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EVA GUTIERREZ SIGUT & CRISTINA BAUS

3. Lexical processing in comprehension and production – experimental perspectives

Eva Gutierrez-Sigut & Cristina Baus

1. Introduction

The study of sign language has received increasing interest in the last decades. As an example, in 2000, only 30 published articles included ‘sign language’ in their title or topic. In 2015, this number had increased to 285 articles. Within this growing field, research on sign language processing – including both comprehension and production – has also received a remarkable boost in recent years. This is to a large extent due to technical developments and the extensive use of various neuroimaging techniques to study commonalities and differences between speech and sign processing. The comparison of the behavioural and neural correlates of speech and sign processing has allowed us to identify the components of a modality independent language network. This finding, in turn, contributed – together with linguistic studies – to the acceptance of sign languages as natural languages and not mere pantomime. In the initial stages of research, efforts were concentrated on demonstrating universal aspects of language processing; thus, little attention was paid to the differences between modalities or to the specific aspects of the sign-modality. However, the wide recognition of sign languages as natural languages has supported a greater interest in furthering our understanding of modality specific factors (e.g., the use of proprioceptive and spatial information for phonological encoding or the greater potential for iconicity). This chapter offers a comprehensive overview of the most relevant studies of sign language comprehension and production that focus on the lexical level of processing. Our aim is to determine how similarities and differences between sign and speech processing are reflected in behavioural data and at the brain level. With this purpose in mind, we review the contributions of a large pool of studies, including those employing more classic offline methodologies (e.g., study of spontaneous errors) as well as recent studies using online tasks and neuroimaging techniques.

One major goal of studies of sign language processing has been to understand the psychological reality of signs and their formational parameters, as well as the biological basis of the linguistic constructs. For many years, much attention has been paid to the identification of modality independent mechanisms, taking advantage of the fact that sign languages provide unique insight into universal aspects of language processing. Researchers have investigated whether sign languages are sensitive to the same linguistic phenomena (e.g., lexicality, priming of formal features) and sustained by the same brain networks as the spoken modality. More recently, the study of modality specific aspects of sign comprehension and production has received increasing attention (e.g., iconicity, tighter relationships between form and meaning, etc.). In this chapter, we review the main behavioural and neuroimaging findings that contribute to our understanding of the lexical processing of signs from the perspectives of sign comprehension and sign production. We start by considering whether neural changes due to

sensory deprivation alone can account for sign language processing patterns found in the deaf. Next, we discuss how processing of signs differs from other kinds of non-linguistic movement and how it is similar to spoken language processing. We then address several lexical effects in comprehension and production (e.g., lexicality, lexical frequency, and semantic priming effects), as well as how properties of sublexical units – phonological parameters and syllables – affect the lexical access of signs. Finally, we consider how sign and speech processing are linked by examining studies that show cross-linguistic influences between types of languages.

By including brain-lesion and neuroimaging findings as well as behavioural results, we aim to offer a richer picture of lexical access to signs. While behavioural measures give a late measure of processing, neuroimaging techniques allow us to explore the brain substrates of sign comprehension and production. In this way, we are able to answer different but complementary questions. Electroencephalography (EEG) and magnetoencephalography (MEG) offer a very precise temporal resolution. These techniques have proved to be a useful resource to study how cognitive processes unfold over time and whether this is similar during word and sign processing. In contrast, positron emission tomography (PET), functional magnetic resonance imaging (fMRI) and to a certain degree functional near-infrared spectroscopy (fNIRS) offer a very good spatial resolution to compare the brain areas underlying sign and word processing between modalities.

Finally, the signing population is very diverse. The pursuit of a reduced variability among participants has led many studies to focus on a very small group of participants: deaf native signers. In addition to the study of deaf native signers, researchers have contrasted sign processing in various groups of signers. The use of this comparative approach has allowed us to explore the effects of a number of factors on lexical processing, depending on which characteristics are similar or different between groups. For instance, the comparison between native and late deaf signers has provided evidence of the impact of age of acquisition (AoA) in sign processing. Similarly, hearing signers (as a type of bimodal bilinguals) have offered a unique window into the nature of language co-activation in bilinguals. Throughout this chapter, we report findings of sign processing in various types of signers as well as similarities/differences between groups.

2. Deafness, plasticity, and the language network

One initial question in sign language processing is whether the findings – or which findings – are mainly a result of the sensory deprivation caused by deafness or, rather, are attributable to the linguistic aspects of signs. To address this question, researchers have studied the effects of cross-modal plasticity on language processing. Cross-modal plasticity refers to the cortical reorganization of deprived brain areas – auditory areas, in the case of deafness – for processing another sensory modality, e.g., the visual modality. In a MEG study, Leonard et al. (2012) compared brain activation in hearing non-signers and deaf signers triggered by spoken words and signs, respectively. Results showed modality specific early sensory processing (100 ms after stimulus onset), where the auditory cortex was involved in speech and visual brain areas

were involved in sign. However, the later lexico-semantic processing (300 to 500 ms after stimulus onset) lead to activation of left lateralized fronto-temporal areas (the language network) in both modalities, suggesting the existence of a modality independent language network. Similarly, Cardin et al. (2013) showed that plastic changes in the left temporal areas (e.g., left Superior Temporal Cortex, left STC) have a linguistic origin, while changes in their right counterpart (right STC) are tied to both linguistic processing and sensory deprivation. More recently, Cardin et al. (2016) furthered this finding by showing that during a low-level phoneme-monitoring task, signers and non-signers engage different sensorimotor neural networks for diverse phonological parameters of signs. However, signers perform linguistic processing of both handshape and location in the same brain areas. Taken together, these results indicate that the involvement of the language network during sign processing is not merely due to auditory deprivation and the cross-modal rewiring, but rather to sign language experience (see also Neville et al. (1997) and Newman et al. (2002)).

It is worth noting that lesion and neuroimaging studies have shown that sign language comprehension and production appear to rely on a left lateralized network that is strikingly similar to the language network involved in spoken language processing (Bellugi et al. 1988; Corina 1999; Corina et al. 1999; Damasio et al. 1986; MacSweeney et al. 2008a,b; Newman et al. 2015). However, although neural networks supporting speech and sign processing are very similar, there are specific requirements of the modality that should be taken into account (see e.g., Neville et al. (1998); Neville et al. (1997), for a similar conclusion in an ERP experiment). In addition to analogous activation in the classical left perisylvian areas for sign and speech, previous neuroimaging studies have identified the left parietal lobe as having a greater role in signed than spoken language processing (for a review see Corina et al. (2012); Emmorey et al. (2014); MacSweeney et al. 2008a,b).

