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REVIEW

Shedding Light on the Neurocognitive Explorations of Interpreting: What Do We Know from Brain-Based Research?

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ABSTRACT

Interpreting is highly complex and cognitively demanding, arousing interest from the neuroimaging community. In the past three decades, dozens of investigations have been done to figure out how one language transfers into another in the brain. This article reviews the published studies concerning interpreting, shedding light on interpreting asymmetry effect, the neural plasticity and the brain regions activated during interpreting tasks. Based on the findings in previous studies, the article argues that interpreting training and practice might contribute to neuroplasticity both functionally and structurally. It also suggests that apart from traditional language areas, the prefrontal cortex, the superior temporal gyrus, the inferior parietal lobule and the anterior cingulate cortex also play a key role during the rendering process.

Keywords: Neurocognition; Neuroplasticity; Interpreting; Review

1. Introduction

In the past few years, there has been an increasing interest in neurocognitive investigations concerning the fields of interpreting. The interest stems from the recognition that interpreting, the immediate rendering from one language to another (including orally translating one single word as well as interpreting sentences and paragraphs), involving complex and multifaceted cognitive processes [1, 2]. Different from written translation, interpreting produces the non-written target text with immediacy and on the basis of a one-time presentation of the original text in a source language. Researchers

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want to figure out what happens when interpreters conduct interlingual brokering. In the past three decades, researchers leveraged the tools and technologies of neuroscience to acquire a more profound comprehension of the cognitive processes and to answer new questions about interpreting that are grounded in empirical evidence. Several early empirical studies investigated the brain regions activated during interpreting tasks (e.g.,[3–5]), while more recent research has focused on functional connectivity (e.g.,[6–9]). Other studies have examined the asymmetrical neural mechanisms associated with different interpreting directions (e.g.,[8, 10–14]). Additionally, some researchers have explored the role of executive function in interpreters, suggesting that years of training and practice may enhance cognitive control (e.g.,[15–18]). Collectively, these studies are shedding light on the complex cognitive processes occurring within the "black box" of the brain during interpreting.

The advancement of brain imaging technology in the 20th century has significantly enhanced researchers' ability to observe changes in the central nervous system and infer human psychological activities. The earliest application of neurocognitive technologies in interpreting[3] was electroencephalography (EEG), which is prized for high temporal resolution, recording brain activity continuously in real time, and is therefore valuable for examining the time courses over which cerebral processes occur. Early neurocognitive interpreting studies have also seen the application of positron emission tomography (PET)[4, 5, 10], a technique that records the decay of radioactive tracers. However, PET's experimental utility is limited due to its invasive nature and the restricted amount of data that can be obtained in a single session. The most widely used technology applied in interpreting studies is (functional) magnetic resonance imaging ((f)MRI). Apart from its application in investigating the brain regions activated during interpreting tasks (e.g.,[8, 17, 19]), the comparison between the neuroanatomy of simultaneous interpreters and non-interpreter bilinguals[18, 20] can provide hints that interpreting training results in change to specific brain areas, implying a role for these areas in the task. Recently, more researchers turn to functional near-infrared spectroscopy (fNIRS) in neurocognitive investigation (e.g.,[2, 9, 13, 21–23]). Extensive evidence demonstrates the reliability of this method as a tool for investigating higher cognitive functions, primarily attributed to its notable spatial resolution capable of mapping cortical processes[24]. Additionally, fNIRS can be seamlessly integrated with other neurophysiological techniques, such as EEG and event-related potentials (ERP), enhancing source localization and temporal resolution[25]. The aforementioned technologies have significantly advanced interpreting research by providing more direct methods to observe brain activation, intensity, and connectivity during specific tasks.

