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The Role of Multiple Articulatory Channels of Sign-Supported Speech Revealed by Visual Processing

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Abstract

Purpose: The use of sign-supported speech (SSS) in the education of deaf students has been recently discussed in relation to its usefulness with deaf children using cochlear implants. To clarify the benefits of SSS for comprehension, 2 eye-tracking experiments aimed to detect the extent to which signs are actively processed in this mode of communication.

Method: Participants were 36 deaf adolescents, including cochlear implant users and native deaf signers. Experiment 1 attempted to shift observers' foveal attention to the linguistic source in SSS from which most information is extracted, lip movements or signs, by magnifying the face area, thus modifying lip movements perceptual accessibility (magnified condition), and by constraining the visual field to either the face or the sign through a moving window paradigm (gaze contingent condition). Experiment 2 aimed to explore the reliance on signs in SSS, by occasionally producing a mismatch between sign and speech. Participants were required to concentrate upon the orally transmitted message.

Results: In Experiment 1, analyses revealed a greater number of fixations toward the signs and a reduction in accuracy in the gaze contingent condition across all participants. Fixations towards signs were also increased in the magnified condition. In Experiment 2, results indicated less accuracy in the mismatching condition across all participants. Participants looked more at the sign when it was inconsistent with speech.

Conclusions: All participants, even those with residual hearing, rely on signs when attending SSS, either peripherally or through overt attention, depending on the perceptual conditions.

Keywords: sign-supported speech, eye tracking, cochlear implant users, native deaf signers, peripheral vision.

Introduction

Sign-Supported Speech and Bilingual Approaches in the Education of Deaf Children

Sign-supported speech (SSS), also known as simultaneous communication or SIMCOM, is a communicative approach commonly used in the education of deaf children as an alternative or complementary option to oral communication (OC). SSS involves the use of speech accompanied by signs and fingerspelling of the indigenous sign language. It is different from code-blending, which is the natural communication used by bimodal bilinguals who have acquired both a spoken and a signed language. Whereas in SSS, the syntax always follows the spoken language and requires continuous simultaneous use of lexicon from both spoken and sign language, natural code-blend is less structured, with either spoken or sign language used as matrix, and providing the syntactic structure of the sentence (Emmorey, Giezen, & Gollan, 2015). There is evidence that the combined use of signs and oral language enhances comprehension in code-blending. Emmorey, Petrich, and Gollan (2012) found that bimodal bilinguals were faster in making semantic categorisation decisions in a code-blend than in spoken or sign language alone. Similarly, the redundant information provided by SSS might help deaf individuals by enhancing comprehension. SSS has recently been reported to help children to acquire new vocabulary (van Berkel-van Hoof, Hermans, Knoors, & Verhoeven, 2016) and to improve verbal fluency in cochlear implant users (CIs) (Jiménez, Pino, & Herruzo, 2009). Also children mainly trained in oral language, such as those wearing cochlear implants from an early age, might benefit from the use of SSS instead of oral language alone (Giezen, Baker, & Escudero, 2014; Giezen, 2011; Knoors & Marschark, 2012). In particular, SSS has been shown to improve speech recognition and comprehension for adults with CIs in noisy contexts (Blom, Marschark, & Machmer, 2016).

The impact of sign language exposure on the development of spoken language in children with cochlear implants has been largely debated. A recent study (Geers, Mitchell, Warner-Czyz, Wang, & Eisenberg, 2017) has raised substantial concerns about the efficacy of early exposure to sign language (American Sign Language) or signing systems, besides spoken language, before and immediately after cochlear implantation. Results from a large sample of ninety-seven children did not reveal lasting advantages in the use of signs. In late elementary grades, children who used signs were delayed in spoken language and reading with respect to children only trained in spoken language However, this study did not differentiate among children exposed to a sign language or to a signing system; it included children that were exposed to various amount of sign language, total communication/SSS, signed English, sign support or pidgin sign. Similarly, a recent systematic review on early intervention showed that the evidence in favour or against the use of bilingual approaches or total communication/SSS is still very limited (Fitzpatrick et al., 2016),

The role of sign language on language and cognition.

Unlike for signing systems, positive evidence has been consistently reported for the role of sign language on the development of linguistic and cognitive skills. In a discussion on the linguistic and communicative choices that hearing parents of deaf infants face, Mellon et al. (2015) indicated that American Sign Language overall entails more benefits than risks. This is the case even despite the fact that hearing parents can rarely offer their children an intact grammatical model of sign language.

The benefits of a proper sign language model from birth is especially demonstrated by studies on deaf children with cochlear implants born from deaf parents. These children, exposed to an intact and fluent model of sign language, either American (Davidson, Lillo-Martin, & Pichler, 2014), Spanish (Mastrantuono, Saldaña, & Rodríguez-Ortiz, 2017) or Italian (Rinaldi & Caselli, 2014), develop age-appropriate spoken language skills..

The exposure to an intact model of sign language from birth also benefits the development of executive functions, as tested for French Sign Language (Courtin, 2000) and American Sign Language (Dye & Hauser, 2014; Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017b; Schick, de Villiers, de Villiers, & Hoffmeister, 2007). However, some skills, such as implicit learning, have been found to be age-appropriate in American deaf children, regardless of whether they grew up in a spoken or signed context (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2017a)

Visual Processing of Sign-Supported Speech and Sign Language

Most studies have analysed the final impact of the use of SSS on spoken vocabulary acquisition (Giezen et al., 2014; van Berkel-van Hoof et al., 2016) or performance on a comprehension task (Mastrantuono, Saldaña, & Rodríguez-Ortiz, 2018), but have not explored the processing of signs and their role during comprehension assisted by SSS. An exception is an eye-tracking study by De Filippo and Lansing (2006) aimed at analysing whether participants' eye movements related to the source of critical information while perceiving a message with SSS. In this study, stimulus sentences were presented in SSS with no sound. Sentences contained critical contrasts that could be disambiguated by speech — when two words were signed the same way but appeared distinct through lipreading— or by sign —when two words were homophonous, with same lip movements, but were signed differently —. Participants, who were adults with early onset deafness, were highly accurate, even when the signs carried the critical information to disambiguate the sentence meaning. Another study, exploring the role of iconic gestures instead of signs in a sample of hearing individuals, highlighted the positive effects of the simultaneous exposure to lip movements and iconic gestures, compared to the exposure to lip movements only, when the auditory input is degraded (Drijvers & Özyürek, 2017).

Interestingly, in the study of De Filippo and Lansing, high accuracy was found even though participants were looking at the faces of the sign model, rather than at the hands, more than 80 % of the time. This result was not surprising in view of the findings of the literature on sign language. Studies in that field indicate that deaf observers mainly foveate the face area. Deaf perceivers, both cochlear implant users and native signers, have been observed to look at the face more than 95% of the time when attending sign language (Spanish Sign Language), as well as when attending spoken language and SSS (Mastrantuono et al., 2017). More specifically, in sign language deaf observers are likely to watch the eyes area of the interlocutor during live interactions, as observed for American Sign Language (Emmorey, Thompson, & Colvin, 2009), and the mouth area if watching the sign model on a monitor, as observed for British Sign Language (Agrafiotis, Canagarajah, Bull, & Dye, 2003; Muir & Richardson, 2002). This might be in part due to the smaller size of the sign model on a monitor compared to live interactions: the reduced visibility of mouth patterns might drive deaf individuals to foveate the mouth area, where perceivers can obtain critical information even in sign languages. In fact, almost all sign languages present a significant amount of mouthing, consisting in mouth patterns associated to signs and time locked to the signs' manual component articulation (Braem & Sutton-Spence, 2001; Sutton-Spence, 2007). Mouthing was estimated to accompany 69% of signs of British Sign Language (Sutton-Spence, 2007) and 64% of signs of Spanish Sign Language stories used in a recent study (Mastrantuono et al., 2017). It is assumed that sign perception while looking at the face area involves covert attention. The locus of fixation does not necessarily correspond to the locus of attention, as we can shift attention to stimuli into the peripheral area of vision without moving the eyes (Posner, 1980). When the attended and the fixated object do not coincide, attention is said to be covert, oriented towards peripherally perceived objects (Gullberg & Holmqvist, 1999). Peripheral vision is hypothesised to be especially successful in perceiving large moving targets (Swisher, Christie, & Miller, 1989): signs would be perceptually easier to recognise than fine-grained information available through lip movements. Since peripheral vision might be better in discerning motion than form, the extent of motion and size of the hands would be more easily perceivable than lip movements (Anstis, 1986). In addition, and possibly by virtue of the primacy of the visual channel for communicating, peripheral vision is greatly enhanced in deaf observers (Bavelier, Dye, & Hauser, 2006). Even if there is a broad consensus in the opinion that deaf people do not see any better than hearing individuals due to their hearing loss, it has been argued that there is a spatial redistribution of attention in deaf individuals (Dye & Bavelier, 2013). Confirming this hypothesis, a number of studies, either concerning visual attention (Bosworth & Dobkins, 2002; Colmenero, Catena, Fuentes, & Ramos, 2004; Dye, Hauser, & Bavelier, 2009; Parasnis & Samar, 1985) or reading tasks (Bélanger & Rayner, 2015; Bélanger, Slattery, Mayberry, & Rayner, 2012), have provided evidence for a better developed peripheral vision in deaf than in hearing observers.

De Filippo and Lansing (2006) suggested that their participants might have been primarily fixating the face, even when signs disambiguated the sentences, adopting the strategy to foveate on the face and perceive signs through peripheral vision. They found that adjusted fixation duration was overall shorter when directed towards critical sign trials rather than when directed towards critical speech trials. Given that foveal fixation duration is linked to processing speed (Rayner, 1998), De Filippo and Lansing suggested that the face and lip movements occurring in a smaller space of the display, with densely packed fine-grained information, required longer foveal fixation for encoding. Conversely, perceiving the more gross movements of larger-sized hands represented an easier perceptual task and required shorted fixation duration. Besides the perceptual hypothesis, De Filippo and Lansing also speculated on the role of experience in SSS in influencing aspects of fixation patterns, with more experienced users of SSS producing shorter and more frequent fixations than less experienced users. With regards to the role of signing expertise in influencing the gaze direction towards the face or the hands, an eye tracking study on British Sign Language (Agrafiotis et al., 2003) found that native signers spent less time foveating the signs than beginning signers, suggesting that native experience in sign language makes it easier to obtain information from signs by using isolated and anticipatory cues. In this respect, De Filippo and Lansing found inconsistent visual patterns, with more experienced deaf users of SSS fixating towards the signs to a larger extent than less experienced deaf and hearing users. The authors attributed the somewhat higher extent to which deaf signers looked towards the hands in comparison to Agrafiotis and colleagues to the critical role of signs in their experiment in disambiguating the sentence message. Overall, results from eye behaviour and sentence comprehension in SSS in De Filippo and Lansing confirmed eye tracking data from British and American Sign Language studies (Agrafiotis et al., 2003; Emmorey et al., 2009; Muir & Richardson, 2005) according to which covert attention would be involved in sign perception. Nevertheless, the role of signing expertise in modelling gaze patterns towards a major or minor foveal attention to the signs in SSS should be further investigated, given the inconsistent findings in the distribution of gaze fixations of expert SSS users (De Filippo & Lansing, 2006) and sign-language signers (Agrafiotis et al., 2003).

A further issue which might deserve to be further explored is the perception of SSS by deaf individuals with any residual or restored hearing, when speech, besides lip movements and signs, is available. De Filippo and Lansing (2006) eliminated sound input to ensure that their participants could only be visually informed by lip movements or signs. Their results, therefore, are not informative of how SSS is perceived and used when all information channels —lip movements, speech, and signs— are available.

The Current Study

Visual studies on deaf observers provided evidence of a strong tendency of deaf individuals to look at the face when perceiving sign language (American Sign Language) (Emmorey et al., 2009) and SSS (De Filippo & Lansing, 2006; Mastrantuono et al., 2017). In the case of sign language, since they are the primary source of information, it is obvious that individuals are not ignoring sings but perceiving them peripherally. However, this is not so obvious in the case of SSS, where individuals have a dual source of information available. It might be that deaf observers obtain incoming information from the oral message and largely ignore sign information. Alternatively, they might process signs of SSS using peripheral vision, especially in the case of native signers. Our main research question is if deaf individuals –in particular those with functional hearing who can fully use all sources of SSS, visual and auditory–perceive signs in SSS through peripheral vision and integrate the information they convey with spoken information.

Differently than De Filippo and Lansing (2006) our goal was to analyse if peripheral vision is regularly used to retrieve information from the signs in SSS, even when sound is available. This situation is closer to real communication contexts in which SSS is used.

We manipulated two aspects of language processing: first, we explored whether peripheral vision was potentially being used in SSS, by manipulating normal video conditions to drive observers' foveal attention to either lip movements or signs (Experiment 1). Second, we further explored this possibility by focusing on the linguistic content of the message: we designed a task in which the meaning of speech and sign occasionally mismatched and explored the extent to which deaf participants relied on sign information (Experiment 2). Given that for the current study all subjects participated in both Experiment 1 and Experiment 2, participants' information, their cognitive skills, and the details of the apparatus used for testing are jointly described.

General Method

Participants

Thirty-six Spanish profoundly deaf adolescents (from a total initial pool of 49) aged between 12 and 19 years, participated in both experiments. The sample included 16 females (mean age = 15.2, *SD* = 2.3) and 20 males (mean age = 14.7, *SD* = 1.8), with no specific disorders associated to deafness. We recruited deaf adolescents for two main reasons. Firstly, participants with cochlear implants underwent the cochlear implant intervention before the age of 5, so by the time of the study they were long-term cochlear implant users. Secondly, most previous studies testing the effectiveness of SSS have mainly involved a population of young children or of college students, while, to our knowledge, there is a gap in research in evaluating the effects of SSS in a growing population of deaf children with early CIs. Thirteen participants (of the original 49), who had moderate and severe hearing loss and wore hearing aids, were excluded because they did not fulfil the criterion for level of hearing loss. These individuals did not fit easily into any of the experimental groups necessary to test our hypotheses (see below): they did not have significantly restored hearing, but at the same time did not make extensive use of signs or SSS due to their residual hearing and were not native signers either. Participants' characteristics are summarised in Table 1. Participants were clustered as follows: 1) 13 users of unilateral cochlear implants (CI group); 2) 11 native users of Spanish Sign Language (LSE group); 3) 12 control deaf individuals without cochlear implants and non-native users of sign language (CD group).Within the CI group, eight participants had a significantly restored hearing, with a hearing loss below 30dB (for privacy reasons or lack of clinical tests, we did not have access to the audiometric data after implantation of the remaining five participants with CIs). Within the CD group, there was a high variability in the use of the residual hearing: only 6 of the participants of the CD group wore hearing aids on a regular basis, with consequent different outcomes in the optimisation and the use of the residual hearing. Finally, the LSE group included native signers exposed to sign language from birth, with deaf parents. None of them wore hearing aids on a regular basis and none of them wore cochlear implants.