In the following section, we first compare the effects found for sign language processing to those found for other types of body movements, and then detail modality independent and some modality specific aspects of sign processing.

3. Sign Processing

3.1. Signs vs. body movements and gestures

While the motoric and articulatory demands of sign and speech are dramatically different, signing shares articulators with other human movements, including different types of gestures (e.g., meaningless gestures such as scratching one's nose, co-speech gestures, emblems, complex pantomimes, etc.). As many body movements, lexical signs consist of precise movements of the face, torso, arms, and hands. However, unlike other types of motoric actions, signs make use of a structured set of handshapes, locations, and movements, as well as hand orientations and non-manual features. This raises the question of whether the effects observed are linguistic in nature or somehow influenced by processing of non-linguistic movements. To tackle this question, Gutierrez-Sigut, Daws et al. (2015) measured blood flow velocities to both

brain hemispheres in hearing native signers during both British Sign Language (BSL) and English production. Lateralization strength was compared to that of hearing non-signers repeating sign-like movements (non-linguistic). Results showed a stronger left lateralization for BSL than English production that could not be accounted for exclusively by the constant movement of the right hand, inherent to signing. This finding was also replicated with deaf native signers (Gutierrez-Sigut et al. 2016), who also showed stronger laterality indices for sign than for speech. This stronger lateralization was found in both covert and overt tasks and hence not due to motor movement alone. This result replicates previous findings that linguistic processing of signs is performed in a left lateralized network. Furthermore, it indicates that the increased left lateralization found may be driven by specific properties of sign production such as the increased use of self-monitoring mechanisms or the nature of the phonological encoding of signs.

The fact that signing is different from gesture and pantomime was documented early on by sign language researchers (see Klima & Bellugi 1979). For instance, lesion studies described cases of aphasia in deaf people with preserved meaningful gesture comprehension and production after a left frontotemporoparietal lesion (Corina et al. 1992; Marshall et al. 2004). More recent research has furthered our knowledge of how processing of signs differs from gesture processing (see Goldin-Meadow & Brentari (2015), for a review).

Comprehension of lexical signs and gestures may share some of the earliest perceptual processing mechanisms. In a series of behavioural studies, Corina and colleagues (Corina et al. 2011; Corina & Grosvald 2012) investigated the early stages of sign and human action processing. Reaction times were measured while deaf signers and hearing non-signers decided whether the actions displayed on the screen were a lexical sign or a gesture. Results showed that signers were better than non-signers at discriminating signs and actions. However, perceptual variations in the stimuli affected both groups similarly, suggesting the use of the same general perceptual systems to recognize signs and other human actions.

However, later stages of processing seem to engage different mechanisms. Grosvald et al. (2012) examined event related potential (ERP) responses to sentence-endings that could be non-linguistic gestures (e.g., scratching one's face), signs or pronounceable non-signs. Results showed that while linguistic endings modulated the amplitude of the N400 component (associated with semantic processing, see more details below), gestures elicited a longer lasting positivity that started in the same time window. Although more research is needed, electrophysiological evidence suggests the existence of an early filtering mechanism based on semantic properties (see, Grosvald et al. 2012) that allows us to discriminate linguistic items from gestures. ERP findings are also consistent with other neuroimaging studies that have found differences in brain activation for signs and gestures in deaf signers (Corina et al. 2007; Emmorey et al. 2010; MacSweeney et al. 2004; Newman et al. 2015). MacSweeney et al. (2004) found greater activation in the left posterior superior temporal sulcus and gyrus for sign language than Tic Tac (manual-brachial signalling code without phonological structure), extending into the supramarginal gyrus. This difference in activation was found in signers, but not in non-signers. In a recent study, Newman et al. (2015) found that the classic left hemisphere language areas were activated more strongly for American Sign Language (ASL) than for

meaningful gestures in native signers. Crucially, this activation was different from that of non-signers, who mostly engaged brain regions involved in human action perception for both ASL and gesture. To sum up, it seems clear that linguistic processing of signs – at the behavioural and brain levels – is different from that of other human movements with varying degrees of meaning. Nonetheless, it is also worth noting that the line between body movement and sign processing is not clear-cut. For instance, there seem to be differences between the way in which signers and speakers gesture (see e.g., Emmorey 2002). Additionally, it might be the case that sign language experience could facilitate a ‘language-like analysis of gestures’ (Newman et al. 2015).

3.2. A few notes about lexical access in comprehension and production

Lexical access refers to the process by which a word or sign representation is accessed from the mental lexicon, either to comprehend or to produce it. The main difference between word comprehension and production is the direction in which information flows through the different levels of processing. Broadly speaking, word recognition goes from the word form to phonological and semantic processing while word production goes in the opposite direction, from the concept to the utterance. Accordingly, phonological and semantic effects take place at different times. Note that lexical access is assumed to be a competitive process that is comparable in comprehension and production. However, differential effects often reflect the distinction between processing streams. For instance, while accessing the word *cat*, the activation of a similar concept (e.g., *dog*) would result in facilitation in the case of word recognition but in interference for a production task. These differential effects should be taken into account when comparing comprehension and production results.

3.3. Lexicality, lexical frequency, and semantic effects in sign comprehension

Recognition of signs is faster than recognition of spoken words. Gating studies in which participants see increasingly longer segments of a sign until they can identify it correctly have shown that signs are accurately recognized after seeing only 35% of the sign (Emmorey & Corina 1990). Spoken words, however, need approximately 83% of the word displayed before participants can accurately recognize them (Grosjean 1980). It has been proposed that sublexical features specific to signs – such as the large amount of form-based information available from the beginning of the sign and the highly constrained phonotactic structure – contribute to this faster identification of signs.

