusively as a result of LH damage (García, 2012), and the criticisms raised against the validity of behavioral methods to tap language laterality in bilinguals (Paradis, 1992, 1995, 2003), seem to confirm hypothesis 4 and refute studies proposing a more symmetrical representation of linguistic functions in translators/interpreters.

For its own part, hypothesis 5 (‘word translation is critically subserved by temporo-parietal areas implicated in declarative memory’) is only partially supported by relevant neuroimaging evidence. Unlike sentence and supra-sentential task translation, word translation did elicit differential activation patterns in temporal lobe structures implicated in declarative memory (cf. Klein et al., 1995). Frontobasal areas –especially in and around Broca's area– have also been implicated in word translation,

which seems to contradict hypothesis 5 as presently defined. However, such areas did not figure as prominently in word-translation studies as they did in those using sentences or supra-sentential texts, and their activation was not as prominent as that observed in temporal areas.

As regards hypothesis 6 ('sentence translation is critically subserved by frontobasal areas implicated in procedural memory'), the three studies on sentence translation evidenced differential activation increases for both BT and FT only in frontobasal regions known to be implicated in procedural memory. As opposed to word translation, sentence translation did not elicit differential activations in posterior areas (cf. Hervais-Adelman et al., 2011; Lehtonen et al., 2005). Also, specific frontobasal areas involved in sentence and supra-sentential text translation are different from those implicated in word translation.

Once again, the dissociation implied by hypotheses 5 and 6 is consistent with the declarative/procedural model of bilingualism (Paradis, 2004, 2009; Ullman, 2001, 2005). Still, further research is necessary to provide more direct neuroimaging evidence to contrast such neuroanatomical hypotheses.

6. Conclusion

Nine neuroimaging studies on translation have been reviewed and used to test six clinically-based hypotheses. Their results are inconclusive and, in several aspects, inconsistent. However, their joint analysis reveals a number of broad patterns which are compatible with the hypotheses in question. In particular, which specific neural substrates are involved in translation seems to depend on the nature of the source unit – words, sentences, supra-sentential texts – and the direction of translation. The LH is either predominantly or exclusively involved in the translation of all three types of units, irrespective of direction. Within the LH, Broca's area seems to play a role in all translation tasks. However, no specific cortical or subcortical regions have been identified which are exclusive to translation processes. Further research is required to firmly test the neurofunctional and neuroanatomical hypotheses on translation derived from clinical data.

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