Table 1. *Participants' deafness-related characteristics.*

Group	Participant	Age	Stimulation	Age of implantation	Family first language	Degree of hearing loss diagnosis	Age of hearing loss
CI group	1	18.7	CI	5	Spanish	P	Birth
	2	12.6	CI	2	Spanish	P	Birth
	3	13.1	CI	3	Spanish	P	Birth
	4	13.4	CI	3	Spanish	P	Birth
	5	12.9	CI	2.2	Spanish	P	Birth
	6	13.3	CI	5	Spanish	P	Birth
	7	13.1	CI	2.8	Spanish	P	Birth
	8	13.4	CI	2.6	Spanish	P	Birth
	9	13.8	CI	1.8	Spanish	P	Birth
	10	15.5	CI	2	Spanish	P	Birth
	11	15.3	CI	2.5	Spanish	P	Birth
	12	14.2	CI	3	Spanish	P	Birth
	13	17.3	CI	2	Spanish	P	Birth
LSE group	14	14.6	None		LSE	P	Birth
	15	13.6	None		LSE	P	Birth
	16	14.2	None		LSE	P	Birth
	17	14.3	None		LSE	P	Birth
	18	15.5	HA		LSE	P	Birth
	19	13.6	None		LSE	P	Birth
	20	19.7	None		LSE	P	Birth
	21	16.9	HA		LSE	P	Birth
	22	12.2	None		LSE	P	Birth
	23	13.6	None		LSE	P	Birth
	24	13.7	HA		LSE	P	Birth
CD group	25	15.6	HA		Spanish	P	Prelingual
	26	16	HA		Spanish	P	Birth
	27	15.4	None		Spanish	P	Birth
	28	19.0	None		Spanish	P	Birth
	29	13.9	None		Spanish	P	Birth
	30	14.6	HA		Spanish	P	Birth
	31	12.6	HA		Spanish	P	Birth
	32	13.4	HA		Spanish	P	Birth
	33	17.9	HA		Spanish	P	Birth
	34	16.6	None		Spanish	P	Birth
	35	18.5	None		Spanish	P	Birth
	36	13.9	HA		Spanish	P	Birth

Note. Ages are in years. CI = cochlear implant; P = profound deafness; LSE = Spanish Sign Language; HA = hearing aid; CD = control deaf.

The CD group served as comparison group to measure the performance of the CI group and the LSE group. Previous research has frequently found that cochlear implant users perform better than profoundly deaf age-matched participants with hearing aids when tested on spoken language comprehension and spoken language skills (Dettman & Dowell, 2010; Leigh, Dettman, Dowell, & Sarant, 2011; Spencer, Marschark, & Spencer, 2011; Spencer, Tye-Murray, & Tomblin, 1998; Yoshinaga-Itano, Baca, & Sedey, 2010), or reading skills (Vermeulen, van Bon, Schreuder, Knoors, & Snik, 2007). With respect to SSS, research has especially highlighted the possible benefits of its use in increasing comprehension in CI users (Blom & Marschark, 2015; Blom et al., 2016; Giezen et al., 2014; van Berkel-van Hoof et al., 2016). The redundancy provided by the simultaneous spoken and signed linguistic inputs in SSS would ensure a continuous information input. Our assumption, by comparing the CI group with the CD group, was that, thanks to restored hearing, participants of the CI group might fully take advantage of the multichannel linguistic input of SSS (audition, lipreading and signs), to a higher extent than their peers of the CD group who used hearing aids.

On the other hand, the CD group also served as comparison group for assessing the performance of the native signers of the LSE group. A main interest in this comparison concerned the gaze behaviour, as it might vary on the basis of native experience in sign language (Agrafiotis et al., 2003; De Filippo & Lansing, 2006; Mastrantuono et al., 2017).

Criteria of inclusion to the study were, in addition to profound deafness, a minimum nonverbal IQ of 70 and a basic proficiency in Spanish Sign Language (LSE). Participants' elementary LSE competence, self-reported by participants' parents in a questionnaire aimed to collect information about linguistic background, was also assessed with a non-standardised task developed by Rodríguez-Ortiz (2005a, 2005b). This measure was not included in the analyses as linguistic predictor of visual behaviour or comprehension, as it only aimed to ascertain the familiarity of participants with LSE and did not intend to differentiate them on

LSE proficiency. Also, receptive sign language skills have not been found to significantly predict comprehension in SSS, suggesting that a high level of sign language proficiency is not necessary for cochlear implant users to benefit from the signs of SSS (Blom et al., 2016). None of our participants had regularly used SSS as an augmentative system at school. All participants had normal or corrected-to-normal vision. They all were from monolingual Spanish families. Participants with cochlear implants had mostly used sign language and SSS in classroom contexts with native deaf signer peers, and by attending coenrolment high-schools. These schools typically adopt a bilingual approach, and sign language is shared by all students, hearing and deaf (Martin, Balanzategui, & Morgan, 2014). Although for the current study we recruited participants with CIs exposed to sign language, outside of the specific educational contexts of coenrolment, the education of children with CIs commonly focuses on oral communication (Rodríguez Ortiz, 2005a, 2005b). We used well-established tests to evaluate a set of cognitive and linguistic skills: lipreading skills (Utley, 1946, adapted in Spanish by Manrique & Huarte, 2002), nonverbal IQ (Raven, Court, & Raven, 1995), nonverbal receptive vocabulary (Dunn, Dunn, & Arribas, 2006) and working memory (Robinson & Fuller, 2004). (see "Background skills" Supplemental Material S2 for the description of the tests used). A summary of test results can be found in Table 2. Independent-samples t-tests were conducted to compare the scores in cognitive and linguistic skills across groups. Significant differences with large effect sizes were captured between CI and LSE groups in lipreading, $t(22) = 2.49$, $p < .05$, $d = 1.00$, and in nonverbal IQ, $t(22) = -3.32$, $p < .01$, d = 1.43. The higher proficiency of participants of the CI group in lipreading was consistent with earlier findings, which revealed that lipreading improves over time after implantation (Tyler et al., 1997). In nonverbal IQ, participants of the LSE group scored significantly higher than participants of the CI group. In this latter group, the lowest scores in nonverbal IQ, between 80 and 85, corresponded to the two participants that received the CI at the latest age of 5 years. However, they were not excluded from the analysis because their scores were less than two standard deviations below the mean in their group. Spoken receptive vocabulary size was excluded from the analyses because of the lack of variance across participants: only 5 participants out of 36 performed higher than the minimum score on Peabody Picture Vocabulary Test norms for normal hearing chronological age-matched individuals. Vocabulary comprehension is consistently below average in children with CI who typically score to one half to three fourths of their age-matched peers (Connor, Hieber, Arts, & Zwolan, 2000; Fagan & Pisoni, 2010; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2000). The scores achieved by participants of this study were notably low, although the items were presented not only orally but also in the written form. Nevertheless, we found no specific indicators that might suggest that these participants were not representative of the larger population of Spanish adolescent CI users. School staff and parents did not report any specific disorders associated to hearing loss or difficulties in learning. In addition, participants were from different schools in different areas of Spain (usually 2-3 participants with CIs were from the same school).

Procedure and Apparatus

We recruited participants by contacting mainstream high-schools with co-enrolment teaching and special education schools for deaf students. Participants were tested in a quiet room of their school, after consent was obtained from their parents or guardians. Participants' parents were asked to complete a questionnaire concerning family socioeconomic status, participant's deafness, linguistic background, and educational and speech therapy history and treatment. Ethical approval was obtained from the Andalusian Committee for Biomedical Research, with research ethical standards in compliance with Declaration of Helsinki principles.

In both experiments, stimuli were presented on an 18.5-inch monitor connected to a

ASUS monitor at a refresh rate of 60Hz. Eye movements were tracked by using an EyeLink 1000 with a head-chin rest system (SR Research, Ontario, Canada), which ensured a viewing distance of 60-70 cm. The eye tracker presented a desktop setting, which supported monocular eye tracking. A 35 mm lens was used and the sampling rate for recording was 1000Hz.

Table 2. *Total scores on spoken receptive vocabulary, nonverbal intelligence, lipreading and working memory (WM).*

Group	Spoken receptive vocabulary size	Nonverbal IQ score	Lipreading Z score	WM Z score
CI (n = 13)	59.08 (12.25)	95.41 (11.11)	.41 (1.13)	-.04 (.99)
LSE (n = 11)	58.18 (7.56)	109.09 (7.65)	-.50 (.61)	.28 (.37)[2]
CD (n = 12)	55 (0.0)	103.55 (8.29)	-.14 (.74)[1]	-.12 (.72)

Note. Mean scores in the background skills (standard deviations are in parentheses). Spoken receptive vocabulary was measured by Spanish Peabody Picture Vocabulary test (Dunn, Dunn, & Arribas, 2006); nonverbal intelligence was measured by Raven's Standard Progressive Matrices test (Raven, Court, & Raven, 1995); lipreading was measure by Utley test (Utley, 1946, published in Spanish language by Manrique & Huarte, 2002) and WM was measured by a 3back level task (Robinson & Fuller, 2004). For each participant, Z scores of lipreading and WM were computed with respect to the total sample (36 participants). CI = cochlear implant; LSE = Spanish Sign Language; CD = control deaf.
(1) Outlier lipreading scores for one subject of the CD group were removed.
(2) Outlier WM scores for one subject of the LSE group were removed.

Experiment 1

Experiment 1 focused on visual behaviour during SSS to confirm if signs are being actively perceived using peripheral vision. To do so, we attempted to orient observers' foveal attention to either lip movements or signs, by presenting video-clips in which visual conditions were manipulated. As discussed in the introduction, it has been found that during

SSS perception (De Filippo & Lansing, 2006), as well as during oral and signed communication (Agrafiotis et al., 2003; Emmorey et al., 2009; Mastrantuono et al., 2017; Muir & Richardson, 2002), there is a strong preference of deaf observers for looking at the face area. In particular, they mostly look at the mouth area when the sign model is shown on a monitor (Agrafiotis et al., 2003; Muir & Richardson, 2002). This could be because the information people extract from the lip movements is more complex and, at the same time, lip movements occur in a very restricted visual area. To compensate the effect of the size of the perceived area for signs and lips, we magnified the lip area (compared to the chest area). We named this condition the *magnified* condition.

The next visual manipulation also aimed to test the hypothesis that signs in SSS are peripherally perceived (Agrafiotis et al., 2003; Emmorey et al., 2009; Muir & Richardson, 2002). We constrained the visual field to either the face or the sign by using a moving-window paradigm, thus effectively blocking out the possibility of using peripheral information. The distribution of fixations originated by the visual field manipulation should provide information concerning the default main articulatory channel (lip movements vs. sign). We named this visual condition *gaze contingent*.

Participants' gaze behaviour while attending to video-recorded sentences in such manipulated visual conditions was compared to gaze behaviour when perceiving sentences in the normal visual condition, named *baseline*.

Overall, participants with CIs might be more likely to successfully resort to the auditory stimulus than the CD group. The use of the auditory stimulus is then supposed to differently affect visual language perception in each group.

We expected participants with CIs to behave differently in the two manipulated conditions. The magnified condition could not significantly affect the gaze behaviour of the CI users, compared to the baseline. In spite of the greater accessibility of lip movements that might allow participants to perceive them even peripherally, fixating more frequently at signs, CI users might obtain satisfying comprehension by virtue of the auditory input, thus not modifying their usual gaze patterns and eventually gaining additionally information from signs via peripheral visual perception. In the gaze contingent condition, where signs and face have normal proportions but the moving window does not allow to visualise them together, overall participants are more likely to look at signs more often than in the baseline, looking for confirmation of the auditory information. This effect will be more marked for poorer lipreaders.

Participants of the CD group, with less restored audition, are assumed to be more dependent than the CI group on visual inputs. This difference across groups might especially emerge when considering lipreading skills: poorer lipreaders of the CD group might fixate more frequently on the signs, more markedly in the manipulated conditions, compared to participants of the CI group, who can resort to a higher extent to the auditory resources.

In the group of native LSE signers, we predicted more fixations towards the signing area in both visual manipulations compared to baseline. In the magnified condition, the larger size of the face area might draw attentional resources, at the expense of the peripheral attention. Consequently, native LSE signers should find it easier to get information by fixating directly the signs. In the gaze contingent condition, native LSE signers should mainly look towards the signing area, given the scarcity of information that they could obtain from hearing residuals and lipreading (in which they had lower scores than other groups of participants, especially the CI group). Consistently with previous findings (Agrafiotis et al., 2003), we expected that the LSE group would look at the face to a higher extent than the CD group in the baseline condition, perceiving signs via peripheral vision. In the manipulated conditions, both groups would look at the signs with a higher frequency than in the baseline.

With regards to comprehension, all participants might show poorer accuracy and longer sentence processing times in the manipulated conditions, due to limited input from only one articulatory channel, or to the lack of familiarity with the modified proportions between the face and sign areas. In addition, some differences among groups were hypothesized. We expected that participants with CIs would achieve higher accuracy than those in the CD group across all conditions, because of their better restored audition that would allow them to reinforce the visual input, either referred to lip movements or signs, with the auditory one.

Method.

Material and design.

A set of 42 subject-verb-object sentences, communicated in SSS by a male signer, were video-recorded in a professional recording studio. The sign model was a non-native LSE user who had completed professional training for LSE interpreters. The signs used in the SSS stimuli were verified through the online sign language dictionary *www.spreadthesign.com/es/* and supervised by a LSE native signer. The signs accompanying speech only conveyed content words, primarily nouns and verbs, with no signs conveying functional words, and with sign information syntactically empty. Signs in SSS were only intended to provide participants with a richer lexical input. The sign model appeared in the video from the hips upwards and the video-clips were presented in three different conditions: baseline, gaze contingent and magnified condition. Each condition consisted of 14 trials, including 2 practice trials. Sentences shown in the normal condition in the first list appeared in the gaze contingent condition in the second list and in the magnified condition in the third list. Sentences in the same condition were presented as a block. The order of appearance of conditions and, within each condition, the order of appearance of sentences, were randomized.

The video-clips in each of the conditions had the following characteristics (see Figure

1):

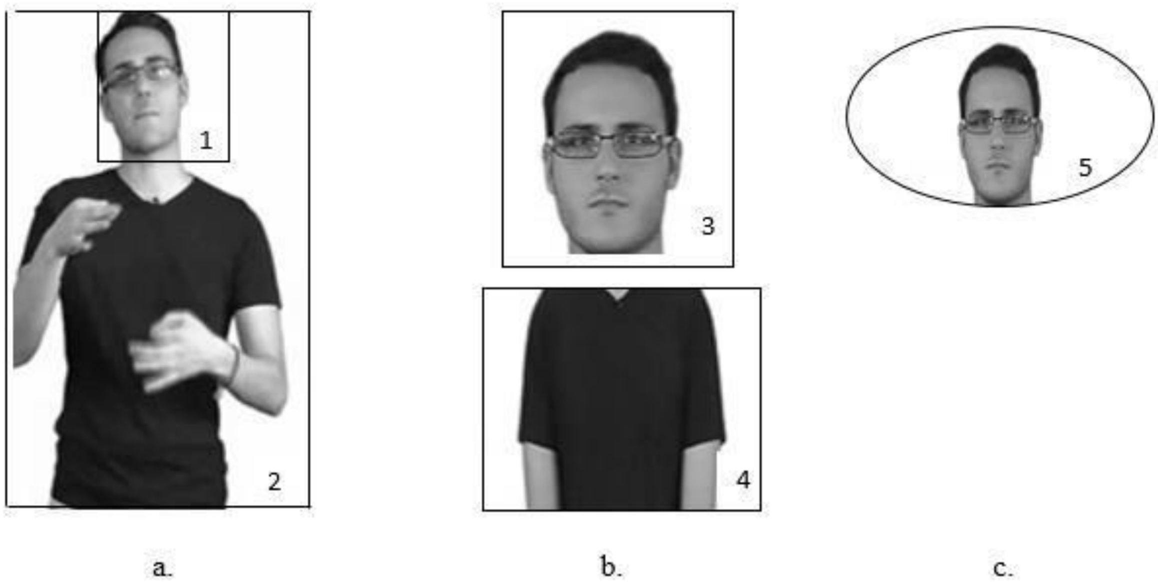
1) Baseline condition: there were not alterations in the visual display. The image was 900 pixels in width and 1200 pixels in height, with a corresponding visual angle of 21º and 39º. Observers' visual angle from the mouth to the chest area, in which most signs fell, varied approximately between 7.5º and 16.5º (peripheral vision is beyond 5º).