One of the key contributions of neuroscience to interpreting studies is its ability to illuminate the neural mechanisms underlying interpreting tasks, providing a deeper understanding of the complex cognitive and neural processes involved. By examining the neural correlates of language transfer tasks, researchers gain valuable insights into the brain's functional organization and the mechanisms that support human communication. This article reviews empirical neurocognitive interpreting studies, highlighting the brain regions involved in interpreting, the resulting neural adaptations, and the differing neurocognitive processing mechanisms between various interpreting directions.

2. Materials and Methods

This review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) extension guidelines for scoping reviews[26]. We reviewed the literature through the following four stages: 1) identification of the research questions, 2) identification of the relevant studies, 3) selection of studies for review, 4) summary of the results. Before we started the investigation, we proposed the broad exploratory research question, namely: what has been found about the neurocognitive processing of interpreting? The more detailed research questions were as follows: what topics have been explored in this line of research? Is there any controversy concerning the result? Which brain regions are activated during interpreting? The search was done through the database of 'PubMed' which comprises more than 37 million citations from neuroscience and life science journals. We developed an adequate search string that combined the terms "neurocognition", "neuroimaging", "language interpreting", "language interpretation", and "language switching", and searched within titles, abstracts, and keywords. To ensure that we captured relevant studies published within the past three decades (from 1993 to 2023), two research assistants independently conducted the search. The study's inclusion criteria were meticulously outlined as follows: (a) empirical studies involving language interpreting activity; (b) examination of brain activation, connectivity or structure, (c) using brain-based technologies of EEG, fNIRS, (f)MRI, or PET recordings, and (d) the employment of healthy participants. There were no further criteria concerning the experiment task, the participant, the technology used, and the analysis method. The retrieved studies underwent a meticulous screening process based on their titles, abstracts, and keywords. Any discrepancies regarding the inclusion of studies were resolved through thorough discussion and further examination of the articles.

3. Results

This paper identifies 34 empirical neuroimaging studies related to interpreting (see **Table 1**). Among these studies, 11 utilized single words as stimuli, 8 focused on sentences, 7 examined supra-sentential material, and 8 incorporated non-interpreting tasks. Regarding methodology, 3 studies employed PET, 12 used EEG/ERP, 11 utilized (f)MRI, and 8 applied fNIRS technology. Participant groups included bilinguals and multilinguals in 13 studies, student interpreters or translators in 10, and professional interpreters or translators in 11.

In terms of research focus, 15 studies primarily investigated brain activation during interpreting tasks, 6 explored neuroplasticity resulting from prolonged interpreting practice, 11 examined differences between forward interpreting (from one's native language to a second language) and backward interpreting (from a second language to the mother tongue), and 5 analyzed the neural networks involved in interpreting activities. The following sections present the results in more detail.

3.1. The Cortical Brain Regions Activated

Twenty studies (e.g.,[4, 10, 14]) reported activation of left inferior frontal/prefrontal cortex during the interpreting task, no matter what language pair the participants worked on, or the expertise level of the participants, or the technologies the studies employed. This result confirms the role the left frontal region plays in such tasks. Several studies also observed activations in the left superior temporal gyrus (e.g.,[2, 19, 27]) or the larger left temporal cortex[3, 28–31], indicating this area might also contribute to the completion of interpreting tasks. Another area may also be involved in cognitive processing of interpreting is the left parietal cortex (e.g.,[27, 32, 33]). It's interesting to be noted that although most studies reported activation in the left-hemisphere, several studied mentioned right hemisphere activation in the temporal, frontal, angular, and parietal gyrus during the task[2, 3, 6, 30] regardless of the language pair, the participant group and the applied technology.

3.2. The Neural Plasticity

Studies comparing bilinguals and experienced interpreters found significant neural adaption in interpreters, though they have different area of interest in the research design. Several studies reported the organic change due to long time and intensive practice, including changes in gray matter[20], in the right caudate nucleus[17], in cortical thickness[33], and in the structure of the brain[34, 35]. Whilst others examined different cognitive mechanisms or executive functions in left dorsal pathway[7], the left frontal pole, the left inferior frontal gyrus, the middle temporal gyrus[18], and the left superior temporal gyrus, the right angular gyrus, the right cerebellum[27]. The physical and cognitive differences between bilinguals and interpreters confirm the neural plasticity at the expense of long-term and deliberate interpreting enhancement.