Despite this faster recognition times, the processing of signs shows remarkable similarities with speech processing when well-established lexical effects, such as lexicality, lexical frequency, and semantic priming, are considered. However, studies have also shown subtle differences in processing that might correspond to modality specific features (Gutierrez et al. 2012; Hosemann et al. 2013; Marshall et al. 2014). The lexicality effect is often measured

using a lexical decision task in which participants are instructed to answer whether the item displayed on the screen is a legitimate sign as accurately and fast as possible. Non-signs are constructed by varying one or more phonological parameters of a lexical sign. Depending on the nature of the study, the resulting non-sign could be a pronounceable sign form (i.e., a pseudo-sign) or an unpronounceable form. Therefore, non-signs lack a representation in the signer's lexicon. Signs, like words, are recognized faster and more accurately than non-signs, the so-called 'lexicality effect' (cf. Carreiras et al. 2008; Dye et al. 2016; Emmorey 1991; Emmorey & Corina 1993; Gutierrez & Carreiras 2009). Gutierrez & Carreiras (2009) found faster and more accurate responses to signs than non-signs during lexical decision-making and visual similarity judgment tasks (which do not require linguistic processing). These findings indicate that participants undergo an automatic linguistic processing of signs. Emmorey (1991) found that repetition priming does not facilitate recognition of non-signs, unlike the case of signs. Emmorey (1995) also showed that non-signs that are more similar to real signs take longer to reject. Electrophysiological responses to pronounceable non-signs are also parallel to those typically elicited by non-words. Specifically, an increased N400 (see details below) in centro-parietal electrode sites has been found for pronounceable non-signs when compared to signs in studies using single signs (Gutiérrez & Carreiras 2009) and sentences (Grosvald et al. 2012).

The 'frequency effect' refers to the finding that more frequent words are recognized faster and more accurately than less frequent ones. In spoken languages, frequency counts are based on corpora studies (e.g., Kucera & Francis 1967). More recently, technological developments have made the flourishing of databases for signs possible (Caselli et al. 2016; Fenlon et al. 2014; Gutierrez-Sigut et al. 2016; see Johnston (2012), for a review) which would facilitate the operationalization of relevant psycholinguistic parameters in the near future. However, this work is still taking its initial steps and normative frequency counts are not yet available for sign languages. Studies so far have used a subjective measure of familiarity, based on deaf signers' ratings of how familiar a sign is. Lexical familiarity is strongly correlated to lexical frequency in spoken languages (e.g., Balota et al. 2001; Gernsbacher 1984). Sign language studies have found robust familiarity effects; that is, familiar signs are recognized faster than less familiar signs (Carreiras et al. 2008; Emmorey & Corina 1993; Ferjan Ramirez et al. 2016; Mayberry & Witcher 2005).

Another well-established finding in spoken language is the 'semantic priming effect' (Meyer & Schvaneveldt 1971). In a typical priming experiment, participants are asked to perform a task on a target item that is preceded by several types of primes. The display time of the primes and the interval between the presentation of prime and target depend on the stage of processing under study (see Carreiras (2010) for a discussion of the possible influence of different stimulus onset asynchronies [SOAs] on sign processing). Typically, responses to a condition in which prime and target are unrelated are compared to an experimental condition in which prime and target hold some kind of relationship, in this case semantic. Differences in processing of one particular target in different conditions are attributed to the influence of the prime. In the case of semantic priming, activation of the prime is thought to result in the spread of activation to semantically related concepts. Hence, when a semantically related target is

displayed, it is more accessible than an unrelated target. There is abundant evidence for facilitatory semantic priming in speech processing (see e.g., Becker 1980; de Groot 1983; Meyer & Schvaneveldt 1971; Neely 1977). Behavioural studies of sign processing have shown that signs (e.g., *DOG*) are recognized faster when they are preceded by a semantically related sign (e.g., *CAT*) than by an unrelated prime (e.g., *PEN*; Bosworth & Emmorey 2010; Emmorey & Corina 1993; Gutierrez & Carreiras 2009; Mayberry & Witcher 2005).

Electrophysiological studies provide complementary evidence of the time course of semantic processing of signs. Most studies have focused on the N400 component, a negative shift in the ERP brainwave that peaks approximately 400 ms after stimulus onset and is larger over centro-parietal electrode sites. It has been widely demonstrated that the N400 is sensitive to semantic relatedness, both within prime-target pairs and in sentence contexts (Bentin et al. 1993; Holcomb & Neville 1990; Kutas & Hillyard 1980; Van Petten & Kutas 1990; Van Petten & Kutas 1991). A larger N400 amplitude for incongruent than for correct sentence endings has been observed for several sign languages (ASL: Capek et al. 2009; Grosvald et al. 2012; Neville et al. 1997; Spanish Sign Language (LSE): Gutierrez et al. 2012; German Sign Language (DGS): Hänel-Faulhaber et al. 2014; Hosemann et al. 2013). Taken together, these findings indicate that semantic processing is essentially modality independent. Results are consistent with other neuroimaging studies that highlight the similarities in the neural networks used for speech and sign processing (e.g., MacSweeney et al. 2008a,b). Still, there are subtle differences that suggest some representational differences in the composition of the sign lexicon. For example, several studies have found that the N400 to semantically incongruent signs had a later onset and peak than what is usually found for spoken languages (Capek et al. 2009; Grosvald et al. 2012; Neville et al. 1997). Some properties of signs, such as having more diverse recognition points and lengthier transition times might contribute to the explanation of these differences (Capek et al. 2009; Neville et al. 1997). A few studies have specifically investigated how the interplay between semantic and phonological properties affects the time course of sign recognition. Hosemann et al. (2013) found that handshape information accessible in the transition phase affects the onset of the N400 for semantically incongruent signs. Moreover, the interplay between semantic information and the sign's handshape further influences the timing of this effect. That is, when the handshape of the critical word classifies the subject according to semantic characteristics (e.g., action verbs such as JUMP or STAND) the effect on the brainwave is found earlier than when the handshape does not carry semantic information. Gutierrez et al. (2012) compared ERP responses to ASL sentences with a plausible ending (baseline) with four types of violations created by crossing factors of semantic and phonological (location) relatedness. The resulting critical signs were implausible (hence considered semantic violations) and could be semantically related and share the location of the baseline sign (+s, +p), semantically related but have a different location (+s, -p), or share the location but be semantically unrelated (-s, +p). Finally, the critical sign could be both semantically and phonologically unrelated (-s, -p). Results showed that all violations elicited an increase in N400 in the 450-600 ms post-stimulus onset time window, reflecting the difficulty of semantic integration with sentence context. Interestingly, those conditions that only shared either location or semantic properties (+s, -p and -s, +p) with the baseline sign elicited an earlier

effect (starting at 350 ms after stimulus onset). The existence of differential effects at these two time windows offer support for two different stages of sign processing, with lexical selection effects operating around 350 ms and semantic integration in the neighbourhood of 450 ms. Crucially, semantic and phonological features may interact at the level of lexical sign selection in different ways to those observed in spoken languages.