2) Magnified condition: this condition had two separate images in the display screen. The image above showed the face and the image below the chest of the signer. Both images had a resolution of 330 pixels in width and 320 pixels in height, corresponding to a visual angle of approximately 8º and 11º; the face had approximately the same size as the chest. Observers' visual angle from the mouth area to the chest image, where signs were performed, varied approximately between 7º and 12º.

3) Gaze contingent condition: this condition was implemented through a mask-flipping technique using boundary triggers. The resulting moving window was 400 pixels in width and 200 pixels in height (a visual angle of 9.5º and 7º) against the background image, which was the same as in the baseline condition (a visual angle of 21º and 39º).

The experiment was programmed in Experiment Builder (EB; SR Research, Ontario, Canada).

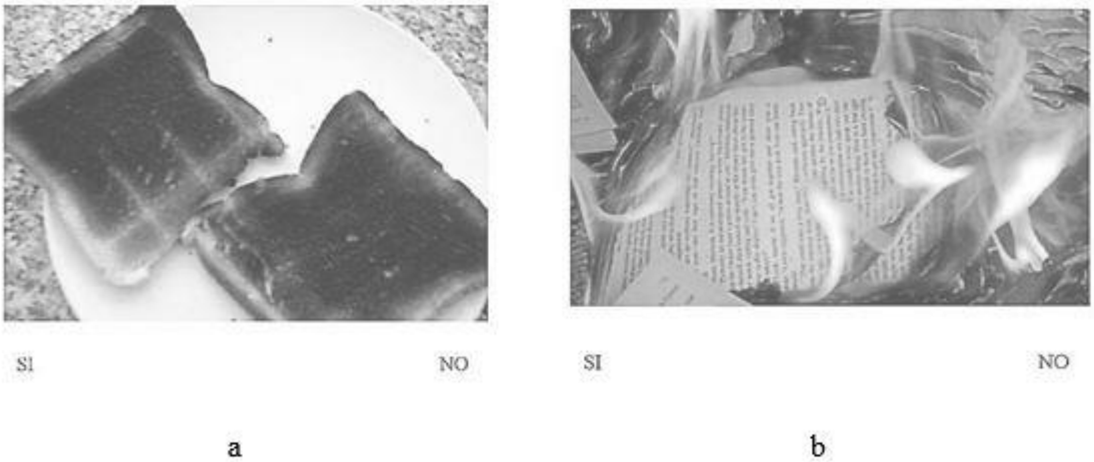
Figure 1. Visual conditions implemented in the experiment: (a) baseline condition, (b) magnified condition, and (c) gaze contingent condition. Stimuli size/proportions are not in scale. Areas of interest (AoI): 1. Face AoI in normal condition; 2. Signing AoI in the baseline condition; 3. Face AoI in the magnified condition; 4. Signing AoI in the magnified condition; 5. Moving window AoI in the gaze contingent condition.



***Procedure*.**

To allow participants to adapt their visual perception to the modified display conditions, each sentence was introduced by the introductory expression: "presta atención a esto" ('pay attention to this'). After watching each video, a picture appeared on the display screen and participants had to decide whether the picture was consistent with the sentence by pressing *yes* or *no* keys on a keyboard. After participants responded, the next trial started. Six lists of the experiment were created, and the examiner randomly administered one of them to each participant. Sentences followed by the correct picture in the first three lists, were followed by the incorrect picture in the other lists and vice-versa. For example, the experimental sentence "la mujer ha quemado el libro" ('The woman burnt the book') was followed either by the incorrect or the correct picture, respectively picture "a" or "b" in Figure 2. The incorrect picture was inconsistent with the sentence in only one element, either the subject, the verb, or the object of the sentence: in this example, the inconsistency concerns the object of the sentence; *some bread* was burning instead of *a book*. The set of stimuli is reported in Appendix A. In the example, the signs in SSS correspond to the nouns "WOMAN" and "BOOK" and to the verb "BURN".

Figure 2. Example of yes/no task referring to the experimental sentence "The woman burnt the bread." (a) Correct picture. (b) Incorrect picture.



Analyses.

Eye movements.

The eye movement data were processed with SR Research Data Viewer software (SR research, Ontario, Canada). Fixations with duration shorter than 80 ms were removed prior to further analysis. Two static areas of interest (AoIs), corresponding to the signer's face and the signing space, were created[1]. In the baseline and gaze contingent condition the AoIs used for

[1] In this study, we were primarily interested in the role of signs of SSS in transmitting information and, to this aim, we focused on the contrast between face and signing AoIs. Relevant findings might also be found from the contrast between eyes and mouth AoIs (Letourneau & Mitchell, 2011; Watanabe, Matsuda, Nishioka, & Namatame, 2011).
Additional analyses from our data revealed two main findings:

1. Native signers of the LSE group typically looked at the mouth region more than the eyes in the gaze contingent condition (79.73%) than in the baseline (69,86%), $\beta = .42$, $SE = .14$, $Z = 2.98$, $p < .01$.
2. Data of participants with functional hearing (CI and CD groups) showed that lipreading differently predicted the gaze behaviour across the baseline and the gaze contingent condition, with more expert lipreaders who looked towards the mouth to a higher extent in the gaze contingent condition than in

the analysis presented the same size, while in the magnified condition, the AoI for the face was bigger to cover the entire face stimulus (see Figure 1). Fixations were recorded from the sentence onset (+ 200 ms) to the sentence offset. We removed eye movements that occurred during the introductory sentence (*M* = 2,064 ms, *SD* = 296 ms). For the statistical analyses we compared the distribution of fixations between the two target AoIs: face vs. sign. Fixations of the actual sentence were analysed with a multinomial logistic mixed model. All logistic analyses were performed in R, version 3.2.3 (R Developmental Core Team, 2015), via a Generalised Linear Mixed Effects Regression (GLMER), with items and participants as random factors and visual conditions, groups, and lipreading as fixed factors. Analyses were run by using the lmer function from lme4 package for R which provided reliable algorithms for parameter estimation. Following Barr, Levy, Scheepers, and Tily (2013), we dealt with non-converging mixed-effect models by a stepwise simplification of random effects structure until convergence was reached. For GLMER models, regression coefficient estimates (β), standard errors (*SE*), *Z*- and *p*- values are reported. Tables including fixed effects of GLMER analyses are reported in Supplemental Material S1 “Fixed effects” file.

The main research question, if deaf individuals attend signs in SSS while fixating the face, was approached focusing on differences between conditions and between groups. Participant groups were predicted to show different gaze patterns following their access to auditory input (CI vs CD groups) and the native knowledge of sign language (LSE vs CD groups).

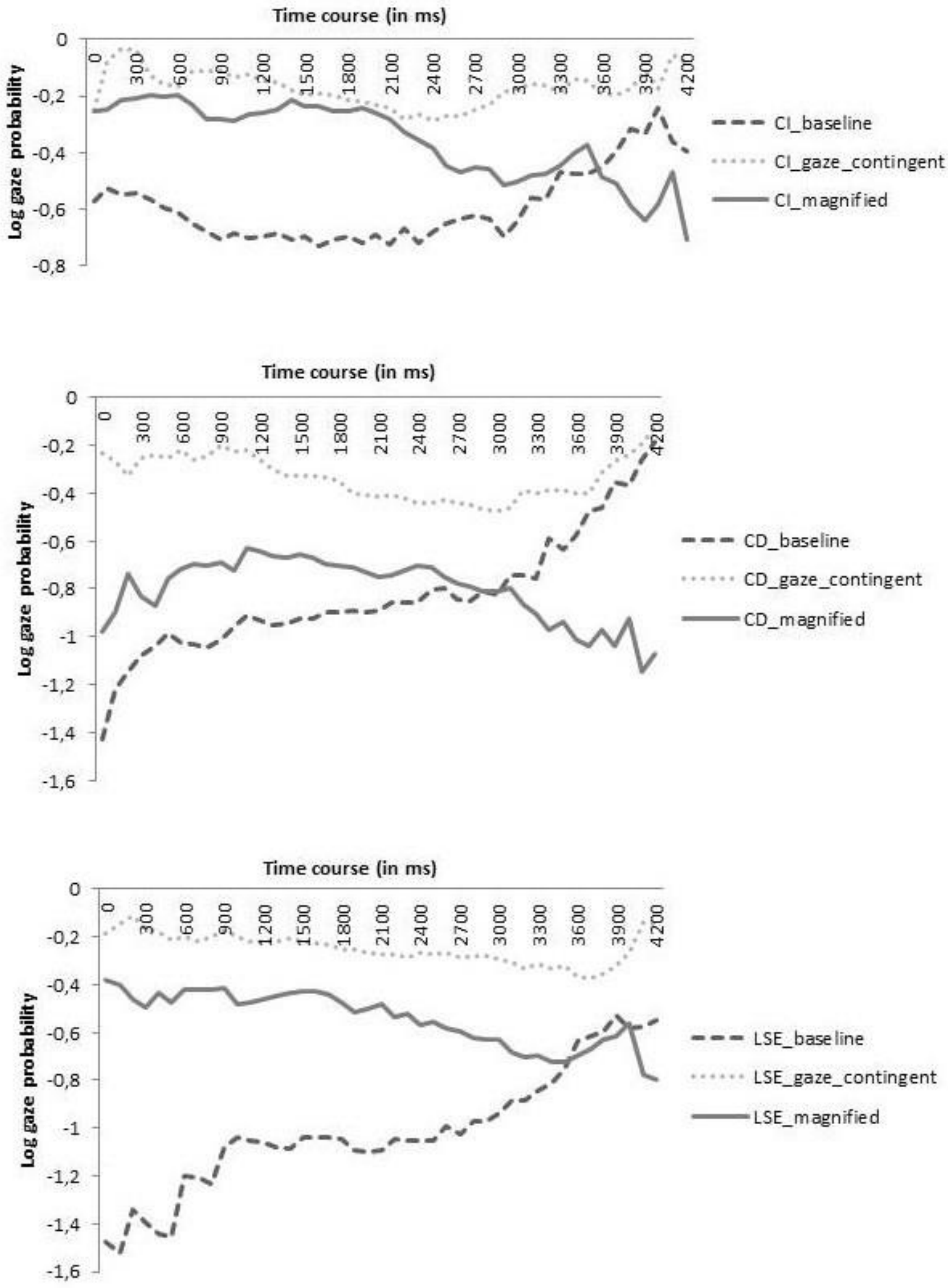
Before reporting results at group level, for each analysis, we also reported a full model with all participants, regardless of group membership, to explore the effect of experimental conditions and the impact of lipreading, working memory, and nonverbal IQ, on eye-movements, and accuracy and reaction time (RT). At the group level, analyses with and

the baseline, $\beta = .40$, $SE = .15$, $Z = 2.74$, $p < .01$.

without working memory and nonverbal IQ were reported and can be found in Supplemental Material S1. Working memory and nonverbal IQ significantly impacted performance in the full model, so we felt they should be controlled for in the group-level analyses to ensure that group effects were not driven by differences in these cognitive factors. However, because of the small sample size of the groups, results of analyses with covariates should be interpreted with caution. In any case, in most cases no substantial differences were found between the analyses involving lipreading, experimental groups, and conditions with and without working memory and nonverbal IQ, and therefore the simplified analyses without these variables, with greater power, were retained.

Factors were analysed by using treatment coding. We first focused on the effect of the magnified condition, running a model that included the three groups and two visual conditions, magnified and baseline, and lipreading scores. A second analysis focused on the effect of the gaze contingent condition, including this condition with the baseline in the model. Means and standard deviations for the relative percentage of fixations towards the signing AoI with respect to face AoI are reported. For the visual inspection of the distribution of fixations in each group, we also calculated the time course of the fixated interest area by computing the log gaze probability ratio according to the formula: $\log(P_{\text{signing AoI}})/(P_{\text{face AoI}})$, which is the log transformed ratio of the probability of looking at the sign area and the probability of looking at the face area. Log gaze probability has the advantage of providing an easy interpretation of its value (Burigo & Knoeferle, 2015): a positive value indicates that participants are more likely to inspect the signing area, while a negative value indicates a higher likelihood to look at the face area. Graphs of the log-gaze probability of fixation for each group across conditions are reported in Figure 3.

Figure 3. Log gaze probability of fixations. The graph illustrates the probability that participants of the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups looked toward the signing (positive values) or the face area (negative values) across the time course in the different visual conditions.



Accuracy and RTs.

Accuracy reflected whether participants correctly decided (by pressing yes or no keys on a keyboard) if the picture appearing after the video corresponded to the SSS sentence. RTs were computed from the presentation of the response options to pressing of the response key. As for eye movements, we analysed accuracy using GLMER with the lme4 package for R (version 3.2.1), including items and participants as random factors and visual conditions, groups and lipreading skills as fixed factors, and treating accuracy as a binomial measure. The distribution of RTs was modelled with a Linear Mixed Effects Regression (LMER), treating groups, conditions, and lipreading skills as fixed effects, and items and participants as random factors. For this analysis, we removed all trials where a wrong response was given. *t*- values were used instead of *Z*- and *p*- values (Kliegl, Masson, & Richter, 2010). We looked at the effects of the visual conditions and lipreading skills on the performance of all participants and, in greater detail, of the CI and LSE groups, each compared to the control group. Following the same procedure as the eye movements' analysis, we first computed a model that included magnified and baseline conditions and, then, a model including gaze contingent and baseline conditions. Tables including fixed effects of GLMER and LMER analyses are reported Supplemental Material S1 "Fixed effects".

Results.

Means (and SD) of the percentage of fixations towards the signing area are reported in Table 3. Within each of the three groups there was a large individual variation in the outcomes of gaze behaviour. The use of mixed-effects models allowed to deal with this heterogeneity across participants. Confirming previous literature (De Filippo & Lansing, 2006; Mastrantuono et al., 2017), in the baseline condition, participants primarily fixated the face AoI, compared to the signing AoI, around 80-90% of overall fixations. Means (and SD) of the percentage of accuracy and of RTs are reported in Table 4.

Table 3. *Fixations percentages towards the signing area of interest (AoI; compared to the fixations towards the face AoI) across conditions in the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups.*

	Fixations Signing AoI		
GROUP	Baseline Condition	Magnified Condition	Gaze Contingent Condition
CI	23.96 (20.57)	29.10 (32.36)	41.91 (36.63)
CD	16.69 (15.12)	13 (15.15)	34.54 (25.92)
LSE	10.23 (8.66)	19.4 (25.5)	36.4 (33.8)

Note. Means (Standard deviations in parentheses) are reported.