3.3. Interpreting Asymmetry

Of the 11 studies that addressed the differences between forward and backward interpreting, 9 claimed there is an asymmetry effect, namely forward interpreting caused more intensified brain activation in the left frontal cortex, parietal region, the bilateral fronto-temporal networks, the temporo-occipital networks in the right hemisphere, the left premotor and supplementary motor cortex, as well as the superior temporal gyrus[2, 6, 8–10, 12–14, 29], despite of the task type, participant group, applied technology, and language pair. Only one claimed that no such an effect was observed during interpreting tasks[5, 11].

Table 1. The reviewed neurocognitive interpreting studies.

Authors(s)	Total Participants	Topic	Technology	Activated Brain Region
Kurz [3]	4 professional interpreters (male=1, female=3, range: 26–48 years)	the neural activation during silent simultaneous interpreting	EEG	left temporal activation and right hemisphere involvement
Klein et al. [4]	12 bilinguals (male=6, female=6, M=22 years)	word generation in proficient L2 speakers	PET	inferior frontal cortex, posterior dorsolateral frontal cortex, left inferotemporal region, left parietal cortex, cerebellum, and left putamen
Price et al. [5]	6 bilinguals (male=6, M=30.5 years)	the neural mechanisms involved in translation and language switching	PET	the anterior cingulate and subcortical structures, the anterior insula, cerebellum and supplementary motor area, Broca's area and the supramarginal gyri
Rinne et al. [10]	8 professional interpreters (male=4, female=4, range: 32–56 years)	the neural activation during simultaneous interpreting compared to shadowing	PET	the left dorsolateral frontal cortex
Quaresima et al. [11]	8 bilinguals (male=8, range: 19–24 years)	the neural substrates in the left lateral frontal cortex that were implicated in translation and language switching	fNIRS	the inferior frontal cortex, including the Broca's area
Proverbio et al. [30]	8 professional interpreters (Age: 23–30 years) and 8 bilinguals (Age: 23-29) (male=7, female=9)	the neural mechanisms of language switching in simultaneous interpreters	ERP	the left and right temporal and frontal area
Lehtonen et al. [36]	11 bilinguals (male=1, female=10, M=31.8 years)	the neural mechanisms of sight translation	fMRI	the left inferior frontal gyrus (Brodmann's area 47) and the left basal ganglia
Grabner et al. [32]	13 student interpreters and translators (female=13, M=24.69 years)	whether similar ERS/ERD patterns emerge during translation and which frequency bands exhibit sensitivity to the difficulty of translation		parietal theta ERS, frontal upper alpha ERD, and larger left-hemispheric upper alpha ERD
Janyan et al. [28]	22 bilinguals (male=3, female=19, M=22 years)	the influence of concreteness and cognate status on translation	ERP	the central-temporal region, the frontal areas
Ahrens et al. [19]	6 student interpreters (male=1, female=5, range: 22–30 years)	the cognitive processing of simultaneous interpreting	fMRI	The left superior temporal sulcus, the inferior postcentral gyrus
Proverbio et al. [31]	19 professional interpreters (male=0, female=19, M=42 years), 16 bilinguals (male=7, female=9, M=23 years)	the lateral preference in simultaneous interpreters and hemispheric asymmetry for language processing	ERP	the left posterior-temporal/lateral occipital site
Borius et al. [36]	7 bilinguals (male=3, female=4, range: 25–58 years)	the cortical regions hypothetically implicated in translation during brain tumour resections	MRI	cortical structures, subcortical areas
Christoffels et al. [12]	20 bilinguals (male=8, female=12. M=20.8 years) for experiment 1; 40 bilinguals (male=6, female=34, M=24.4) for experiment 2	the asymmetry effect in translation	ERP	frontal and parietal region
Elmer et al. [20]	12 professional interpreters (male=4, female=8, M=37.9 years) and 12 multilingual controls (male=4, female=8, M= 28.4 years)	the potential impact of cognitive, linguistic, and articulatory processing demands on gray matter plasticity within the adult multilingual brain	MRI	left middle-anterior cingulate gyrus, bilateral pars triangularis, left pars opercularis, bilateral middle part of the insula, and left supramarginal gyrus
Hervais-Adelman et al. [17]	50 multilinguals (male=24, female=26, M=25 years)	the neural mechanisms of exceptional multilingual language control	fMRI	caudate nucleus and putamen
Hervais-Adelman et al. [17]	19 student interpreters (male=11, female=8, range: 22–32 years)	the brain plasticity resulting from long-term and intensive simultaneous interpretation training	fMRI	the right caudate nucleus