3.4. Sign production

It is commonly accepted that, from the intention to speak/sign to the final articulation, information flows through different and separate levels of processing (i.e., conceptual, lexical, and phonological; Caramazza 1997; Dell & O'Seaghdha 1991; Levelt et al. 1999). The finding of similar linguistic and psycholinguistic phenomena as well as neuroanatomical substrates in both modalities supports the claim that language production follows the same stages in the spoken and signed modalities.

One area where similarities in processing have been found is the so-called 'tip of the fingers' and 'tip of the tongue' effects (ToFs: Thompson et al. 2005; ToTs: Caramazza 1997). Both refer to the momentary inability to retrieve a known lexical item (Brown 1991). During a ToF state, analogously to ToT, ASL signers had access to semantic information but only partial access to the form of the intended sign (Thompson et al. 2005). This result supports a separation between semantic and phonological form during sign production.

Another piece of evidence in favour of the independence of levels of processing comes from the existence of 'slips of the tongue' – or Freudian slips – (cf. Fromkin 1973) and 'slips of the hand', both referring to the spontaneous errors occurring during verbal production. Importantly, errors are non-random and respect the phonotactic constraints and grammar rules of the language. For speech, vowels slip with vowels and consonants with consonants (e.g., 'It's a real mystery' by 'It's a meal mystery'), names with names, and verbs with verbs. In the signed modality, sign error corpora (ASL: Newkirk et al. 1980; DGS: Hohenberger et al. 2002) revealed the same patterns of errors, with the majority of errors involving the exchange of one phonological parameter (especially handshape) and only 1% of the errors involving an exchange of the entire sign. The existence of such errors supports the notion that phonology is an independent level and that phonological parameters constitute the fundamental units composing a sign.

Using fluency tasksⁱ in BSL, Marshall et al. (2014) studied deaf native signers' responses to semantic and phonological categories. They found a larger number of responses for semantic than for phonological tasks, a decline in response rate over time, and rich phonological and semantic clustering. These results parallel findings for spoken languages, suggesting a similar organization of the lexicon of spoken and signed languages. However, results also showed more frequent semantic clusters for handshape and location categories than what is usually found for spoken phonology. This finding indicates that lexical retrieval of signs is modulated by strong links between semantics and phonology. Taken together, these results offer partial support theories such as the 'semantic phonology' theory (Stokoe 1991), which

proposes that the phonological form of a sign is primarily derived from aspects of its meaning (also see iconicity section below) without discarding the idiosyncrasies of sign language processing.

The picture-sign interference paradigm is one of the most extensively used paradigms to explore language production processes. Studies using this paradigm have provided evidence that concepts are retrieved earlier than their corresponding signs, which, in turn, occurs before the corresponding phonemes are accessed. This points to a process equivalent to that proposed for spoken languages (Levelt et al. 1999). In this paradigm, a picture is presented (simultaneously or sequentially) with a distractor sign that can be semantically or phonologically related to the picture's corresponding name. Both the semantic interference and the phonological facilitation effects have been reported in the signed modality (e.g., Baus et al. 2008; see also Navarrete et al. (2015) for semantic effects in the cumulative semantic paradigm in both modalities). Corina & Knapp (2006) were the first to provide evidence of a different time course for semantic and phonological effects during signing. As is often found in spoken languages, phonological effects were presented in synchrony or after the picture (SOA 0 and +). However, authors only found semantic effects when semantically related words/signs preceded the picture. In a later study, in addition to replicating Corina and Knapp's (2006) results, Baus et al. (2008) found semantic effects at SOA 0.

More recent studies have started to explore whether other psycholinguistic variables known to have an effect in spoken language production, such as lexical frequency or neighbourhood density, also influence sign production. It is worth reiterating here that – as there is a lack of databases for psycholinguistic variables of signs – e.g., frequency values for these studies are taken either from a subjective measure of familiarity or from spoken language databases. We acknowledge that this approach is not ideal. Indeed Johnston (2012) recently questioned the use of subjective familiarity as a measure of sign frequency. From 83 signs explored in Australian Sign Language (Auslan), only 12% of high-familiarity signs appeared among the 300 signs of highest frequency in the Auslan Corpus. Consequently, an effort should be made to improve existing databases and create new ones. However, even using a crude estimate of lexical frequency, rather than null results, studies have found results consistent with the spoken language literature. That is, highly familiar (frequent) signs are produced faster and more accurately than less familiar signs (Baus & Costa 2015; Emmorey et al. 2012; Emmorey et al. 2013).

Electrophysiological data has also shown familiarity/frequency effects for signs, similar to those typically found for words. Specifically, Baus & Costa (2015) showed for the first time that low-familiarity signs elicited a larger positivity than high-familiarity signs in the P200 time-window. The P200 component refers to an early positivity indexing the ease with which lexical retrieval occurs, with more difficult to retrieve items showing larger positivities than easier items. Their results largely replicated findings for the spoken modality although the onset of the effect was later for signs than what has been previously described for speech (e.g., Strijkers et al. 2010). Finally, neuroimaging techniques have allowed us to identify the neural circuitry underlying sign production, showing similarities and some differences between modalities. Emmorey et al. (2007) used positron emission tomography (PET) to measure brain

activation for object naming in deaf native ASL signers and hearing English speakers. Strikingly, similar activation was observed in classical language areas for both modalities. Furthermore, there was greater activation in the left supramarginal gyrus and the superior parietal lobe for sign than speech production. These differences were linked to phonological encoding and proprioceptive monitoring. In a $H_2^{15}O$ -PET study, Braun et al. (2001) studied the spontaneous generation of narratives in ASL and spoken English, given by hearing native signers. They found greater activation in left superior parietal and paracentral areas for ASL, which was associated with the integration of somatosensory information. It is worth noting that both of these studies attempted to control for purely motoric effects by subtracting a baseline that required vocal or manual movements equivalent to those of speech and sign production. Although this approach is useful for investigating high-level linguistic processes, it does not allow for the study of lower-level modality dependent features of language production (for a discussion see Emmorey et al. (2014)). Emmorey et al. (2014) used $H_2^{15}O$ -PET data to directly contrast ASL and spoken English production during picture naming in hearing native signers, without removing low-level motoric effects. Sign production led to greater parietal activation than English, especially in the left hemisphere. This greater activation was attributed to somatosensory and proprioceptive feedback (anterior parietal activation), the voluntary production of motor movements (posterior parietal activation), and the sensorimotor integration necessary for phonological encoding of signs (inferior parietal activation).