Table 4. *Accuracy and reaction times (RTs) for correct answers across conditions in the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups.*

	Baseline Condition		Magnified Condition		Gaze Contingent Condition	
Group	Accuracy	RT	Accuracy	RT	Accuracy	RT
CI(1)	79 (19)	2922 (1420)	79 (15)	2491 (1137)	76 (9)	2653 (1296)
CD	80 (22)	2547 (1178)	82 (11)	2368 (863)	69 (18)	3306 (2244)
LSE	81 (14)	2105 (810)	69 (18)	2575 (1312)	67 (12)	2601 (1362)

Note. Means (Standard deviations in parentheses) are reported. Accuracy is in percentage. RTs are in milliseconds.
(1) one subject has been removed from the RT computation of CI group because he had more than 2 SDs above the mean in the baseline condition.

The effect of perceptually easier access to lip movements on fixations, accuracy and RTs: The magnified condition.

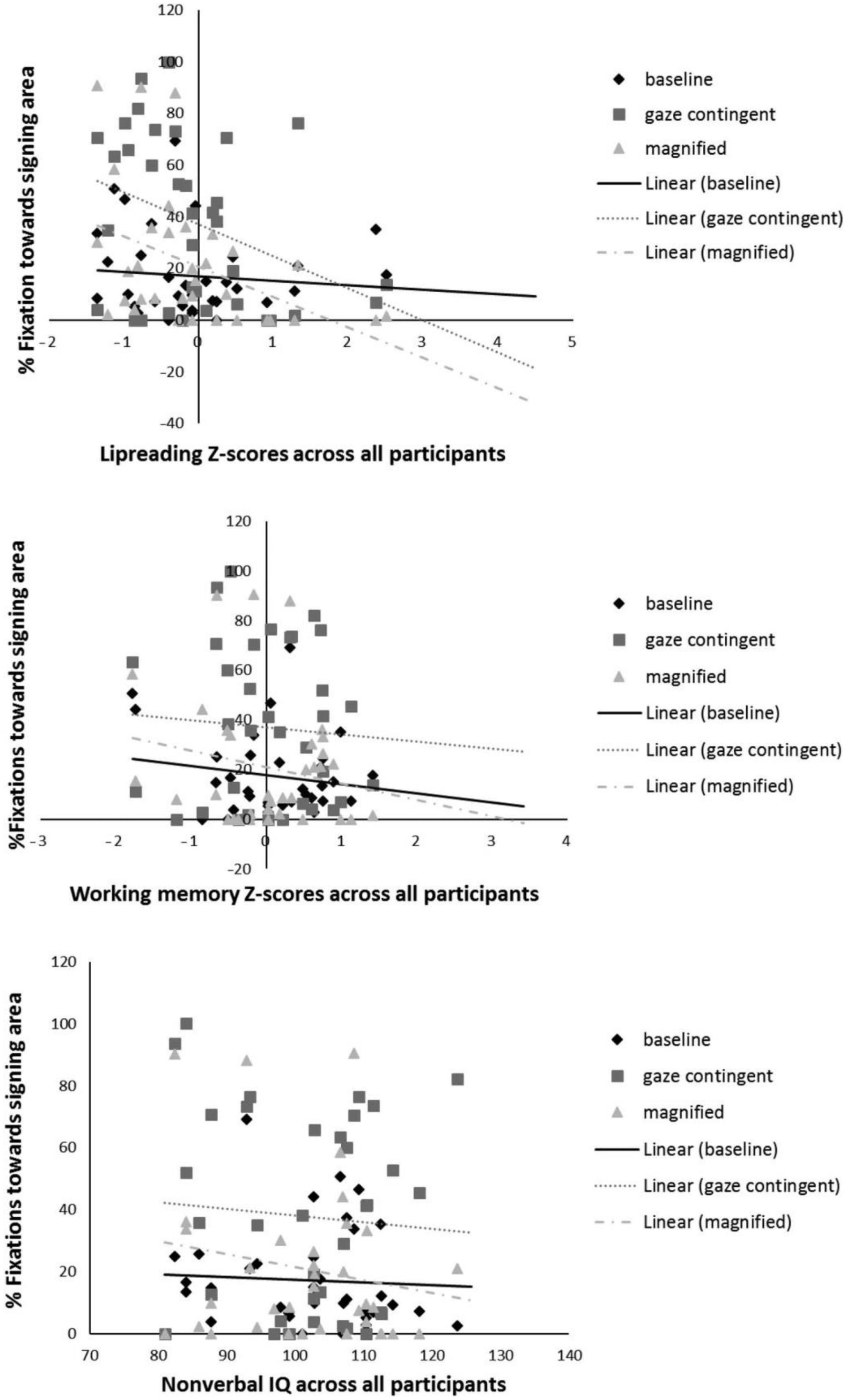
Eye movements.

The full model, including lipreading, working memory, nonverbal IQ, and baseline and magnified conditions as predictors, revealed an effect of conditions on fixations, $\beta = .46$, $SE = .10$, $Z = 4.72$, $p < .001$, with more fixations towards the signs in the magnified condition. Interactions of conditions, magnified and baseline, with lipreading, $\beta = -.28$, $SE = .11$, $Z = -2.53$, $p < .05$, and with working memory, $\beta = -.36$, $SE = .10$, $Z = -3.60$, $p < .001$ (see Table 1s in Supplemental Material S1 "Fixed effects"), showed that participants who achieved lower scores in lipreading or in working memory tasks, had an increased number of fixations towards the signs, especially in the magnified condition (see Figure 4).

The next analysis included group membership as a predictor (CI, CD, and LSE), together with lipreading and experimental condition (see Table 2s in Supplemental Material S1 "Fixed effects"). Means and SD of fixations across groups and conditions are reported in Table 3. No main effects of group were detected. Contrary to our expectations, the significant interaction between CI and CD groups and conditions, $\beta = .52$, $SE = .23$, $Z = 2.29$, $p < .05$, revealed an increased number of fixations towards signs of participants of the CI group in the magnified condition compared to the baseline.

The LSE group was predicted to look towards the signing area to a higher extent in the magnified than in the baseline condition. The interaction between groups and conditions, $\beta = 1.56$, $SE = .27$, $Z = 5.81$, $p < .001$, supported this hypothesis, with the LSE group fixating more often than the CD group on the signs in the magnified than in the baseline condition (see Table 3). As in the full model, the effect of lipreading and its interaction with visual conditions were significant.

Figure 4. Interactions of lipreading, working memory and nonverbal IQ across all participants, and percentage of fixations toward the signing area of interest in baseline, magnified and gaze contingent conditions.



All these effects, related to lipreading and the interactions of groups and conditions, remained also significant when the group analysis was replicated including working memory and nonverbal IQ, as well as the interaction of visual conditions and working memory survived from the full model without the group factor (see Table 3s in Supplemental Material S1 “Fixed effects”).

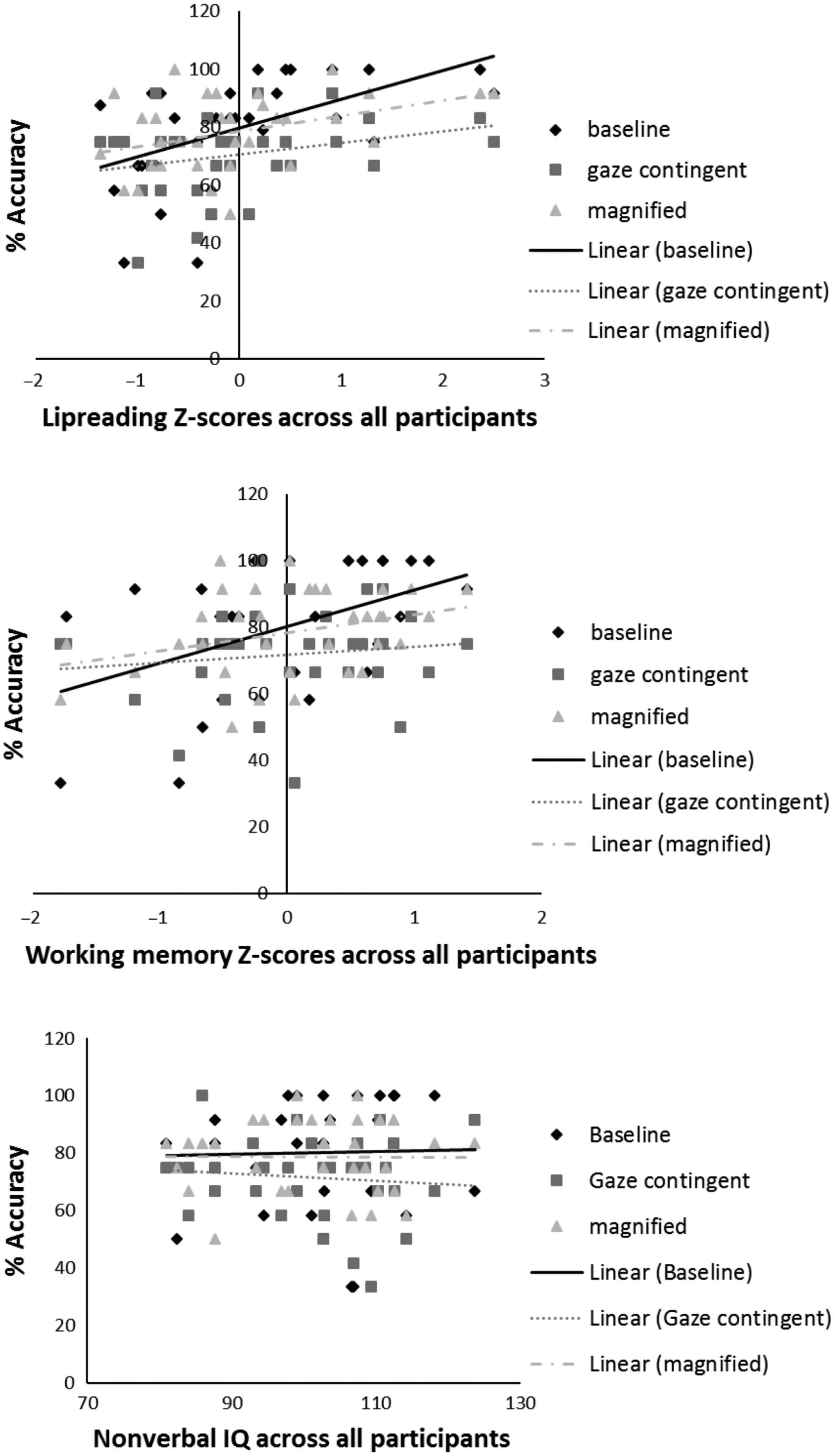
Accuracy and RTs.

The full model without groups showed an effect of lipreading on accuracy in the magnified condition, $\beta = .28$, $SE = .14$, $Z = 2.00$, $p < .05$ (see Table 4s in Supplemental Material S1 “Fixed effects”), with higher accuracy gained by more proficient lipreaders (see Figure 5).

The analysis including groups did not reveal significant differences in the accuracy in the baseline and in the magnified condition ($p = .54$), nor differences between the CD and CI groups ($p = .59$), or the CD and LSE groups ($p = .40$) (see Table 5s in Supplemental Material S1 “Fixed effects”). Lipreading skills positively affected accuracy in the magnified condition $\beta = .31$, $SE = .14$, $Z = 2.20$, $p < .05$.

The group analysis including also working memory and nonverbal IQ did not reveal any effect for groups, conditions, or cognitive skills, and the effect of lipreading, detected in the model without cognitive skills, did not survive to the greater complexity of the model (see Table 6s in Supplemental Material S1 “Fixed effects”).

Figure 5. Interactions of lipreading, working memory and nonverbal IQ across all participants, and percentage of accuracy in baseline, magnified and gaze contingent conditions.



Contrary to our hypothesis, the analysis on RTs did not indicate any effect of the magnified condition compared to the baseline either, neither when considering the full model nor when considering the analysis at group level (see Tables 7s and 8s in Supplemental Material S1 “Fixed effects”). However, a significant interaction showed differences between the LSE and CD group in processing baseline and magnified visual conditions, $\beta = -803.4$, $SE = 392.1$, $t = -2.05$, with the LSE group slower in processing the magnified condition, unlike the CD group.

Similarly, when working memory and nonverbal IQ were introduced in the group analyses, no effects for groups, conditions or cognitive skills were found but the interaction between LSE and CD group and visual conditions survived to the increased complexity of the model (see Table 9s in Supplemental Material S1 “Fixed effects”).

The effect of constraint peripheral vision on fixations, accuracy and RTs: The gaze contingent condition.

Eye movements.

The initial analysis, with all participants regardless of group membership, detected a significant increase in fixations towards the signs in the gaze contingent condition compared to baseline, $\beta = 1.34$, $SE = .09$, $Z = 13.99$, $p < .001$ (see Table 10s in Supplemental Material S1 “Fixed effects”). Significant interactions indicated that nonverbal IQ, $\beta = .45$, $SE = .10$, $Z = 4.43$, $p < .001$, and working memory, $\beta = -.42$, $SE = .09$, $Z = -4.70$, $p < .001$, affected the gaze contingent and the baseline conditions differently: fixations towards signs increased more markedly in the gaze contingent condition than in the baseline in participants with lower nonverbal IQ, while participants with smaller working memory capacity showed increased fixations towards signs more markedly in the baseline than in the gaze contingent condition (see Figure 4).

In the group analysis, the gaze contingent condition significantly differed from the baseline, β= 1.02, *SE* = .16, *Z* = 6.45, *p* <.001 (see Table 11s in Supplemental Material S1 "Fixed effects") and there was no main effect of groups in the gaze contingent condition, not when considering the CI and CD group (*p* = .42) nor the LSE and CD group (*p* = .79), with an increased number of fixations towards the signing area in the gaze contingent condition across all groups (see mean and SD in Table 3). However, in spite of the lack of a main effect of groups, an interaction of conditions and LSE and CD group indicated that that fixations towards the signs in the gaze contingent condition increased more markedly in the LSE group compared to the CD group, β= .85, *SE* = .24, *Z* = 3.53, *p* < .001. Confirming our hypothesis, the model revealed an interaction between conditions and lipreading, β= -.25 *SE* = .09, *Z* = -2.63, *p* <.01 (Table 11s in Supplemental Material S1 "Fixed effects"), with a more marked tendency of participants with poorer lipreading skills across groups to look towards the signs in the gaze contingent condition (see Figure 4). However, when the analysis was re-run controlling for working memory and nonverbal IQ this interaction was no longer significant (see Table 12s in Supplemental Material S1 "Fixed effects"). This more complex model confirmed a main effect of condition, with more fixations towards the signs in the gaze contingent condition than in the baseline (*p* > .001), as well as the interaction between LSE and CD group and conditions. As in the full model without group factor, the interactions of cognitive skills, working memory and nonverbal IQ, and conditions were significant.

Accuracy.