Table 1. *Cont.*

Authors(s)	Total Participants	Topic	Technology	Activated Brain Region
Babcock [34]	15 student interpreters and 8 students translators (male=6, female=17)	the impact of training in simultaneous interpretation on the structure of the brain	MRI	left temporal and bilateral hippocampal regions, bilateral subcortical structures, the left temporal lobe
García et al. [6]	10 professional translators (M=51.8 years)	the connectivity in forward and backward translation	EEG	the bilateral fronto-temporal networks, the temporo-occipital networks in the right hemisphere
Elmer & Kühnis [7]	12 professional interpreters (male=2, female=10, M=37.9 years)	to investigate how practice and interpreting training impact the cognitive processing in the brain	EEG	the left dorsal pathway
Becker et al. [18]	50 interpreters and translators (male=13, female=37, M=41.46 years)	to examine whether simultaneous interpreters exhibit cognitive advantages in cognitive control tasks, compared to fluent multilinguals	MRI	the left frontal pole, the left inferior frontal gyrus, the middle temporal gyrus
Hervais-Adelman et al. [33]	34 student interpreters (male=15, female=19, M=26.03) and 33 multilingual controls (male=14, female=19, M=25.7 years)	the changes in cortical thickness among trainee interpreters prior to and following completion of a Master's program in conference interpreting	MRI	left posterior superior temporal gyrus, anterior supramarginal gyrus, planum temporale, right angular gyrus, right dorsal premotor cortex, right parietal lobule
He et al. [13]	11 student interpreters (male=3, female=8, M=25.73 years)	the neural activation patterns during sight translation tasks	fNIRS	the Broca's area, DLPFC, the prefrontal cortex, including the dorsolateral prefrontal cortex
Van de Putte et al. [27]	18 student interpreters (male=4, female=14, M=21.4 years)	the long-term cognitive and anatomical influence of simultaneous interpreting on the brain	fMRI	the left superior temporal gyrus, the right angular gyrus, the right cerebellum
Klein et al. [37]	16 professional interpreters (female=16, M=34.7 years) and 16 multilingual controls (female=16, M=34.3 years)	to test whether a domain-specific neural network activation pattern could be detected during rest state	EEG	Brodmann's areas, the left frontal cortex, the left inferior frontal region
Lin et al. [22]	10 bilinguals (male=4, female=6, M=24 years)	the neural mechanism of two translation strategies utilized in simultaneous interpreting, focusing on the involvement of the left prefrontal cortex	fNIRS	Broca's area, the left prefrontal cortex
Lin et al. [23]	10 bilinguals (male=4, female=6, M=24 years)	the small-world characteristics of functional brain networks during Chinese to English simultaneous interpreting	fNIRS	the left frontal region
Jost et al. [29]	15 bilinguals (male=5, female=10, (M=23.4 years)	the distinctions in spatial-temporal brain dynamics between a translation task and a control word-generation task, as well as the differences between forward and backward translation	EEG	spatial-temporal brain
Ren et al. [21]	11 student translators (male=3, female=8, M=25.73 years)	a novel phase analysis technique for the examination of fNIRS neuroimaging data related to sight translation	fNIRS	the left prefrontal cortex, including the dorsolateral prefrontal cortex and frontopolar area, the Broca's area
Dottori et al. [38]	17 professional interpreters (male=2, female=15, M=40.35 years) and 15 bilinguals (female=15, M=34.13 years)	the behavioral and electrophysiological indicators of word reading and translation in both native and non-native languages, in both directions		bilateral frontal and posterior region
Zheng et al. [8]	25 bilinguals (female=25, M=23.92 years)	the variations in functional connectivity between backward and forward translation	fMRI	the left anterior temporal lobe, left inferior frontal, left orbitofrontal, bilateral parietal clusters, the right thalamus

