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Lateralization of Auditory Processing of Silbo Gomero

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Abstract: Left-hemispheric language dominance is a well-known characteristic of the human language system. However, it has been shown that leftward language lateralization decreases dramatically when people communicate using whistles. Whistled languages present a transformation of a spoken language into whistles, facilitating communication over great distances. In order to investigate the laterality of Silbo Gomero, a form of whistled Spanish, we used a vocal and a whistled dichotic listening task in a sample of 75 healthy Spanish speakers. Both individuals that were able to whistle and to understand Silbo Gomero and a non-whistling control group showed a clear right-ear advantage for vocal dichotic listening. For whistled dichotic listening, the control group did not show any hemispheric asymmetries. In contrast, the whistlers' group showed a right-ear advantage for whistled stimuli. This right-ear advantage was, however, smaller compared to the right-ear advantage found for vocal dichotic listening. In line with a previous study on language lateralization of whistled Turkish, these findings suggest that whistled language processing is associated with a decrease in left and a relative increase in right hemispheric processing. This shows that bihemispheric processing of whistled language stimuli occurs independent of language.

Keywords: Silbo Gomero; whistle language; cerebral lateralization; brain asymmetry; dichotic listening task

1. Introduction

Both the left and the right hemispheres contribute to language processing, but they are relevant for different aspects of how language is processed. The auditory language comprehension model by Friederici [1] assumes that the left hemisphere is dominant for the processing of syntactic structures, semantic relations, grammatical and thematic relations, and information integration when spoken language is perceived. In contrast, the right hemisphere is dominant for the processing of prosody, intonational phrasing, and accentuation focus. This implies that if a language is processed that requires a greater amount of prosody processing to be understood correctly than spoken language, greater right-hemispheric activation should be expected.

Typically, processing spoken language activates a larger network of brain areas in the left than in the right hemisphere [2,3]. Overall, 96% of strong right-handers, 85% of ambidextrous individuals, and 83% of strong left-handers show left-hemispheric language dominance [4,5]. Left-hemispheric language dominance has been reported for both atonal [6,7] and tonal languages [8], and also for writing [9] as well as sign languages [10–12]. It has been suggested that this dominance of the left hemisphere is caused by superiority to assess fast temporal changes in auditory input, making the left hemisphere ideally suited to analyze voice onset times of different syllables [13–15].

One interesting way to investigate whether language lateralization indeed is based on these properties of the left hemisphere is to compare the processing of stimuli that require different degrees of fast temporal processing in order to be understood correctly. Here, it has been suggested that comparing vocal and whistled languages might be a meaningful approach to do so [16]. A whistled language is a system of communication based on whistling. Whistled articulated languages provide an unlimited number of messages [17], and a whistled sound has a higher pitch and intensity than one produced on the vocal cords, meaning a whistle is the most powerful sound that a human being can produce without any external tool [18]. Whistled languages utilize the vocabulary, grammar, syntax of the local speech, and even the phonology [19], with a reduction in phonemes [18,20], lending major importance to the context in the conversation. Except for isolated cases, whistled languages were, and still are, used for communication over long distances [19]. Depending on the atmospheric conditions (distance to the sea, air, presence or absence of mountains and valleys), a whistled message can be understood in distances over 3 km [19]. Today, 70 whistled languages are still in use [17].

One of the most common uses of whistle languages is communication among shepherds when they work in mountainous regions. This is also the main use of Silbo Gomero (meaning "whistle from La Gomera" in Spanish), a communication system based on Spanish still used today on the Canary Islands in Spain. While historically, there were a number of different whistled languages in use on the Canary Islands [18,20], Silbo Gomero is the only one still widely used today. Despite the arrival of newer communication technologies such as cell phones, Silbo Gomero is still taught in some schools on the Canary Islands. Younger pupils often learn it as part of their cultural heritage education, not so much for necessity. However, it still is very useful in natural contexts like trekking or in several parts of the islands where the telecommunication network is not powerful enough to ensure coverage.