The full model indicated higher accuracy in the baseline than in the gaze contingent condition, β= 56, *SE* = .17, *Z* = 3.25, *p* <.01 (see Table 13s in Supplemental Material S1 "Fixed effects"). These effects also appeared in the analysis at group level. This analysis revealed a significant difference in accuracy between the gaze contingent and the baseline condition, β= -.52, *SE* = .17, *Z* = 3.07, *p* <.01 (see Table 14s in Supplemental Material S1 "Fixed effects") and no differences across groups were captured, with participants less accurate in the gaze contingent condition than in the baseline (see Table 4). The introduction of working memory and nonverbal IQ did not substantially change these results, with condition factor predicting accuracy (see Table 15s in Supplemental Material S1 “Fixed effects”).

The analysis of RTs, both in the general model and in the group analysis (see Table 16s and Table 17s in Supplemental Material S1 “Fixed effects”), revealed longer RTs in the gaze contingent condition. Overall, participants were faster in deciding whether the picture corresponded to the sentence in the baseline than in the gaze contingent condition, $\beta = -551.6$, $SE = 195.0$, $t = -2.83$ (see Table 17s in Supplemental Material S1 “Fixed effects”).

The condition effect also survived in the group analysis including working memory and nonverbal IQ (see Table 18s in Supplemental Material S1“Fixed effects”).

Discussion.

The eye tracking data replicated the findings of previous research (De Filippo & Lansing, 2006) and confirmed that deaf participants, independently from their auditory access or native knowledge of sign language, primarily looked at the face area when attending SSS in a normal visual condition (named baseline condition in this article). The manipulation of video-stimuli presentation aimed to pinpoint the actual use of peripheral vision for perceiving signs and the main source of information, either lip movements or signs.

The magnified condition’s effects.

First, we explored the effects of the magnified visual condition, with a perceptually easier access to lip movements, on fixations, accuracy andRTs. Contrary to our hypothesis, in the magnified condition, participants of the CI group did not show increased fixations towards the face compared to the CD group. The magnified size of the face area in the magnified condition possibly allowed these participants to focus on signs, continuing to perceive lip movements via peripheral vision.

Participants of the LSE group looked more frequently at signs than the CD group in the experimental condition, in the baseline the LSE group looked at them less frequently then the control group. These findings corroborated the hypothesis according to which, in normal conditions, native signers would look less frequently than their non-native peers at signs when perceiving SSS, similarly to what was found for sign-language perception (Agrafiotis et al., 2003). It might be the case that the atypical proportion of face and body of the sign model in the magnified condition had led participants to modify their usual gaze patterns, since they did not need to focus as closely on the face area to lipread.

The relation of lipreading skills and fixations, with poorer lipreaders looking to a higher extent towards the signs than more expert lipreaders, seems to support this idea. A greater size of the head area might free the participants from the need to foveate on the mouth area so closely.

Accuracy was not penalised in the magnified condition compared to the baseline in either group. Contrary to our expectations, no differences in sentence comprehension between the CI and the CD groups were detected. In the baseline condition, no advantages in comprehension were found in the CI group, who was assumed to take advantage of the multiple linguistic channels of SSS. It is possible that the task was so easy that it left no room for eventual additional benefits of SSS for the CI group. This could also explain the similarity of the groups in accuracy in the manipulated conditions. Participants of the LSE group did not miss crucial information for comprehending the sentences compared to the CD group, although they took longer in processing sentences in the magnified condition, contrary to the CD group.

The gaze contingent condition's effects.

The next visual manipulation, the gaze contingent condition, aimed to further explore whether peripheral vision is active in sign perception during SSS perception, by limiting peripheral access to the signs.

As expected, a greater number of fixations towards the signing area was detected in the gaze contingent condition than in the baseline, across all groups, regardless of the auditory access and the native knowledge of sign language. This is an indication that in normal conditions signs are being attended to peripherally, and that when it is not possible to use peripheral vision, participants deliberately foveate towards the signs.

A strong effect of lipreading differentiated the visual conditions across participants of the CI and LSE groups, with less skilled lipreaders fixating more frequently on signs in the gaze contingent condition than in the baseline. Participants of the LSE group, who looked at signs to a lesser extent than the control group in the baseline, perceiving them via periphery, showed a more marked increase of fixations towards the signs in the gaze contingent condition. This suggests that these participants, who could not benefit from the auditory input, or could do so only to a small extent, needed to look at the signs to compensate the insufficient information obtained through lipreading when forced to choose. Nevertheless, when introducing working memory and nonverbal IQ in the model the effect of lipreading on gaze behaviour decreased. Although lipreading continued to be a relevant predictor, working memory also seems to have a role in driving fixations, and impacts accuracy.

In the gaze contingent condition, accuracy significantly decreased compared to the baseline across all groups of participants. Jointly with the longer RTs of participants of the LSE and CD groups, these results indicated that participants had more difficulties in processing information in the gaze contingent condition compared to the baseline. Participants were clearly affected by the lack of the simultaneous availability of all SSS linguistic channels, and therefore unable to concurrently integrate information from lip movements and speech with information from signs. In addition, signs are not usually perceived with isolated attention to the hands and this unfamiliar condition might have made it harder to process the signs.

Summary of findings.

Overall, Experiment 1 revealed that deaf individuals under visual conditions that facilitated the visual perception of the mouth area by increasing its size or limited the access with peripheral vision to the sign area, tended to look more often towards the signing area. The need of participants, with or without cochlear implants, to focus on signs when visual conditions limit the possibility of perceiving them peripherally, leads us to infer that in normal visual conditions, although they focus on the sign model's face, participants are attending to the signs, perceiving them via peripheral vision. This would be a useful strategy, since to obtain any information from lipreading from mouth and face in a typically small area, it is necessary to foveate precisely there, due to the difficulty in discerning lipreading even by expert lipreaders (Bernstein, Demorest, & Tucker, 2000; Kelly & Barac-Cikoja, 2007) and the reduced visual acuity that can be gathered from peripheral areas of vision compared to the point of foveal vision (Siple, 1978). More strongly, these findings might suggest that participants prefer to have access to signs, either peripherally or through overt attention depending on the perceptual conditions, even when they have access to auditory information. Although this experiment confirms the role of peripheral vision for the perception of signs in SSS and suggests that signs were important for message comprehension for our participants, the results are not conclusive. The reduction in accuracy in the gaze contingent condition might be partially due to the lack of familiarity of participants with the time window paradigm, which might have required greater perceptual effort, limited their access to lipreading, and caused a possible loss of information. Experiment 2 explores with more detail the input provided by the signs, introducing a paradigm in which speech and signs were inconsistent.

Experiment 2

Experiment 2 addressed the extent to which signs in SSS are relevant in transmitting information to deaf individuals, by presenting stimuli where speech and sign information mismatched because signs carried a different meaning than the lipread/spoken words. Participants were instructed to pay attention to the orally transmitted message. This design allowed us to detect the extent to which participants referred to signs for understanding the message, even if explicitly told to focus on speech. We know from prior studies that deaf individuals primarily look at the face area when perceiving sign language (Emmorey et al., 2009; Muir & Richardson, 2002), and that native signers look more at the face than non-native sign-language users (Agrafiotis et al., 2003). Even in SSS, deaf participants mainly look at the face, even when the sign is essential to disambiguate the meaning of the sentence, although no correspondence has been found between greater expertise in the use of SSS and the number of fixations towards the face (De Filippo & Lansing, 2006). Differently from De Filippo and Lansing (2006), in this study, speech and sign produce a conflict that might orient participants' visual attention towards the signs. We expect different outcomes in accuracy and gaze patterns depending on participants' access to auditory input, on the one hand, and, on the other, on their native expertise in sign language. If participants of the CI group rely on all articulatory channels of SSS, they are likely to rapidly notice the mismatch between speech and sign. Driven by the incongruency, they should fixate the signs for longer in the mismatching condition than in the matching condition. In the mismatching condition, the CI group might fixate the signs longer also with respect to participants of the CD group, who might be less aware of the mismatch, due to the limited access to audition. Consistently with these hypotheses related to the gaze behaviour, we did not expect accuracy in participants of the CI group be significantly influenced by the mismatching condition, as they will be more cautious in taking into account the sign meaning, once they have detected that there is a mismatch. Also these participants are likely to achieve higher accuracy than the CD group in the mismatching condition.

On the other hand, native signers (the LSE group) should look primarily at the face, more frequently than non-native signers of the CD group, and perceive signs via peripheral vision, consistently with previous literature and Experiment 1 (Agrafiotis et al., 2003). Deprived of the auditory input, the linguistic channels of LSE participants are limited to lip movements and signs. Broadly speaking, accuracy in lipreading is estimated in a range of 5-45% (Rönnberg, Samuelsson, & Lyxell, 1998) and decreases to 5% for words in sentences without appropriate contextual constraints (Rönnberg, Andersson, et al., 1998). In our study, participants of the LSE group had poorer lipreading skills, significantly worse than the CI group. Given the general limitations of lipreading and the specifically low lipreading proficiency of participants of the LSE group, we expected them to mostly ignore information from lipreading and rely on signs, even when fixating the face area. Consequently, accuracy in the LSE group was expected to dramatically decrease in the mismatching condition, with a large preference to get the message information from signs, and to be lower than in non-native LSE users (CD group). Longer RTs in a decision task were expected in the mismatching condition, due to the interference originated by the competing messages transmitted by lip movements and signs. However, native LSE signers, who should be less likely to notice the mismatch between speech and sign, might take the same time to process the task in matching and mismatching sentences. As for Experiment 1, greater lipreading skills were predicted to rely to better spoken language comprehension.

Method.

Material and Design.

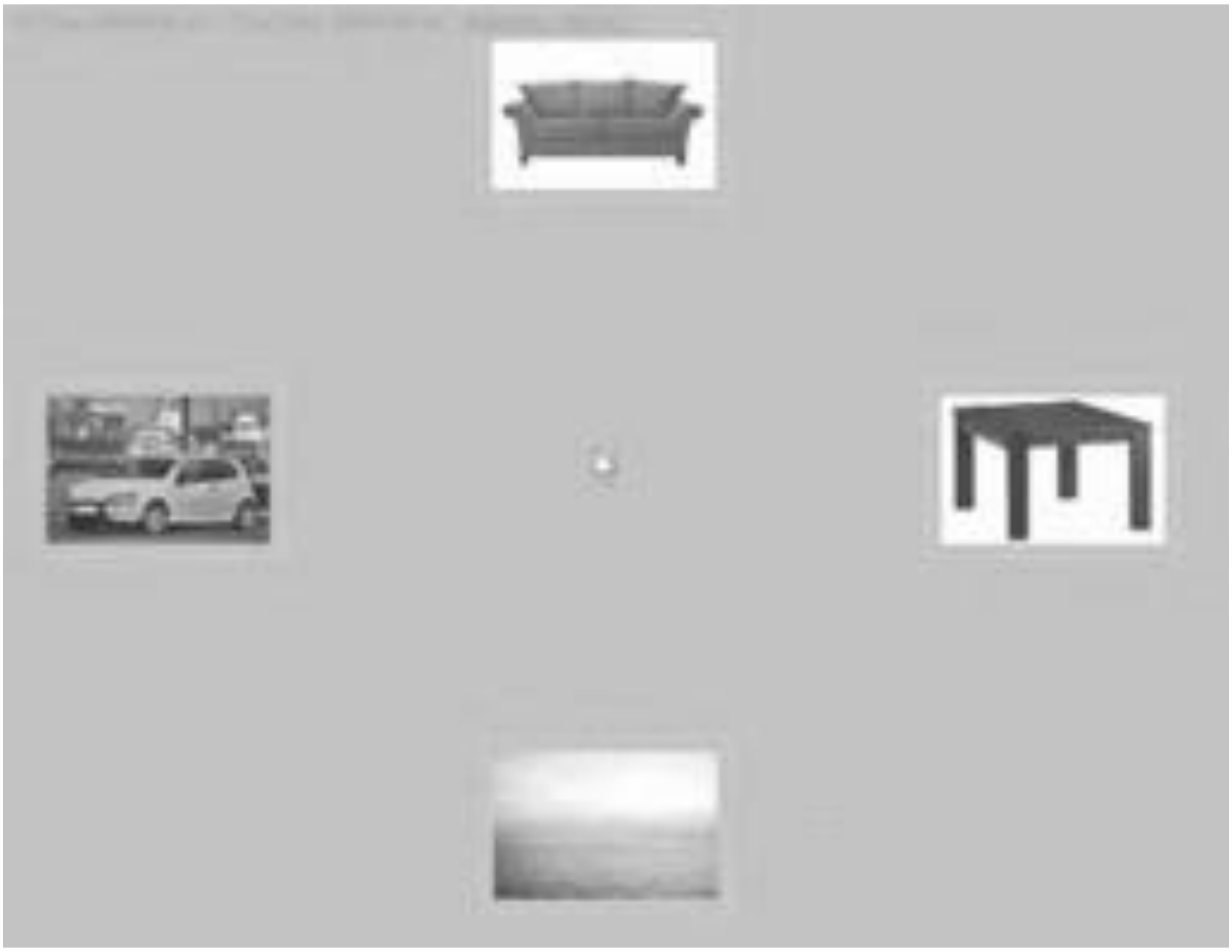
Stimuli consisted of 30 subject-verb-object sentences in SSS, including 2 practice trials. Stimuli sentences were different on the object node, where critical signs either matched or mismatched with speech. We called this variable, “mis/matching condition”. All critical signs were performed in the signing area proximal to the sign model’s chest. The same sign model as in Experiment 1 participated in video-recording stimuli in a professional recording studio. The sign model appeared in the video from the hips upwards. The image was 900 pixels in width and 1,200 pixels in height, corresponding to a visual angle between 21º and 39º. Observers’ visual angle from the mouth to the chest area varied approximately between 7.5º and 16.5º.

The task consisted of identifying, among four pictures, one referring to the object orally communicated. The display with the four pictures appeared after a related video. In the matching condition, one picture represented the target object —communicated by matched congruent speech and sign—, two pictures representing objects semantically related to the verb, and one picture representing an object semantically unrelated to the verb. In the mismatching condition, one picture represented the target object which the oral input referred to, one represented the competitor object —referred to with a mismatching sign—, one picture was semantically related to the verb, and one picture represented an object semantically unrelated to the verb. The mismatching sign was also semantically related to the verb and a plausible ending for the sentence. Pictures appeared at the four cardinal points of the display.

Procedure.

Participants watched the practice trials, one for each condition, with sign and speech matching or mismatching. Later, the experimental trials were administered in a randomised order across conditions and participants. Participants were not aware of the possible mismatch of sign and speech, but they were instructed to pay attention to the orally transmitted message. After each sentence in SSS, a display appeared showing the four pictures (see Figure 6): participants were asked to select the picture depicting the object previously orally communicated by clicking on it with the mouse. The target picture randomly appeared at different cardinal points across trials. Figure 6 shows the task display appearing after the sentence “Mi novio empuja el sofá” (‘My boyfriend is pushing the sofa’), where, in the mismatch condition, the sign for the object was “car” instead of “sofa”. The complete set of stimuli is reported in Appendix B. The experiment was programmed in Experiment Builder (EB) (SR Research, Ontario, Canada).

Figure 6. Example of display for the selecting picture task in the mismatching condition, referring to the sentence “Mi novio empuja el sofa” (‘My boyfriend is pushing the sofa’).



Analyses.

Eye movements.