Table 1. *Cont.*

Authors(s)	Total Participants	Topic	Technology	Activated Brain Region
Shinozuka et al. [14]	43 bilinguals (male=23, female=20, M=20.81 years)	the neural activation patterns involved in oral translation and the influence of translation directions and word familiarity	fNIRS	the left prefrontal cortex around the Broca's area, the left temporal area including the superior temporal gyrus
He et al. [2]	16 student interpreters (male=2, female=14, M=25 years) and 16 bilinguals (male=4, female=12, M=23.88 years)	the interplay among directionality, text complexity and interpreting experience on brain activation	fNIRS	the right Broca's area and the left premotor and supplementary motor cortex; the superior temporal gyrus, the dorsolateral prefrontal cortex (DLPFC), the Broca's area, and visual area 3 in the right hemisphere
He and Hu, [9]	16 student interpreters (male=2, female=14, M=25 years) and 16 bilinguals (male=4, female=12, M=23.88 years)	the brain connectivity between forward and backward sight translation	fNIRS	the frontal and Wernicke's area,
Boos et al. [39]	40 student interpreters, 29 professional interpreters, and 39 bilinguals (male=26, female=82, M=34.57 years)	the subjective and objective workload parameters induced by different sub-processes of simultaneous interpretation	EEG	frontal region

4. Discussion

4.1. Translation Asymmetry

Studies in neuroimaging have been conducted to explore the neural mechanisms underlying the asymmetry effect in interpreting. Typically, it pertains to the imbalanced cognitive effort involved between forward and backward interpreting. However, early studies have yielded inconclusive results [3–5, 10, 11].

The primary focus of these studies was to investigate the manifestation of the asymmetry effect and identify the brain regions associated with the interpreting process. For instance, Through a PET study conducted by Klein et al. [4], it was discovered that both forward and backward translation were associated with significant neural activity in the inferior and dorsolateral frontal and prefrontal regions. Specifically, increased neural activity was detected in the left putamen, a region implicated in forward translation, when contrasted with backward translation. Similarly, in a study conducted by Rinne et al. [10], a parallel asymmetry effect was observed, with both forward and backward translation tasks exhibiting heightened activity in the left frontal lobe, involving the dorsolateral frontal cortex, compared to shadowing. Moreover, increased brain activity was observed in Broca's area, a region crucial for forward translation. Through an EEG study by Kurz et al. [3], an asymmetry effect was also demonstrated. They found that through interpreting tasks, greater brain activation existed in the left temporal cortex compared to the resting state, while the right hemisphere showed greater involvement in forward translation. More recent studies have provided additional insights. In an EEG study conducted by Jost et al. [29], it was deduced that translating from L1 to L2 entails heightened activation in brain regions linked to attention, arousal, and awareness. García et al. [6], in an study, concluded that distinct connectivity patterns were observed between the two translation directions. Specifically, forward translation showed increased connectivity in the bilateral fronto-temporal networks. According to the authors, this suggests that forward translation involves a greater exchange of information among brain areas associated with cognitive control mechanisms. On the other hand, backward translation demonstrated greater connectivity in the temporo-occipital networks, primarily in the right hemisphere. This indicates that backward translation relies more on the automatic integration of low-level information. These findings suggest that forward and backward translation engage distinct neural networks and cognitive processes, with forward translation involving enhanced information exchange among areas supporting cognitive control mechanisms. In an fNIRS study, He et al. [13] also observed the asymmetry effect during Mandarin/English sight translation tasks. Their findings revealed stronger brain activity in the Broca's area for the forward interpreting. The study suggested that the cognitive processing of the two kinds of language (English as a phonographic language vs Chinese as an ideographic language) may recruit different brain areas. Additionally, their findings unveiled the engagement of the prefrontal cortex, including the dorsolateral prefrontal cortex, during the sight translation process of the language pair. Later, they conducted another fNIRS study to investigate the interplay between translation asymmetry and expertise and found expertise modulates the asymmetry effect[2]. Among bilingual individuals with expertise in translation, the brain regions that exhibited activation encompassed the right Broca's area, as well as the left premotor and supplementary motor cortex. In contrast, for bilingual individuals without translation expertise, the activated brain areas encompassed the superior temporal gyrus, the dorsolateral prefrontal cortex, the Broca's area, and visual area 3 in the right hemisphere.