In sum, although still scarce, studies of sign production have found that levels of sign processing are separate, and their time course is different. In addition, lexical access is sensitive to the lexical properties of signs, such as frequency and neighbourhood density. Neuropsychological studies have observed activation of the classical left lateralized language network. Interestingly, some extra parietal areas seem to be sensitive to the particular characteristics of the signed modality (see e.g., Emmorey et al. (2014) and Corina et al. (2003) for discussion of specific proprioceptive feedback and phonological encoding requirements of signs.) In Section 4, we will describe studies exploring the influence of sublexical variables (such as phonological parameters) in the processing of lexical signs, but first we will pay close attention to studies on iconicity.

3.5. Iconicity: The link between meaning and form

The relationship between the linguistic form of a word (e.g., speech-sound) and its meaning, whether arbitrary or iconic, has intrigued researchers for decades. Spoken language is primarily conceived as a system of arbitrary symbols. A priori, there is nothing in the sequence of sounds composing a given word – for example [Kæt] – that encloses information referring to its meaning that we have experience with – a ‘four-legged feline mammal’. It is worth noting, however, that spoken languages include a small repertoire of non-arbitrary form-meaning mappings that map directly onto our sensory, motor, or emotional experiences of the world, namely onomatopoeias (words that sound like their referents) or sound-symbolic mappings

(certain sounds are able to capture information about the form of an object; *kiki/bouba* effect: Ramachandran & Hubbard 2001).

In sign languages, the presence of non-arbitrariness or *iconicity* is much more evident (e.g., Mandel 1977; Pietrandrea 2002; Taub 2001). The visual-gestural modality, apart from regular arbitrary signs, favours a high degree of transparency between the form and its referent (see e.g., Klima & Bellugi (1979); and see Armstrong et al. (1995); Cuxac (2000), for a view that considers signs as essentially iconic). Therefore, there is space for a more direct mapping between the visual properties of our experiences and the phonology of signs. Consider for instance the sign SCISSORS in Catalan Sign Language (LSC); the handshape and movement of the index and middle fingers clearly resemble the action of cutting with scissors. This higher degree of iconicity found in signs offers a unique opportunity to explore the natural link between the form and its conceptual representation of lexical items. Indeed, within sign language, iconicity has generated substantial work trying to determine the linguistic relevance of this property.

It is widely assumed that iconicity aids lexical retrieval during sign language learning. Campbell et al. (1992) showed that after a brief exposure to signs, non-signers were able to correctly identify and recall iconic signs more than non-iconic signs (see also Baus et al. 2012; Lieberth & Gamble 1991; Ortega & Morgan 2015). Indeed, Thompson et al. (2012) recently suggested that iconicity plays a fundamental role in language development, both in signed and spoken languages. However, beyond language learning, results describing the impact of iconicity in sign language processing have been mixed (see Perniss et al. (2010), for a review). For sign comprehension, there is some evidence in favour of iconicity strengthening the links between meaning and form, aiding semantic processing but having the opposite effect when phonological processing is required (Linz 2003; Ormel et al. 2009; Thompson et al. 2009, 2010; but see Bosworth & Emmorey (2010)). Using a picture-sign matching task, Thompson et al. (2009) showed that deaf signers were faster when pictures (e.g., showing a BIRD which is signed by resembling the beak of a bird) highlighted the same iconic property than the sign (a beak) rather than another property (the wings; see also Linz 2003; Ormel et al. 2009; Vinson et al. 2015). However, the existence of an automatic activation of semantic features for iconic signs has been challenged by Bosworth & Emmorey (2010) who used a semantic priming task where iconic target signs (PIANO) could be preceded by an only semantically related prime (MUSIC), an iconic and semantically related prime (GUITAR) or an unrelated prime. Although there was a semantic priming effect, it was not modulated by iconicity. That is, MUSIC and GUITAR had the same effect over the target sign PIANO. Ortega & Morgan (2015) also failed to find an effect of iconicity in a cross-modal priming study. Using a phonological task ('decide whether a sign has one specific handshape'), Thompson et al. (2010) reported slower responses for iconic than non-iconic signs. Baus et al. (2014) observed a similar detrimental effect for bimodal bilinguals, who were slower translating iconic than non-iconic signs into English. Bosworth & Emmorey (2010) argued that the influence of iconicity on sign processing might be strongly affected by other variables related to the items (e.g., number of translations, neighbourhood density, AoA) or the task used.

The results from sign production – scarcer than those from comprehension – are also mixed regarding the role of iconicity. While iconicity does not seem to affect the rate of ToF or anomic states in aphasic patients (Marshall et al. 2014; Thompson et al. 2005), it increases the speed with which signs are retrieved from the lexicon (Baus & Costa 2015; Vinson et al. 2015). In a picture naming task, deaf signers (Vinson et al. 2015), as well as bimodal bilinguals (Baus & Costa 2015), were faster at signing pictures whose corresponding signs were iconic than non-iconic (see also Navarrete et al. 2017; Pretato et al. 2018). Additionally, in both cases, iconicity had a greater impact on signs that were more difficult to retrieve from the lexicon – namely low-frequency signs and later acquired signs – supporting the interaction between iconicity and other lexical properties of the signs, as suggested by Bosworth & Emmorey (2010). Interestingly, together with AoA effects, lexical frequency is often considered a relevant factor for phonological retrieval (e.g., Kittredge et al. 2008). Therefore, this interaction between lexical frequency and iconicity lends support to the existence of a link between meaning and form for iconic signs.

In addition to the behavioural results, Baus & Costa (2015) were the first to report data on the temporal course of iconicity for sign production. Importantly, ERP modulations associated to iconicity were present very early in the course of signing. Around 100 ms (N100), iconic signs elicited a larger negativity than non-iconic signs, indicating an early engagement of the conceptual system for iconic signs. Iconicity also modulated ERPs at a later time-window (400-600 ms; P300), in which phonological retrieval has been hypothesized (see Indefrey & Levelt (2004) for a meta-analysis on the chronometry of word production).