Similarly to Experiment 1, eye movements data were viewed, filtered and processed with SR Research Data Viewer (SR research, Ontario, Canada). For the analyses of gaze fixations, we drew two areas of interest (AoIs), corresponding to sign model face (face AoI) and to the signing space (signing AoI), respectively, as we did for the baseline visual condition in Experiment 1 (see Figure 1). For a visual inspection of the time course of fixations, we computed the log gaze probability according to the formula: $\log(P_{signing\ AoI})/(P_{face\ AoI})$, which informed about the bias of inspecting the signing AoI (positive values) related to the face AoI (negative values). Distinct time courses illustrate fixations in the matching and mismatching conditions, highlighting the distribution of gaze fixations, across CI, CD, and LSE groups (see Figure 7). The charts show the line indicating the average onset of the object (M = 3,263 ms) where the mismatch between speech and sign could occur.

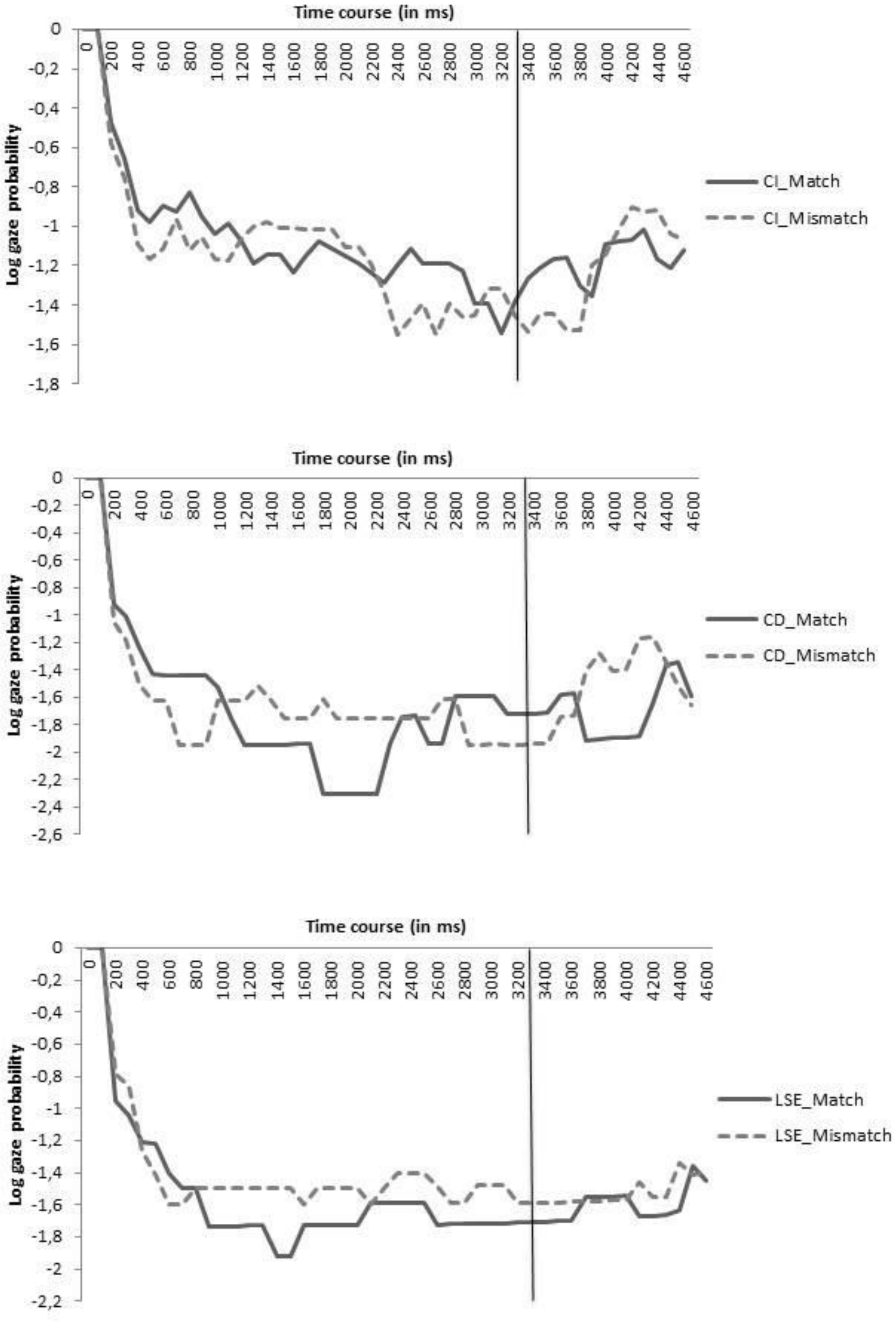
We performed multinomial logistic mixed model analyses, comparing the distribution of fixations towards the face or the signing AoIs across matching and mismatching conditions. We considered the number of fixations occurred in the critical time window during which the mismatch between speech and sign could occur, from 200 ms after the onset of the object and 200 ms after the offset of the object. Analyses were performed in R, version 3.2.3 (R Developmental Core Team, 2015), via a Generalised Linear Mixed Effects Regression (GLMER), with items and participants as random factors and mis/matching condition and groups as fixed factors. As for Experiment 1, the final model for each analysis was obtained by a stepwise simplification of the random effects structure until convergence was reached (Barr et al. 2013). Regression coefficient estimates (β), standard errors (*SE*), *Z*- and *p*- values are reported. The models included lipreading as predictor of fixations. Tables including fixed effects of GLMER analyses are reported in Supplemental Material S1 “Fixed effects". We included in the same model the three groups, CI, CD and LSE, with the CD as reference level. We focused, first, on the use of cochlear implants and the access to oral input, comparing the distribution on gaze fixations in participants with cochlear implants (CI group) and in participants using hearing aids or no aids at all (CD group), and, second, on the effect of native proficiency in sign language, comparing the distribution of gaze fixations in native LSE signers (LSE group) and non-native LSE users (CD group). Means and standard deviations for the relative percentage of fixations towards the signing AoI with respect to face AoI are reported.

Accuracy and RTs.

Accuracy was analysed by using GLMER with the lme4 package for R (version 3.2.1), including items and participants as random factors and groups, mis/matching condition, and lipreading as fixed factors, and treating accuracy as a binomial measure. The binomial codification opposed the correct target picture, corresponding to the orally communicated object, to all other pictures, including the picture representing the sign in the mismatching condition. The distribution of RTs for accuracy was modelled with a Linear Mixed Effects Regression (LMER), treating groups, mis/matching conditions and cognitive and linguistic skills as fixed effects, and items and participants as random factors. Only RTs for correct answers were analysed. Tables including fixed effects of GLMER and LMER analyses are reported in Supplemental Material S1 "Fixed effects". Analyses looked at the effects of the mis/matching condition on the accuracy and RTs across the three groups (CI, CD, and LSE).

As in Experiment 1, all initial analyses for eye movements, accuracy, and RTs, included all participants, regardless of group membership, and working memory and nonverbal IQ to explore how these skills impacted the performance. Analyses involving groups were run with and without working memory and nonverbal IQ.

Figure 7. Log gaze probability of fixations. The graphs illustrate the probability that participants of the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups looked toward the signing (positive values) or the face area (negative values) across the time course, in matching and mismatching condition. The line at 3,263 ms indicates the average onset time for the possible mismatch.



Results.

Eye movements.

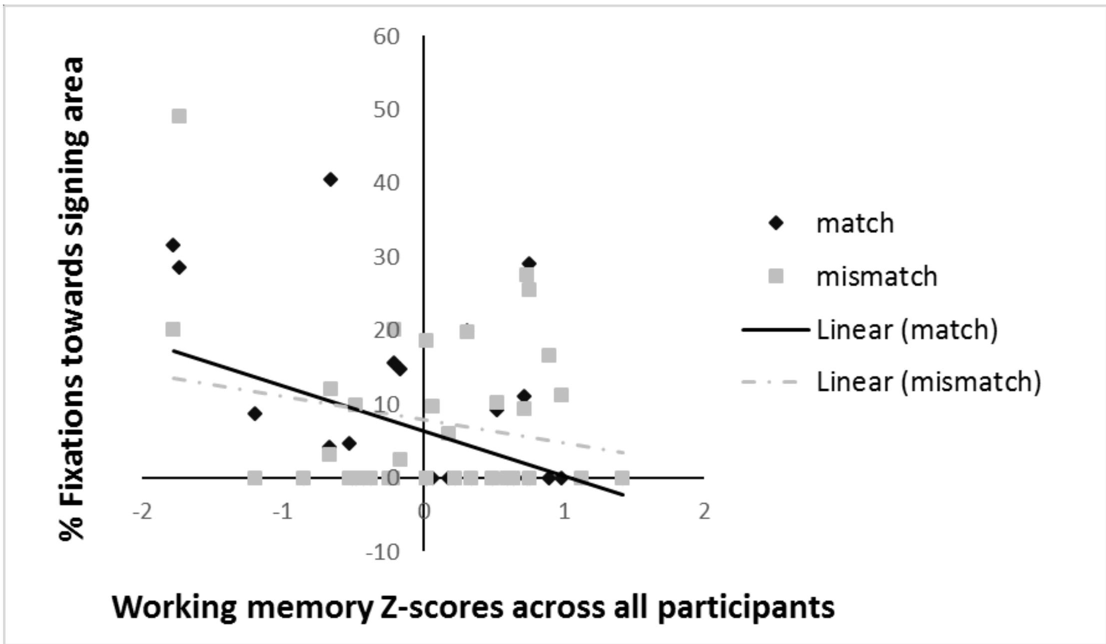
Means and standard deviations of the percentage of fixations towards the signing AoI with respect to fixations towards the face AoI across groups are reported in Table 5. In the full model including working memory, nonverbal IQ, lipreading, and conditions, participants showed more fixations towards the signs in the mismatching condition, $\beta = .74$, $SE = .35$, $Z = 2.10$, $p < .05$ (Table 19s in Supplemental Material S1 "Fixed effects"). No effects of cognitive or linguistic predictors were detected, other than a significant interaction of conditions and working memory, $\beta = .59$, $SE = .27$, $Z = 2.21$, $p < .05$, with participants with smaller working memory capacity fixating at signs more frequently in the matching than in the mismatching condition (see Figure 8).

Table 5. *Fixations percentages toward the signing area of interest (AoI; compared to the fixations toward the face AoI) across conditions in the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups.*

	Fixations Signing AoI	
Group	Matching Condition	Mismatching Condition
CI	11.00 (14.62)	14.31 (12.98)
CD	4.53 (5.82)	8.35 (9.36)
LSE	1.70 (5.65)	1.74 (4.02)

Note. Means (Standard deviations in parentheses) are reported.

Figure 8. Interactions of working memory across all participants and percentage of fixations toward the signing area of interest in matching and mismatching conditions.



The analysis at group level confirmed the effect of condition, β = .68, *SE* = .34, *Z* = 1.98, $p < .05$ (Table 20s in Supplemental Material S1 “Fixed effects”), with more looks towards the signing area in the mismatching than in the matching condition. No differences between CI and CD groups ($p = .20$) were detected, suggesting that participants of these two groups were equally aware of the mismatch, regardless for the access to audition. In contrast, a main effect of group revealed differences between the LSE and the CD group, β = 1.46, *SE* = .73, *Z* = 2.00, $p < .05$. As predicted, LSE signers predominantly fixated the face, even in the mismatching condition. Their eye movements did not therefore reveal whether they noticed the inconsistency between speech and sign in the mismatching condition (means and SD in Table 5). No effects of lipreading on the eye movements in the mismatching condition were detected ($p = .23$).

These effects remained significant when working memory and nonverbal IQ were introduced, with LSE and CD group significantly differing on fixations, as well as the condition (see Table 21s in Supplemental Material S1“Fixed effects”).

Accuracy and RTs.

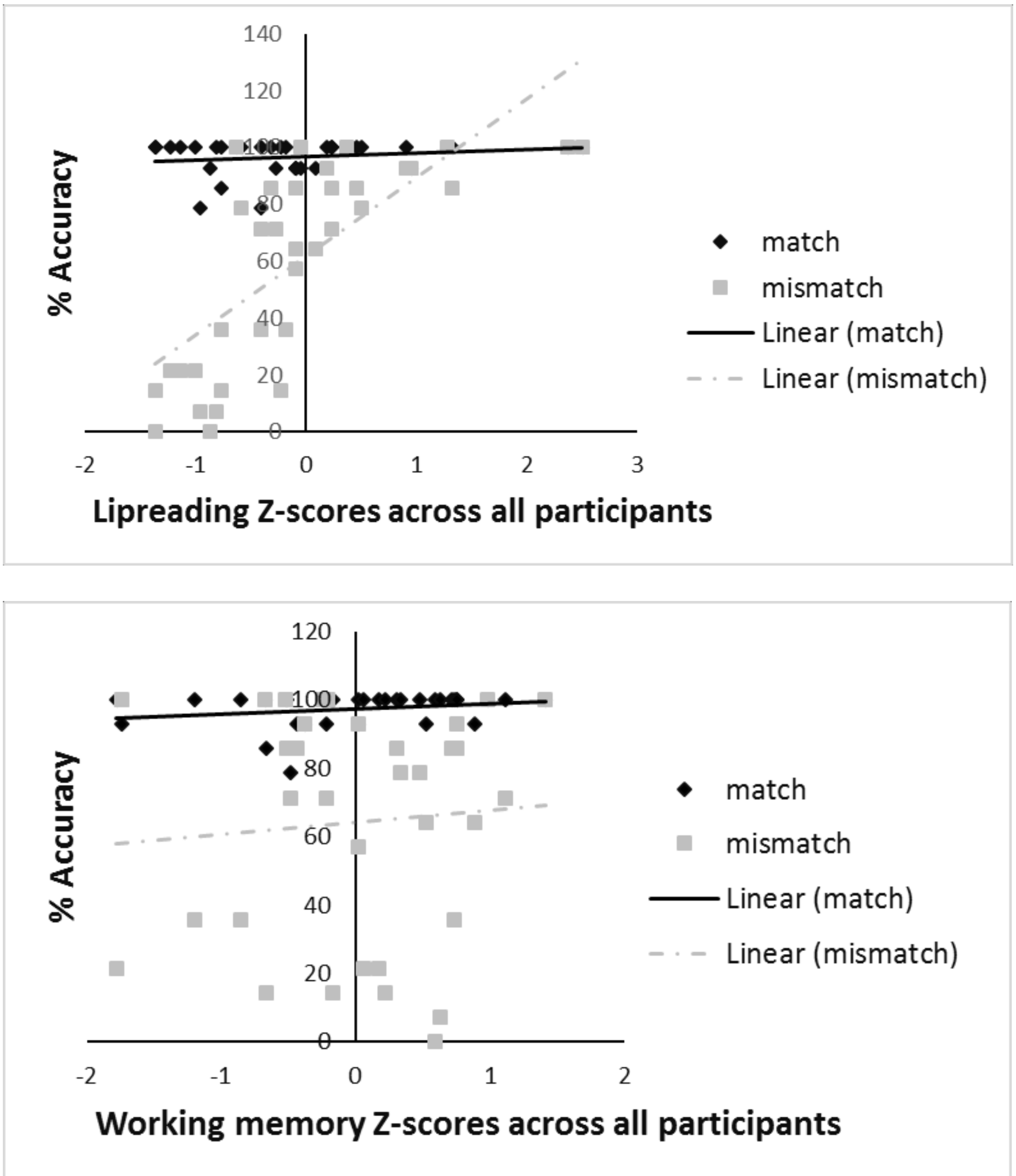
In the full model without groups, accuracy was affected by the condition, β= 5.99, *SE* = .77, *Z* = 7.81, *p* < .001 (see Table 22s in Supplemental Material S1 “Fixed effects”), as well as in the model including groups, β = 5.71, *SE* = 1.17, *Z* = 4.89, *p* < .001 (Table 23s in Supplemental Material S1 “Fixed effects”). Participants, as predicted, achieved higher accuracy in the matching condition (means and SD in Table 6). Lipreading and working memory related to accuracy differently in the mismatching and in the matching condition, with participants with lower lipreading skills and smaller working memory capacity decreasing in accuracy more markedly in the mismatching condition (see Figure 9). The analysis at group level detected differences across participants β= 1.02, *SE* = .16, *Z* = 6.45, *p* < .001. Significant differences between the LSE and the CD groups, β = -2.35, *SE* = .86, *Z* = -2.73, *p* < .01, were determined by the more marked decreased accuracy in the mismatching condition in the LSE group than in the CD group (see Table 6). As for participants of the CI group, a significant interaction between groups and conditions, β = -2.78, *SE* = 1.18, *Z* = -2.36, *p* < .05, showed that, although all participants decreased in accuracy in the mismatching condition, the difference across matching and mismatching conditions was less marked for participants of the CI group than the CD group.