However, not all neuroimaging studies have revealed the translation asymmetry effect. Price et al.[5] and Quaresima et al.[11] did not find clear evidence of asymmetry using neuroimaging techniques. Up to this point, despite the growing neuroimaging evidence related to the process of translation and interpretation, there is still a lack of comprehensive neural evidence concerning specific distinctions between forward and backward translation.

4.2. The Interpreter Advantage

García[40] proposed the interpreter advantage hypothesis that extensive training and practice in interpreting improve various aspects of executive functions in bilingual individuals. García explains that the task of interpreting involves intricate processes that heavily rely on executive functions, which gradually adapt through continuous exposure to interpreting. Empirical studies have provided compelling evidence relating to the impact of interpreting expertise on executive functions during the interpreting process[40–42]. They suggest that expertise in interpreting leads to the following enhancements. Firstly, it improves the storage capacity of the phonological loop, as supported by Bajo et al.'s study[41], which found that articulatory suppression disrupted interpreting students more than professionals. Secondly, expertise appears to improve the ability to handle concurrent memory processing and storage. Professionals outperform other bilingual individuals in tasks where item encoding trials alternate with short sentence reading trials, as revealed in studies by Bajo et al.[43] and Yudes et al.[42]. Thirdly, expertise may enhance cognitive flexibility. According to the study conducted by Yudes et al.[42], professionals demonstrated enhanced cognitive flexibility compared to non-interpreter bilinguals.

Neuroimaging studies have demonstrated that expertise in interpreting influences brain activity during interpreting, as well as inducing physical changes in the brain (e.g.,[2, 7, 9, 17, 18, 27, 30, 31, 33, 34, 38]). Dottori et al.[38] argued that experience of interpreting results in explicit neural patterns across translation mechanisms. He et al.[2] also observed incongruent activation patterns between interpreters and non-interpreters. In addition to brain activation, studies on functional connectivity suggest different patterns. Becker et al.[18] found stronger connectivity between the following regions, including left frontal pole, left inferior frontal gyrus, and middle temporal gyrus in professional interpreters compared to multilingual controls. Elmer & Kühnis[7] detected heightened left-hemispheric theta phase synchronization and increased functional connectivity strength within the left dorsal pathway of simultaneous interpreters, suggesting a positive relationship with interpreting training and practice. More recently, He & Hu[9] found functional connectivity between the frontal and Wernicke's areas in interpreters during forward sight translation task, whereas the group of non-interpreter demonstrated functional connectivity between Broca's and the frontal cortex area during backward sight translation task. These findings suggest that expertise additionally influences functional connectivity, potentially due to distinct cognitive abilities associated with executive functions among different groups with expertise.