In sum, studies on iconicity in sign comprehension and production show that iconicity plays a modest role in sign processing. It is more apparent when lexical retrieval is more difficult (e.g., when non-signers are learning a sign language) and interacts with other psycholinguistic variables (e.g., lexical frequency, AoA). Future studies should be aware of these issues and seek information in lexical sign databases (e.g., Caselli et al. 2016; Gutierrez-Sigut et al. 2015).

4. Processing of lexical signs: sublexical units

4.1. Comprehension

It is generally accepted that, similarly to spoken language lexical access, signs are decomposed into smaller units which play a role in lexical access (although see Corina & Grosvald (2012) for a discussion of signers relying on the configuration of the articulators instead of decomposing the signs into parts). Lexical access to signs is considered a two-stage process comprised of sublexical and lexical levels (Caselli & Cohen-Goldberg 2014). Caselli & Cohen-Goldberg (2014) propose that, once factors specific to sign languages are accounted for, a single mechanism can be responsible for lexical access in both languages. Specifically, their computational model controls for the fact that various parameters seem to have distinct activation timings (locations seem to be activated earlier than handshapes) and that their

representation might have different strengths. That is, the representation of location seems to be more robust than that of handshapes due to a higher sublexical frequency, perceptual saliency, or amount of attention received.

A range of behavioural and neuroimaging studies provide evidence that people use signs' sublexical structure to organize their lexicon and achieve lexical access. Furthermore, studies have shown that signs' major phonological parameters (handshape, movement, and location) have a differential status. Although behavioural results are somewhat mixed regarding the direction of the effects, findings often support the idea that location has a prominent status in the early stages of sign processing. Studies investigating signers' working memory have found that participants remember signed stimuli according to their phonological structure. Klima & Bellugi (1989) found, that serial recall was poorer when the signs within a list shared phonological parameters than when they were unrelated. Likewise, signers seem to perform an internal monitoring of phonological parameters during signing (Wilson & Emmorey 1997, 1998). Categorical perception effects for handshape, but not for location (Baker et al., 2005; Emmorey et al. 2003) also suggest that signers use handshape as a sublexical unit during sign recognition. Gating studies have shown that location, especially of signs in the neutral space, is recognized first, followed by handshape and then movement (Emmorey & Corina 1990; Grosjean 1980). Orfanidou et al. (2009) found that location and handshape play different roles during BSL sign recognition. Authors studied misperceptions during a sign-spotting task in which participants spotted signs embedded in nonsense contexts. The smallest number of errors occurred with respect to location, followed by handshape. Using the priming paradigm, Corina & Emmorey (1993) investigated lexical access in ASL during a lexical decision task. Results showed inhibitory priming when targets and primes shared location and facilitation effects for movement overlap. No effects were found when pairs shared handshape. In a later priming study, Corina & Hildebrandt (2002) used a longer interval between the presentation of the prime and target and did not find significant differences, thus not replicating previous findings. The use of a shorter interval, similar to the one used in the original study, led to a non-significant inhibitory trend for both location and movement. These results replicate the original effect for location but not for movement. Carreiras et al. (2008) found that both location and handshape affected recognition in LSE signs in different ways. In a lexical decision task over single signs, responses to less familiar signs were faster for cases with frequent—compared to infrequent—handshapes. On the other hand, the pattern of results for location was the opposite. That is, inhibition was found for signs containing frequent locations. In addition, results from a form-priming experiment showed that the facilitatory priming effect of handshape affects non-signs while the inhibitory effect of location affects only signs (Carreiras et al. 2008). A few behavioural studies have assessed the overlapping effects of multiple parameters on lexical access. Corina & Hildebrandt (2002) used a similarity judgment task in which participants were asked to decide which of four non-signs was more similar to a given target sign. They found that non-signs sharing location and movement with the target were judged as more similar than those sharing location and handshape or handshape and movement. Similarly, Dye & Shih (2006) reported data from native users of BSL that showed evidence of facilitatory phonological priming for signs that shared both location and movement with a previously presented sign. No

effects were found in this study for other combinations of parameters or for single parameter overlap. In a similar priming study in LSE, Gutiérrez & Carreiras (2009) found no effects for location and movement overlap, but facilitation for movement and handshape and inhibition for location and handshape overlap. These findings suggest that phonological overlap of more than one parameter may influence processing in different ways (see Meade et al. (2017) for a recent discussion). However, further research is needed to understand the complex interactions at play. Finally, Mayberry & Witcher (2005) compared reaction times to target signs preceded by unrelated signs to those preceded by phonological minimal pairs, without explicitly studying the different combinations of parameter overlap. Results showed differences in the use of phonological information during lexical access depending on the age at which sign language was acquired (AoA). Specifically, early signers had a facilitatory effect of phonological overlap, while late signers showed the opposite pattern. There was no effect for native signers. These findings suggest a more automatic processing of signs for early learners than for late learners, whose lexical decisions might be based on more strategic processes. Gutiérrez et al. (2012) used ERPs to investigate the influence and time course of handshape and location overlap during a lexical decision task in native and late signers. Findings indicate that the two parameters under study play different roles in the process of lexical access. While location overlap resulted in a higher amplitude N400 (300-500 ms window) for both groups of signers, handshape overlap showed a later effect (600-800 ms) that was restricted to non-sign targets and native signers. These results suggest that location-driven lexical competition occurs early on in sign recognition. The effects of handshape occur later and are weaker. Differences in the strength of brain responses to both parameters suggest that handshape is influenced more by factors such as age of acquisition of the sign language, maybe reflecting less efficient processing by late signers. Interestingly, Cardin et al. (2016) found differences in the processing of handshape and location at the perceptual but not the linguistic level. In an fMRI phoneme monitoring study, handshape and location engaged the linguistic network similarly but not the perceptual one.

Lesion studies of signers have shown severe comprehension difficulties as well as paraphasic signing – signing with phonological errors – after lesions that involved Wernicke’s area and the left SMG (see e.g., Chiarello et al. 1982; Corina et al. 1992; Poizner et al. 1987). This suggests that sign language comprehension may be more dependent on left-hemisphere parietal areas, such as the SMG (Supramarginal gyrus), than speech. In an fMRI experiment investigating rhyme judgement, MacSweeney et al. (2008a,b) reported activation of a similar left lateralized neural network for both English and BSL. Participants were presented two pictures and decided whether the corresponding signs shared location or whether the English words rhymed. Brain activation for both languages was strikingly similar, but not identical. The left parietal lobe was more strongly activated for the BSL than for the English task. A growing number of studies have identified the left parietal lobe as having a greater role in signed than spoken language processing (for a review see Corina & Knapp (2006); Corina et al. (2013); MacSweeney et al. (2008a,b)). This suggests that phonological encoding of signs might entail the recruitment of a more general system of actions’ observation and production (Corina & Knapp, 2006, Corina & Gutiérrez 2016). In a recent study, Corina & Gutiérrez (2016) found that sign recognition might rely on the signer’s internal body representation, especially when

processing conditions are not optimal (e.g., having learned ASL later in life.)