Table 6. *Accuracy, and reaction times (RTs) for correct answers across conditions and selection of sign in the mismatching condition in the cochlear implant (CI), control deaf (CD), and Spanish Sign Language (LSE) groups.*

	Matching condition				Mismatching condition				
GROUP	% Accuracy	RT	% semantically related object	% semantically unrelated object	% Accuracy	RT	% Sign	% semantically related object	% semantically unrelated object
CI	95.6 (6.9)	2514 (726)	4.0 (7.5)	0.4 (1.8)	75.3 (30.7)	3114 (1319)	21.4 (27.0)	0.9 (2.1)	2.4 (6.7)
CD	99.4 (2.1)	2246 (659)	0.6 (1.6)	0	68.4 (31.9)	2861 (1660)	28.6 (29.4)	2.1 (5.3)	1.0 (3.7)
LSE	95.4 (6.6)	2461 (766)	3.7 (4.4)	0.9 (2.3)	35.7 (33.6)	2467 (744)	63.0 (35.3)	1.3 (3.1)	0

Note. Means (Standard deviations in parentheses) are reported. Accuracy is in percentage. RT for accuracy is in milliseconds. The percentages of selecting the semantically related and unrelated objects and the percentage of selecting the sign option for the mismatching condition are also reported.

Figure 9. Interactions of lipreading and working memory across all participants and percentage of accuracy in matching and mismatching conditions.



None of these effects changed when working memory and IQ were introduced in the analyses, except that the interactions between groups and conditions were no longer significant (see Table 24s in Supplemental Material S1 "Fixed effects"). Accuracy was predicted by differences between the LSE and the CD group and the matching and the mismatching condition.

No effects for RTs were detected in any of the analyses (across participants and with groups; see Tables 25s and 26s in Supplemental Material S1 “Fixed effects”). RTs were not significantly longer in the mismatching condition task than in the matching condition (t = 1.79; see mean and SD in Table 6).

The introduction of working memory and nonverbal IQ did not substantially change these results for RTs, with no effect of groups, condition, or cognitive and linguistic skills on RTs (see Table 27s in Supplemental Material S1 “Fixed effects”). When failing to select the target option corresponding to speech, all participants predominantly selected the sign option and only occasionally another wrong option, as appears from the percentage of speech and sign preference in the mismatching condition (see Table 6).

Discussion.

The results revealed different gaze patterns for the matching and mismatching conditions across groups. The CI and CD groups looked more frequently to signs when speech and sign mismatched. Confirming our hypotheses for the CI group, the distribution of gaze fixations suggests that they have noticed the inconsistency between speech and sign, therefore inspecting the signing area more frequently when speech and sign mismatched. Contrary to our expectations, the same findings were detected in participants of the CD group, suggesting that they were as likely to notice the incongruency between speech and signs as the CI group. Despite the awareness of this incongruency, accuracy outcomes revealed that also participants with CIs, as well as participants of the CD group, were less accurate during the mismatching condition. Lower accuracy and greater number of fixations directed to signs in the mismatching condition suggest that these participants were processing the inconsistency between speech and sign. When they could not fully succeed in discriminating the lip-read and/or heard words, they referred to the information transmitted by signs.

Differently from the other groups, the likelihood that LSE signers looked off the face was very small in both conditions. The CD group differed from the LSE group in somewhat higher fixations towards the signs, more marked in the mismatching condition. The behaviour of the LSE group of primarily looking at the face area was a further confirmation of our hypothesis, based on previous findings in sign language perception (Agrafiotis et al., 2003), that native signers perceive signs peripherally to a greater extent than late-acquisition non-native signers. This happened also when perceiving SSS, where the signedmessage is incomplete and syntactically empty, only spoken language can be fully perceived, and native signers predominantly fixated at the face even when speech and sign mismatched.

More dramatically than in the other groups, participants of the LSE group had a drop in the accuracy in the mismatching condition, significantly larger than the CD group. The decrease in accuracy was predicted by lipreading skills in the mismatching condition, where poor lipreaders considerably pulled down the scores. The role of lipreading in determining the accuracy partially sustained our hypothesis on the gaze behaviour in the LSE group. The lack of effect for the mis/matching condition in the gaze patterns of the LSE group might be produced by poor lipreaders who did not notice the inconsistency between speech and signs and kept their habitual behaviour of gazing the face, while peripherally attending the signs in sign language. RTs during the offline task, equivalent across conditions, might provide additional evidence in favour of the hypothesis that LSE participants were not aware of the inconsistency between speech and sign.

Overall, these results provide evidence for the relative relevance of information from signs with respect to information from speech/lipreading, even in individuals mostly trained in oral language and with a significantly restored hearing and access to audition (CI group).

The gaze patterns and accuracy scores in our study are somewhat different from those reported in De Filippo and Lansing's study (2006). Their participants did not attend to the signs even when these carried the critical information to disambiguate the meaning of the sentence, and they were highly accurate across all trials. However, their stimuli are not exactly equivalent to ours. While they presented messages in SSS without sound, our sentences had the sound available and sign and speech mismatched, because our goal was to evaluate the relevance of signs with respect to speech in SSS as it is usually presented, with all its resources, visual and auditory. The availability of the sound might explain why participants with cochlear implants and, to a lesser extent, participants without cochlear implants, fixated the signing area more when they processed the mismatch between speech and sign. On the other hand, differently from results in SSS (De Filippo & Lansing, 2006), but confirming findings for sign language (Agrafiotis et al., 2003), the native knowledge of sign language led participants to focus towards the face to a higher extent than non-native deaf users of sign language, regardless for the consistency of sign and speech and despite the preference for getting information from signs. Overall, results of the current study suggest that, whether they were or not looking directly at the signs, our participants were processing them.

General Discussion

SSS is a form of communication commonly used in education with deaf students where spoken language is accompanied by signs. Since the peculiarity of SSS is that the message can be received via the sign as well as the lip articulation, in two eye tracking experiments we explored the role of signs in transmitting information in SSS and how the presence of dual articulatory channels would affect deaf individuals gaze patterns. Prior research has shown that deaf individuals primarily focus on signers' faces when perceiving sign language (Agrafiotis et al., 2003; Emmorey et al., 2009; Muir & Richardson, 2002) and SSS without sound (De Filippo & Lansing, 2006). However, it was not clear whether such outcome would hold in conditions closer to the natural context use of SSS —i.e., with auditory input also available—, and if individuals would still covertly perceive signs, or whether they would mostly ignore them in favour of an exclusive focus on sound and on lip movements.

We addressed this issue by creating experimental visual conditions that allowed to explore if signs are effectively attended through peripheral vision: first, we tested a perceptual hypothesis that deaf individuals mainly look at the face in signed communication, because it is perceptually more difficult to distinguish lip movements than the gross movements of signs. We created an experimental condition, named magnified condition, in which we increased the size of the sign model face area, aiming to balance the perceptual accessibility of lip movements and signs (Experiment 1). A second experimental condition tested the effective role of peripheral vision in perceiving signs by using a moving window paradigm that constrained the visual field to either the face or the signs. This condition was referred to as the gaze contingent condition (Experiment 1). Finally, the role of signs in transmitting information was further investigated by testing with a paradigm based on semantic inconsistency between speech and sign (Experiment 2).

We explored these paradigms focusing on individual deafness-related characteristics: the access to audition (CI group) and the native expertise in sign language (LSE group). The CI group included long-term cochlear implant users, with implants activated before age of five and significantly restored hearing. The LSE group included profoundly deaf participants with deaf parents, which learned sign language as their first language. The gaze behaviour and the attention to signs of participants of each of these groups were compared to participants of a control group (CD group). This latter group included participants who wore hearing aids discontinuously, with highly variable outcomes in their auditory performance and who were non-native signers.

SSS perception in CI users

Our results show that the distribution of gaze fixations, as well as of accuracy, across the magnified and baseline conditions, did not experience significant changes in the CI as well as in the control group (Experiment 1). Despite no differences between conditions were captured, the perceptual hypothesis was somewhat sustained by the significant impact of lipreading in the magnified condition. It might be the case that the easier perceptual access to lipreading drove poor lipreaders to fixate more frequently the signs, trying to integrate or confirm with information from signs and in support of the auditory input, the words they missed through lipreading.

When perceptual constraints refrained participants from using their peripheral vision (gaze contingent condition in Experiment 1, that limited the visual field only to the face or to the signing area), participants of the CI group also tended to look to a higher extent towards the signing area, and this effect was more marked in poor lipreaders. This suggests that in normal conditions they are monitoring the signs even though they do not fixate on them, through covert attention. Lower accuracy observed in CI users in the gaze contingent condition points to the relevance of the multiple articulatory channels of SSS, and their role in increasing the opportunities for understanding a message. Experiment 2 contributed to shed further light on this issue, providing evidence for the relevant role of signs in processing information. Consistently with the gaze behaviour in Experiment 1, a tendency of CI users in increasing the fixations towards the signs when speech and sign mismatched suggests participants were processing both channels. Even when instructed to pay attention exclusively to oral information, participants were often not able to fully ignore information from signs, as shown by poorer performance in the mismatch condition. Overall, CI users' data from eye tracking, jointly with lower accuracy scores, converge in suggesting that participants were engaged in semantic integration of signs and spoken/lipread words. Emmorey et al. (2012)

argued this code-blending facilitation is a normal phenomenon in bimodal bilingual English-American Sign Language users. As first identified by Miller (1986), referring to a cognitive phenomenon called *redundant signals effects* (RSE), individuals are faster when processing two stimuli with the same meaning in different modalities than when processing a single stimulus, because the redundant information is combined and coactivates a response. This code-blend facilitation might not be due uniquely to the redundant lexical information in which one cue, spoken or signed, might be identified before the other. Code-blend might involve a semantic integration which speeds comprehension, similarly to what has been proposed for co-speech gesture (Kelly, Özyürek, & Maris, 2010). However, given the few significant results related to longer RTs when experimental conditions disrupted the simultaneous perception of the redundant stimulus provided by speech and sign in SSS, direct evidence for code blend facilitation is limited in the current study.

SSS perception in native signers

The eye tracking data of the LSE group with native signers, confirming previous findings in sign language (Agrafiotis et al., 2003), captured a massive bias of this group — more marked than in late signers— to look at the face when visual constraints did not obstruct in any way the visibility of signs. Although the sign message in SSS is syntactically empty and incomplete, the semantic contribution of signs to comprehend the spoken message proved to be essential to our native-signer participants. When experimental visual conditions (the magnified and gaze contingent conditions in Experiment 1) altered the normal use of peripheral vision, native signers foveated to a higher extent the signs. When speech and sign mismatched (Experiment 2), although they fixated on the face, they preferably relied on sign meaning. The fundamental role of sign to model gaze patterns and comprehend the sentence for native signers may have been driven by poor lip readers. The gaze behaviour of LSE signers in the gaze contingent condition corroborated the hypothesis that native signers mainly attend signs in SSS and that, in a normal visual condition, this happens via peripheral vision. On the other hand, gaze patterns of native signers in the magnified condition also corroborated to some extent the perceptual hypothesis. This hypothesis predicted that an easier perceptual access to lip movements could lead to a more balanced redistribution of fixations towards signs and face. A redistribution of gaze patterns was found in native signers, with more fixations towards the signs in the magnified condition than in baseline condition. Although the body was approximately the same size in the baseline and in the gaze contingent condition, the face was larger. Therefore, it could be that signers would no longer need to foveate on the face to access lipread words, and could centre on signs, their main source of information.

Limitations of the study

We discussed the findings of these experiments driven by our main hypothesis that deaf perceivers would attend signs in SSS via peripheral vision, as it had been found for sign language perception (Agrafiotis et al., 2003; Emmorey et al., 2009; Muir & Richardson, 2005). The obvious limitation of this study is that we tested the visual processing of SSS in highly controlled experimental visual conditions. Although they allowed us to isolate gaze patterns towards the target factors, lip movements and signs, they are to a great extent unnatural conditions. Furthermore, visual processing does not relate in a straightforward way to language comprehension. Therefore, our findings should be generalised to real-word processing of SSS with caution. Furthermore, in Experiment 1, we considered the average distribution of fixations over large time windows, as we did not know at what point signs contributed most. This makes the eye movement interpretation more difficult than if it referred to a specific event or to a specific signed word, as in the case of Experiment 2.

The other limitation of this study is the low number of participants per group, which limits the statistical power in the analyses. A first difficulty in recruiting participants concerns the great number of variables that should be considered when forming comparison groups within such a vastly heterogeneous population. A further challenge was to recruit deaf participants that attended bimodal settings or at least schools where more deaf students attended the same classroom. These difficulties added to the limitations of the use of the eye tracking equipment and the individual eye's features that sometimes prevented prevent eye tracking data collection. Considering all these issues, it is not uncommon that eye tracking studies on deaf population include a limited number of participants (De Filippo & Lansing, 2006; Emmorey et al., 2009).

Implications of these findings for deaf education

Even with these limitations, our data suggest that SSS could contribute to the comprehension of short sentences in deaf individuals. The results sustain the positive evidence for the use of SSS reported in earlier research that compared the effectiveness of SSS vs spoken language-only in supporting the acquisition of new vocabulary (Giezen et al., 2014; van Berkel-van Hoof et al., 2016). SSS might be a useful augmentative system to support the uptake of lexical information of the spoken language input, that can often be disrupted in noisy contexts, such as the classroom (Blom et al., 2016).

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Appendix A

Stimuli Materials Designed for the Experiment 1

Sentences are reported in the original Spanish version with English translation in parenthesis. By convention, the signs are transcribed in capital letters as spoken language glosses. Citation forms of verbs were used.