To provide a clearer understanding, brain plasticity resulting from extensive and prolonged training in simultaneous interpreting was examined in a longitudinal investigation by Hervais-Adelman et al.[17]. Their study revealed a diminished engagement of the right caudate nucleus during simultaneous interpretation as a direct outcome of the training. In another longitudinal study conducted by Van de Putte et al.[27], whole-brain fMRI analysis revealed increased engagement of the left superior temporal gyrus during the Simon task and compared to translators, after 9 months of simultaneous interpreting training, increased engagement of the right angular gyrus was observed in the color-shape switch task, despite no initial differences between the two groups.

Regarding the physical impact on the brain, Babcock[34] found that interpretation students exhibited reduced volume of gray matter in the bilateral hippocampal and left temporal regions, along with enhanced white matter integrity in the language connections, predominantly in the left hemisphere. Training-related effects were evident in both gray and white matter. Interpreting students exhibited a lesser decline in gray matter volume in the left temporal lobe as well as bilateral subcortical structures. Likewise, within the language tracts of the left hemisphere, interpreting students exhibited greater resistance to decreased white matter integrity. Hervais-Adelman et al.[33] also identified physical changes in the brain due to interpreting training. The observed enhancements in cortical thickness were specific to trainee interpreters and existed in regions involved in lower-level phonetic processing (anterior supramarginal gyrus, left posterior superior temporal gyrus, and planum temporale), advanced formulation of propositional speech (right angular gyrus), transformation of working memory items into a sequence (right dorsal premotor cortex), and domain-general executive control and attention (right parietal lobule). Yet despite of the results, the issue of how translation or interpreting expertise influences brain activity as well as causing structural modifications in the brain are far from well-understood and thus call for more attention from neuroscientific researchers.

4.3. The Cortical Brain Regions Involved

The neuroimaging studies have provided insights into the brain areas which are activated during interpreting tasks. Apart from the traditional language areas, such as Broca's area[2, 5, 9, 11, 13, 14, 20, 23] and Wernicke's area[3, 9, 14, 18, 28, 34], some other cortical brain areas have also been reported to be involved in interpreting. These include the prefrontal region[4, 10, 14, 15, 28, 35], the anterior cingulate cortex[5, 20], the superior temporal gyrus[2, 14, 19, 27], as well as the parietal lobe[8, 27, 32, 33, 43].

The prefrontal cortex plays a role in various cognitive processes, such as working memory, executive control, and decision-making, and has been found to be activated during language transfer tasks that require the selection and integration of relevant linguistic information[44, 45]. The anterior cingulate cortex is situated in the medial region of the frontal cortex. It is suggested to be involved in attention allocation[46], performance monitoring and error detection[47], and decision-making[48]. It is reported that the inferior parietal lobules are involved in the cognitive processes of mapping words with meaning[49], obtaining meaning from visually presented words[50], memory retrieval[51], and accessing content memories as well as episodic memories, before making inferences for the intentions from these memories[52]. It is suggested that the superior temporal gyrus involved in selective attention[53] and attention-related modulation of brain activation[54]. The activation of these cortical brain regions indicates interlingual brokering is cognitively highly complicated. It involves not only linguistic processing, but also such executive functions as monitoring and attention allocation.

It is interesting to be noted that there might be language-specificity in brain activities. The collected studies seem to suggest that different languages may recruit different brain regions. For instance, He et al.[2] conducted a study and found activation in right Broca's area during English-Chinese sight translation task. This seems to suggest a trend of right hemisphere engagement, along with the left hemisphere, during Chinese language processing. This echoes the previous claim that the processing of Chinese, which is an ancient ideographic language, has been indicated to involve different or additional brain regions as well as deeper processing depth[55, 56]. Overall, the findings suggest that language-specificity is a complex phenomenon which is affected by factors such as the linguistic structure of the languages being used, the proficiency level of the bilingual individual, and the task demands of the language transfer task. A lot more investigations are needed to provide a clearer picture of this issue.