Altogether, these results show that signers engage in phonological decoding during lexical access in a similar way to spoken language users, using a strikingly similar left lateralized brain network. However, we should not assume that language processing is identical for signed and spoken languages. Specific features of signing can shape lexical access in ways that are unique to signing. Differences in the direction and timing of the effects for each of the parameters, in the use of phonological information depending on AoA, and involvement of additional left parietal brain areas during sign comprehension should be taken into account. Remarkably, parietal areas involved in sign comprehension are also active during sign production, which can lead us to consider the notion that these areas are in charge of the action/motion aspects of signs rather than the linguistic and more abstract ones.

4.2. Production

As mentioned above, sign error corpora and picture-naming paradigms have allowed to determine that semantic and phonological levels of processing are separate in sign languages. In addition, those studies have provided evidence in favor of a lexical organization according to the phonological properties of signs. As for comprehension, most of the evidence favors the idea that phonological parameters constitute separate units in the lexicon that do not play the same role during sign production. For instance, slips of the hand studies report an uneven distribution of errors (Klima & Bellugi 1979), with more errors involving handshape than location or movement (see also Hohenberger et al. 2002). Additionally, during ToF states (Thompson et al. 2005), despite the momentary inability to retrieve a sign, signers had partial access to its phonological form, mostly concerning handshape and location. Similarly, phonological parameters differed in retrieval accessibility in the fluency task (Marshall et al. 2014). Specifically, movement was less readily retrieved than handshape and location. Furthermore, there were richer semantic clusters for the location and handshape tasks than those found for spoken languages.

Picture-sign interference tasks have also been employed to explore the role of handshape, location, and movement, during phonological encoding in sign production, although the results are somewhat mixed. Baus et al. (2008) presented deaf signers pictures superimposed with sign distractors that could be phonologically related (on one parameter) or unrelated. The phonological facilitation effect reported in the spoken modality was uniquely observed for sign production when the target picture and the distractor shared the handshape. In contrast, movement did not influence signing and location showed an interference pattern: Signs sharing location with the distractor-sign were produced slower than signs in the unrelated condition. This pattern of results clearly replicates those reported in sign comprehension (e.g., Carreiras et al. 2008), although the origin of the effects remains unclear. One possibility for the observed interference effect might be that location is semantically mediated. There is evidence of semantic families sharing the same location (e.g., signs referring to feelings tend to be located close to the heart; Cates et al. (2013)), which might modulate the observed effects. However,

more research is needed to fully characterize the relationship between phonological parameters and meaning, as it is not yet clear how this modulation might occur. One must acknowledge that, using the same picture-sign interference paradigm, Corina & Knapp (2006) did not observe any effects when one phonological parameter was manipulated. Interestingly, they only observed a facilitatory effect for the combination of two parameters: location and movement. When pictures and distractor-signs shared these two parameters, signing latencies were reduced compared to the unrelated condition (see also Baus et al. (2014) for the same result when two-phonological parameters were manipulated). These results replicate those reported in comprehension (Carreiras et al. 2008; Dye & Shih 2006). Altogether, findings support the phonological privilege of the combination of location and movement, both in comprehension and production (e.g., Sandler 1987, 1989; but see Chinchor 1978; Wilbur 1993). We do not expand more on the syllabic explanation here as Chapters XX provide a more detailed theoretical description.

Lesion and neuroimaging studies of sign production have shown, in addition to activation of left perisylvian language areas, a greater involvement of the left parietal lobe in signed than spoken language production. This parietal activation has been linked to phonological encoding and proprioceptive monitoring in sign production. Studies of aphasic signers have documented phonological paraphasias and substitution errors involving handshape, location, and movement separately (Corina et al. 1992; Poizner et al. 1987). While location is often preserved, handshape seems to be the most affected parameter. Corina et al. (1999) tested name generation and repetition of ASL signs and non-signs during cortical stimulation in a deaf signer that was undergoing brain surgery. Electric stimulation of the left Broca's area and SMG resulted in phonological errors. Global phonetic reductions (lax fist and rubbing movement in the correct location) were observed after stimulation of Broca's area, while SMG stimulation led to errors in the selection of specific phonological parameters (e.g., substitution of the correct handshape for a pronounceable handshape), especially in handshapes. Interestingly, stimulation of SMG resulted in errors that the authors attribute to a disruption of integration of semantic and phonological information.

In sum, despite phonological encoding proceeding similarly in the spoken and signed modalities, the role that minimal units – i.e., phonological parameters – play during comprehension and production seem to be modality specific. Mixed results regarding the influence of handshape, location, and movement call for further studies to understand better the reality is of phonological units during sign processing.

5. Cross-linguistic influences on sign language processing

5.1. Bimodal bilingualism

On the topic of bilingualism, it is widely assumed that bilinguals' two languages are active when reading (Dijkstra 2005), listening (Marian & Spivey 2003), and speaking (Kroll et al. 2006). Indeed, the current dominant view is that bilingual language processing implies a

constant interaction between languages (at all levels of processing) even when lexicalizations are restricted to one language. Accordingly, during language processing, words in the language in use are active, as well as their translations. That is, when a Spanish-English bilingual is presented with the word ‘table’, its translation ‘mesa’ becomes automatically activated (hereafter, we refer to bilinguals with two spoken languages as unimodal bilinguals). This impossibility to turn off one language has generated substantial work trying to address questions such: how do bilinguals’ two languages interact at different levels of processing, how are the two languages organized in the brain, what are the linguistic and cognitive consequences of bilingualism, and how is all this modulated by the age in which the second language is acquired and the level of proficiency attained.