All sentences were preceded by the introductory sentence "Presta atencion a esto" (Pay attention to this) to familiarise the observer with the unusual visual condition (magnified or gaze continent conditions). Each sentence presentation was followed by a right or wrong picture. The wrong picture was inconsistent with the sentence for only one element (subject, verb or object).

Experimental Trials

A1. "El agricultor recoge las aceitunas" (The farmer gathers olives).

AGRICULTOR RECOGER ACEITUNA (FARMER GATHER OLIVE)

The wrong picture showed a girl gathering olives instead of a farmer.

A2. "El tigre duerme en el sofá" (The tiger sleeps on the sofa).

TIGRE DORMIR SOFA (TIGER SLEEP SOFA)

The wrong picture showed a cat sleeping on a sofa instead of a tiger.

A3. "La viajera descansa dentro una tienda" (The traveller has a rest in a tent).

PERSONA-VIAJAR DESCANSAR TIENDA (PERSON-TRAVEL REST TENT)

The wrong picture showed a dog laying in a tent instead of a traveller.

A4. "El médico se ha pintado las manos" (The doctor painted her hands).

MEDICO PINTAR MANOS (DOCTOR PAINT HANDS)

The wrong picture showed a baby with painted hands instead of a doctor.

A5. "La dueña está fregando el suelo" (The landlady is cleaning the floor).

DUENA FREGAR SUELO (LANDLADY CLEAN FLOOR)

The wrong picture showed a child cleaning the floor instead of a woman.

A6. "El joven se está ensuciando la cara" (The young man is getting his face dirty).

JOVEN ENSUCIAR CARA (BOY DIRT FACE)

The wrong picture showed a child getting his face dirty instead of a young man.

A7. "La niña está escribiendo a la pizarra" (The girl is writing on the blackboard).

NIÑA ESCRIBIR PIZARRA (GIRL WRITE BLACKBOARD)

The wrong picture showed a professor writing on the blackboard instead of a girl.

A8. "La pareja está sentada bajo el paraguas" (The couple is sitting under the umbrella).

PAREJA SENTAR BAJO PARAGUAS (COUPLE SIT BELOW UMBRELLA)

The wrong picture showed a woman under an umbrella instead of a couple of people.

A9. "El gorila ha recuperado un palo" (The gorilla has taken a stick).

GORILA RECUPERAR PALO (GORILLA TAKE STICK)

The wrong picture showed two dogs taking a stick instead of a gorilla.

A10. "El héroe está limpiando los cristales" (The hero is cleaning the windows).

HÉROE LIMPIAR CRISTAL (HERO CLEAN WINDOW)

The wrong picture showed a woman cleaning the windows instead of Spiderman.

A11. "El gato ha robado las salchichas" (The cat has stolen sausages).

GATO ROBAR SALCHICHAS (CAT STEAL SAUSAGES)

The wrong picture showed a dog stealing sausages instead of a cat.

A12. "Las amigas han mezclado los huevos" (The girlfriends are scrambling eggs).

FRIEND-FEMALE MEZCLAR HUEVO (FRIEND-FEMALE SCRAMBLE EGG)

The wrong picture showed a boy scrambling eggs instead of three girlfriends.

A13. "El ciclista corrió bajo la lluvia" (The cyclist rode under the rain).

CICLISTA CORRER LLUVIA (CYCLIST RIDE RAIN)

The wrong picture showed a cyclist riding in a sunny day instead of a rainy day.

A14. "El niño está jugando con la pelota" (The boy is playing with the ball).

NIÑO JUGAR PELOTA (BOY PLAY BALL)

The wrong picture showed a boy playing with a swing instead of playing with a ball.

A15. "El fontanero está arreglando el fregadero" (The plumber is reparing the sink).

FONTANERO ARREGLAR FREGADERO (PLUMBER REPAIR SINK)

The wrong picture showed a plumber repairing a toilet instead of a sink.

A16. "El vaso de café se volcó sobre el ordenador" (The coffee spilled on the computer).

CAFÉ VOLCAR ORDENADOR (COFFEE SPILL COMPUTER)

The wrong picture showed the coffee spilling on a book instead of spilling on the computer.

A17. "El hombre está recogiendo setas" (The man is gathering mushrooms).

HOMBRE RECOGER SETAS (MAN GATHER MUSHROOMS)

The wrong picture showed a man gathering chestnuts instead of mushrooms.

A18. "La mujer empuja el carro" (The woman pushes the trolley).

MUJER EMPUJAR CARRO (WOMAN PUSH TROLLEY)

The wrong picture showed a woman pushing a swing instead of a trolley.

A19. "Las chicas están tomando un café" (The girls are drinking a coffee).

CHICA TOMAR CAFÉ (GIRL DRINK COFFEE)

The wrong picture showed some girls drinking cocktails instead of coffee.

A20. "El hombre lleva el bañador" (The man wears a swimsuit).

HOMBRE LLEVAR BAÑADOR (MAN WEAR SWIMSUIT)

The wrong picture showed a man wearing a suit on the shore instead of a swimsuit.

A21. "Los chicos están tocando la guitarra" (The guys are playing the guitar).

NIÑO TOCAR GUITARRA (CHILD PLAY GUITAR)

The wrong picture showed some guys playing the flute instead of the guitar.

A22. "El deportista está escalando la montaña" (The athlete is climbing the mountain).

PERSONA-DEPORTE ESCALAR MONTANA (PERSON-SPORT CLIMB MOUNTAIN)

The wrong picture showed an athlete climbing the indoor climbing wall instead of a mountain.

A23. "Dos hombres están robando un coche" (Two men are stealing a car).

DOS HOMBRE ROBAR COCHE (TWO MAN STEAL CAR)

The wrong picture showed two men stealing a bag of a woman instead of a car.

A24. "La mujer está tendiendo en el jardín" (The woman is hanging the clothes in the garden).

MUJER TENDER ROPA JARDIN (WOMAN HANG CLOTHES GARDEN)

The wrong picture showed a woman hanging clothes in the balcony instead of hanging clothes in the garden.

A25. "La mujer está subiendo la escalera" (The woman is going up the stairs).

MUJER SUBIR ESCALERA (WOMAN GO UP STAIRS)

The wrong picture showed a woman going down the stairs instead of going up the stairs.

A26. "La mujer está dibujando las flores" (The woman is drawing flowers).

MUJER DIBUJAR FLORES (WOMAN DRAW FLOWERS)

The wrong picture showed a woman watering flowers instead of drawing flowers.

A27. "El hombre está resbalando con su bicicleta" (The man is falling down his bicycle).

HOMBRE RESBALAR BICICLETA (MAN FALL DOWN BICYCLE)

The wrong picture showed a man riding his bicycle instead of falling down the bicycle.

A28. "El hombre está escribiendo en el teclado" (The man is writing on the keyboard).

HOMBRE ESCRIBIR TECLADO (MAN WRITE KEYBOARD)

The wrong picture showed a man laying on a keyboard instead of writing on the keyboard.

A29. "La pareja está pintando la pared blanca" (The couple is painting the white wall).

PAREJA PINTAR PARED BLANCA (COUPLE PAINT WALL WHITE)

The wrong picture showed a couple hanging pictures on a wall instead of painting the wall.

A30. "El perro está mordiendo a su dueña" (The dog is biting his owner).

PERRO MORDER DUENO-MUJER (DOG BITE OWNER-FEMALE)

The wrong picture showed a dog licking his owner instead of biting the owner.

A31. "La ranchera está acariciando su caballo" (The rancher is caressing her horse).

RANCHO-MUJER ACARICIAR CABALLO (RANCH-WOMAN CARESS HORSE)

The wrong picture showed a woman washing a horse instead of caressing the horse.

A32. "La mujer está nadando en el mar" (The woman is swimming in the sea).

MUJER NADAR MAR (WOMAN SWIM SEA)

The wrong picture showed a woman on a mattress floating in the sea instead of swimming.

A33. "El jugador está cogiendo la pelota" (The player is taking the ball).

PERSONA-JUEGO RECOGER PELOTA (PERSON-PLAY TAKE BALL)

The wrong picture showed a football player kicking a ball instead of taking a ball.

A34. "Los chicos están saltando desde el acantilado" (The guys are jumping off a cliff).

CHICO SALTAR ABAJO ACANTILADO (BOY JUMP OFF CLIFF)

The wrong picture showed people sitting at the edge of a cliff instead of jumping off the cliff.

A35. "La peluquera está lavando el pelo" (The hairdresser is washing the hair).

PELUQUERIA-MUJER LAVAR PELO (HAIRDRESSING-WOMAN WASH HAIR)

The wrong picture showed a woman cutting hair instead of washing hair.

A36. "La mujer está bailando en la playa" (The woman is dancing on the shore) .

MUJER BAILAR PLAYA (WOMAN DANCE SHORE)

The wrong picture showed a woman running on the shore instead of dancing on the shore.

Practice Trials

A37. “El gato corre detrás de una mariposa” (The cat chases a butterfly).

GATO PERSEGUIR MARIPOSA (CAT CHASE BUTTERFLY)

The wrong picture showed a cat chasing a mouse instead of a butterfly.

A38. “Las mujeres luchan en el gimnasio” (The women are fighting in a gym).

MUJER LUCHAR GIMANASIO (WOMAN FIGHT GYM)

The wrong picture showed two children fighting in a gym instead of two women.

A39. “La mujer ha quemado el libro” (The woman burnt the book).

MUJER QUEMAR LIBRO (WOMAN BURN BOOK)

The wrong picture showed some bread burnt instead of a book burning.

A40. “El estudiante escribe en el folio” (The student writes on the paper).

PERSONA-ESCUELA ESCRIBIR FOLIO (PERSON-SCHOOL WRITE PAPER)

The wrong picture showed a student reading a paper instead of writing on a paper.

A41. “El niño odia las verduras” (The boy hates vegetables).

NIÑO ODIAR VERDURAS (BOY HATE VEGATABLES)

The wrong picture showed a boy eating vegetables with a happy instead of a disgusted face.

A42. “La abuela cose el vestido” (The grandmother sews the dress).

ABUELA COSER VESTIDO (GRANMOTHER SEW DRESS)

The wrong picture showed an old woman cutting some fabric instead of sewing a dress.

Appendix B

Stimuli Materials Designed for Experiment 2

Sentences are reported in the original Spanish version with English translation in parenthesis. Stimuli 1 to 15 include sentences with sign and spoken word mismatching. Stimuli 16 to 30 include sentences with sign and spoken word matching. By convention, signs are transcribed in capital letters. In the mismatching condition, the four response options were as follows: one correct picture representing the target object orally referred (T), one picture representing the competitor object referred through the mismatching sign (S), one picture semantically related to the verb (SR) and one picture representing an object semantically unrelated to the verb (SU). In the matching condition, the four response options were as follows: one picture representing the target object communicated by speech and sign matching (T), two pictures representing objects semantically related with the verb (SR) and one picture representing an object semantically unrelated to the verb (SU). For each sentence trial, the corresponding response options are reported.

Sentences with Sign and Spoken Word Mismatching

Practice trial.

B1. "Mi hermano compró un libro / COCHE" (My brother bought a book / CAR).

book (T); car (S); laptop (SR); hands (SU).

Experimental trials.

B2. "Mi tío cocina arroz / MEAT" (My uncle cooks rice / MEAT).

rice (T); meat (S); fish (SR); airplane (SU).

B3. "El niño jugó en el campo / PARQUE" (The boy played in the field / PARK).

field (T); park (S); beach (SR); laptop (SU).

B4. "Mi amiga viajó en avión / TREN" (My friend travelled by airplane / TRAIN).

airplane (T); train (S); bus (SR); milk (SU).

B5. "La mujer descansa en la playa / CASA" (The woman has a rest on the beach / HOME).

beach (T); house (S); mountains (SR); apple (SU).

B6. "El gato duerme en la mesa / SILLA" (The cat sleeps on the table / CHAIR).

table (T); chair (S); sofa (SR); fork (SU).

B7. "Mi sobrino busca el lápiz / RELOJ" (My nephew looks for the pencil / WATCH).

pencil (T); watch (S); ball (SR); mountains (SU).

B8. "Mi novio empuja el sofa / COCHE" (My boyfriend pushes the sofa / CAR).

sofa (T); car (S); table (SR); sea (SU).

B9. “Mi primo lanzó la pelota / BOTELLA” (My cousin threw the ball / BOTTLE).

ball (T); bottle (S); tomatos (SR); canyon (SU).

B10. “Mi tía comió tomate / PLÁTANO” (My aunt ate tomato / BANANA).

tomatos (T); banana (S); cherries (SR); pencil (SU).

B11. “El joven lavó los platos / ROPA” (The guy washed the plates / CLOTHES).

plates (T); clothes (S); salad (SR); mountains (SU).

B12. “La profesora bebe leche / CAFÉ” (The professor drinks milk / COFFEE).

milk (T); coffee (S); orange juice (SR); windows (SU).

B13. “Mi amigo vende quesos / HUEVOS” (My friend sells cheese / EGGS).

cheese (T); eggs (S); tomatoes (SR); arm (SU).

B14. “Mi padre perdió el partido / DINERO” (My father lost the match / MONEY).

football match (T); money (S); watch (SR); hands (SU).

B15. “Mi abuela planchó el pantalón / ABRIGO” (My grandmother ironed the trousers / COAT).

trousers (T); coat (S); shirt (SR); computer (SU).

Sentences with Sign and Spoken Word Matching

Practice trial.

B16. La mujer se cortó el dedo (The woman cut her finger).

finger (T); apple (SR); hair (SR); glass (SU).

Experimental trials.

B17. “Mi amigo miró el cuadro” (My friend looked at the painting).

finger (T); apple (SR); hair (SR); glass (SU).

B18. “El niño pintó un gato” (The boy drew a cat).

cat (T); house (SR); tree (SR); sweets (SU).

B19. “El director encendió el ordenador” (The boss turned on the computer).

computer (T); heater (SR); lamp (SR); sofa (SU).

B20. “El médico me aconsejó inyecciones” (The doctor recommended injections).

injections (T); tablets (SR); bed (SR); box (SU).

B21. Mi prima me regaló flores” (My cousin gave me flowers).

flowers (T); sweets (SR); book (SR); wood (SU).

B22. “La madre decoró la casa” (The mother decorated the house).

house (T); Christmas tree (SR); cake (SR); apple (SU).

B23. “El jefe destruyó el papel” (The boss destroyed the paper).

paper (T); computer (SR); car (SR); cherries (SU).

B24. “La anciana pidió la sal” (The old lady asked for salt).

salt (T); ice-cream (SR); sweets (SR); hands (SU).

B25. “Mi vecino encontró la llave” (My neighbor found the keys).

keys (T); wallet (SR); book (SR); feet (SU).

B26. “Mi tía me envió dulces” (My aunt sent me sweets).

sweets (T); doll (SR); book (SR); canyon (SU).

B27. “El estudiante ganó una medalla” (The student won a medal).

medal (T); computer (SR); money (SR); orange juice (SU).

B28. “La niña se sentó en la cama” (The girl sat on the bed).

bed (T); sofa (SR); car (SR); potatoes (SU).

B29. “Mi abuelo vende flores” (My grandfather sells flowers).

flowers (T); bicycle (SR); shoes (SR); sunset (SU).

B30. “Mi marido guardó la caja” (My husband stored the box).

box (T); jewels (SR); medal (SR); sea (SU).