5. Reflections on the Neurocognitive Route

Neuroimaging investigations are progressively elucidating the cognitive mechanisms underlying interpreting, offering insights into the "black box" of language transfer and comprehension. However, despite the advances in this research area, the field remains underexplored due to incongruences in findings and the tentative nature of conclusions drawn from studies with limited resources and experimental constraints. One major gap is the lack of understanding regarding whether there is a language-specific brain region involved in interpreting. Most studies have predominantly used phonographic languages, such as English, French, and German, as stimuli, while largely excluding ideographic languages like Chinese and Japanese. This exclusion has resulted in an incomplete understanding of the differences in brain activation between phonographic and ideographic languages. Previous studies have suggested that distinct brain regions are recruited when processing Chinese, as compared to phonographic languages [2, 9, 56]. Therefore, empirical investigations that address this gap are highly anticipated.

Moreover, future research should consider employing more advanced technologies to overcome the limitations of the tools previously used. EEG, while valued for its temporal resolution, is highly susceptible to disruptions caused by participant movement, and both (f)MRI and fNIRS are limited by their low temporal resolution. The integration of more cutting-edge technologies could yield more authentic data. For example, researchers in language processing have turned to magnetoencephalography (MEG) for enhanced data acquisition (e.g., Blanco-Elorrieta et al. [57]). Additionally, combining multiple neuroimaging techniques is recommended to provide converging evidence of neural activity, thereby strengthening the reliability of findings.

Despite the promise of neuroscience in the studies of interpreting, there are also challenges and limitations to consider, including reliability of the interpretation of the results, cost, ecological validity, and ethical concerns. To start with, the interpretation of neuroscientific results in interpreting research can be challenging. Though neuroscientific techniques can provide highly detailed and complex data, the findings are complex and multifaceted. The interpretation of the data requires careful consideration of multiple factors, including the experimental design, statistical analysis, and theoretical framework. Misinterpretation or overinterpretation of results can lead to incorrect or misleading conclusions. Thus, it is recommended to use multiple methods and approaches so as to ensure the validity and reliability of the findings. For example, researchers can combine neuroscientific technologies with traditional behavioral and linguistic approaches, to provide more convincing evidence for the research question. Next, the technologies can be expensive to use and require specialized expertise to operate. This can limit the accessibility of these techniques to researchers and language professionals who do not have access to the necessary resources. Thus, multilateral cooperation among neuroscientists, language experts and technology experts are urgently needed. Also, neuroscientific research often takes place in artificial laboratory settings, which may not accurately reflect the real-world conditions in which interpreting takes place. This can undermine the generalizability of the findings to real-world situations. Thus, the translation of neuroscientific findings to practical applications may require careful consideration of the context and constraints of the task. Careful experimental design and task selection are also needed to help to address this limitation. For example, researchers can use ecologically valid tasks that more closely resemble real-world language transfer tasks, or they can use a combination of behavioral and neuroimaging measures to assess performance. Moreover, the use of neuroscientific technologies raises ethical concerns around privacy, informed consent, and potential stigmatization of language professionals. Researchers must carefully consider these ethical issues and take steps to ensure that their studies are conducted in a responsible and ethical manner.

6. Conclusion

Neurocognitive investigations provide a window into the ‘black box’ of interpreters when fulfilling their interpreting tasks. To summarize the achievements in this line of research, this article reviews the published empirical neurocognitive studies on interpreting or its practitioners, discussing the major area of investigation, as well as the involved brain regions. Reviewing previous studies, it might suggest that forward and backward interpreting recruit different mode of brain activation and related training do contribute to neuroplasticity. Yet far more studies are needed to address the influence of social and cultural factors, individual variations and real-life situation on the validity of research findings.

Author Contributions

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The authors declare no conflict of interest.

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