In the recent years, there has been a growing interest in studying processing in bimodal bilinguals (see Abutalebi & Clahsen (2016); Emmorey et al. (2016); Thompson & Gutiérrez-Sigut (2019) for reviews). Bimodal bilinguals are those people who employ two languages in two different modalities, namely spoken and signed. Note that the term frequently refers to hearing people born from deaf parents (children of deaf adults: CODAs), but hearing signers that learn sign language late (M2L2 bilinguals; Pichler & Koulidobrova 2015) and deaf signers that acquire a written second language have also been considered bimodal bilinguals (e.g., Morford et al. 2011). Importantly, the management of two sensory-motor systems confers bimodal bilingualism as a unique window to explore the nature of language co-activation and control mechanisms, as well as their brain organization.

Different studies have demonstrated that cross-linguistic activation is an automatic and unconscious process for bimodal bilinguals. As for speech (see Thierry & Wu 2007), evidence for parallel activation comes mainly from bilinguals being sensitive to properties of the language not in use. Morford et al. (2011) showed an activation of the first language (ASL) during second language processing (written English). In an implicit priming experiment, deaf signers saw written English word-pairs and decided whether the pairs were semantically related (*heart-brain*) or not (*paper-cheese*). Importantly, translations into ASL of some of these word-pairs were phonologically related. Signers were faster to accept semantically related words when phonologically related in ASL than when phonologically unrelated. In contrast, they were slower to reject semantically unrelated words when word-pair ASL translations were phonologically related (see also Kubus et al. 2014; Ormel et al. 2012). Recently, Villameriel et al. (2016), who tested hearing signers, extended these results by showing that cross-language interactions are bidirectional and the non-dominant language (L2 sign language) becomes active during processing in the dominant language (L1 spoken language). In addition, bimodal co-activation was observed regardless of the age at which sign language was acquired, suggesting that bilinguals’ co-activation is a pervasive phenomenon (see also Giezen & Emmorey 2015; Marian & Shook 2012; but see Williams & Newman (2016) for limitations of cross-language activation).

Neuroimaging studies have shown that sign language experience seems to influence the functional brain network of the first language (Zou et al. 2012a). Bimodal bilinguals and monolinguals’ brain activation was compared while performing a picture-naming task in L1 (Chinese). While the recruited brain areas were very similar for both groups, bimodal bilinguals

showed a greater engagement of the right supra-marginal gyrus (SMG), the right superior temporal gyrus (STG), and the superior occipital gyrus (SOG). This was interpreted as enhanced non-linguistic visuospatial abilities after experience with a sign language (see also Zou et al. (2012b) for structural brain changes after sign exposure).

Another type of evidence supporting the existence of cross-language activation in bimodal bilinguals comes from the ability of bimodal bilinguals to simultaneously speak and sign, producing ‘code-blends’ at a very little cost (Casey & Emmorey 2009; Emmorey et al. 2012). This ability of bimodal bilinguals is a unique opportunity to test language control mechanisms and the cognitive consequences associated to their constant use. The impossibility of unimodal bilinguals to speak both languages at the same time requires language control mechanisms that restrict lexicalization to the intended language while avoiding interference from the language not in use (Green 1998). Given that bimodal bilinguals are free of this articulatory restriction, the question is whether they apply similar control mechanisms. The relationship between language control mechanisms and general executive control functions has been tested in bimodal bilinguals in several ways. First, studies have explored whether language switching between modalities engages the frontal brain areas linked to control (e.g., dorsolateral prefrontal cortex, anterior cingulate cortex; see Thompson & Gutiérrez-Sigut (2019) for a recent review). Kovelman et al. (2009) used functional near infrared spectroscopy (fNIRS) to compare brain activity of bimodal bilinguals during naming in two linguistic contexts: a monolingual context (lexicalizations restricted to one language) and bilingual context (sign and speech used simultaneously or in rapid succession). Data showed a larger engagement of the language network for both bilingual contexts than for the monolingual context. However, the lack of extra engagement of frontal areas was interpreted as suggesting that bimodal bilinguals do not need to solve motor-articulatory competition as unimodal bilinguals do (although see Dias et al. (2017) for a different account).

Second, researchers have investigated the bilingual ‘cognitive advantage’ – the observation that bilinguals suffer less interference than monolinguals in non-linguistic tasks that require ignoring irrelevant stimuli (e.g., Simon task). The origin of such advantage has been placed in the constant engagement of control mechanisms during bilingual production to avoid interference from the not-in-use language, enhancing cognitive control (Bialystok 2001). Emmorey et al. (2008) tested whether the cognitive advantage extended to bimodal bilinguals by comparing bimodal and unimodal bilinguals with monolinguals in a task requiring executive control. Their results revealed a cognitive advantage for unimodal but not bimodal bilinguals, over monolinguals. This suggests that the bilingual cognitive advantage arises from the experience of controlling two languages of the same modality. Giezen et al. (2015) also failed to find a cognitive advantage for bimodal bilinguals when compared to monolinguals. However, their results showed a correlation between the linguistic and non-linguistic performance and control mechanisms involved in controlling competing lexical entries only for bimodal bilinguals, suggesting a partial overlap between language and more general cognitive control mechanisms.

Thus, while previous results consistently show that both languages of bimodal bilinguals are active during production and comprehension, results are mixed on whether bimodal

bilingualism entails the same language control mechanisms as unimodal bilinguals and whether they are similar to those engaged in more general executive functions. It is important to note, however, that more evidence is needed to determine whether control mechanisms are modulated by the output modality of the two languages. This is especially the case with evidence from the ‘cognitive advantage’, as such phenomenon seems to be more elusive than previously thought in the unimodal bilingual literature. Thus, the lack of ‘cognitive advantage’ might result from other issues (e.g., language use) rather than the modality itself.

6. Conclusion

To sum up, there are striking similarities between spoken and signed language processing. Results from behavioural studies, as well as evidence of similar neural substrates underlying speech and sign processing, have led to the widely accepted assumption that universal language processing principles can explain lexical access in both signed and spoken languages. However, although psycholinguistic and cognitive mechanisms as well as neural networks underlying speech and sign processing are very similar, they are not identical. We propose that the study of the differences in processing of speech and signs can lead to a more complete picture of human language processing. Acknowledging these differences can also point researchers to factors influencing spoken language processing that might have been under-researched so far (e.g., study of sound symbolism).

ⁱ In a fluency task, participants are asked to generate as many items from a semantic (e.g., animals) or a phonological category (e.g., letter A, I-handshape) for a given amount of time (usually 1 minute).

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