Lateralization of whistled languages is still not well understood. The first and only study to investigate language lateralization in whistled languages was conducted in Turkey [16]. In this study, 31 proficient whistled Turkish speaking participants were tested with a dichotic listening task divided into two sections: hearing spoken Turkish syllables in the first one and whistled Turkish syllables in the second one. Dichotic listening is one of the most commonly used behavioral tasks to assess language lateralization [21,22]. Participants listen to pairs of syllables simultaneously on headphones. They have to indicate which syllable they understood best, and typically a right-ear/left-hemisphere advantage is observed for spoken syllables. In contrast to that, it was demonstrated that whistled Turkish is processed more bilaterally than spoken Turkish [16].

For Silbo Gomero, language lateralization has not been investigated yet. However, an fMRI study of Silbo Gomero has been performed, in which samples of spoken and whistled Spanish sentences and isolated words were presented to a group of five proficient whistlers (Silbadores) and a control group who were Spanish speakers but unfamiliar with Silbo Gomero [23]. The results indicate that the temporal regions of the left hemisphere that are usually associated with spoken-language function were also engaged during the processing of Silbo in experienced Silbadores. Both passive listening and active-monitoring tasks produced a common activation in the left superior posterior temporal gyrus. Activation of the right superior–midtemporal region was also evident across both the Silbo and Spanish speech conditions. Furthermore, activity increased in the right temporal lobe in response to non-linguistic pitch changes, tones, and complex sounds, but according to the authors, the same regions may also be associated with linguistic processing tasks. Group analysis indicated that the areas activated during both Spanish and Silbo processing in Silbadores differed significantly from those activated in non-whistlers. In particular, there was less ventral–anterior temporal activation during the processing of Silbo Gomero than during speech processing. The authors argued that this is due to there being less need to correctly identify specific phonological contrasts. Moreover, there was a stronger premotor activation for Silbo Gomero.

In the present study, we used the dichotic listening task to investigate language lateralization in Silbo Gomero. On the one hand, we wanted to test whether the results obtained in Turkish whistlers in Küşköy [16] could be replicated with Silbo Gomero in Tenerife and Gran Canaria. On the other hand, we wanted to test whether experience with the whistled language modulated the extent of left- and right-hemispheric contributions. To answer these questions, we tested 75 Spanish speakers separated into a non-whistling control group (CG) and an experimental group that was able to whistle and understand Silbo Gomero (WG) with vocal and whistle dichotic listening [16]. Based on the literature, we expected to find leftward lateralization in the spoken dichotic task, but a more bilateral pattern in the whistled dichotic listening. Moreover, within the WG, we assessed experience with Silbo Gomero by comparing individuals that were still learning Silbo Gomero with experienced whistlers. This was done since whistle experience and aptitude to learn a new language [24] could affect overall performance in the whistled dichotic listening task, as well as the lateralization pattern.

2. Materials and Methods

2.1. Participants

The sample consisted of 75 native Spanish speakers aged between 15 and 80 years. The cohort was separated into two groups according to their Silbo Gomero abilities. Participants in the control group (CG) were not able to whistle or understand Silbo Gomero (n = 25; aged between 22 and 80 years, mean age: 35.24 years, SD: 13.81; 12 women; 13 men). In contrast, participants in the whistlers' group (WG) were able to whistle and understand Silbo Gomero (n = 50; aged between 15 and 57 years, mean age: 38.27 years, SD: 10.30; 17 women and 33 men). There was no significant age difference between the WG and the CG ($t_{(67)} = -1.04$, $p = 0.30$).

Handedness was determined using the Edinburgh Handedness Inventory (EHI) [25]. The EHI is a ten-item questionnaire designed to assess handedness by self-report of the preferred hand for performing common activities such as writing and using utensils such as a toothbrush. Participants had five different answer options. They could indicate that they always used their right/left hand for a specific activity, mostly used their right/left hand for a specific activity, or used both hands equally for a specific activity. A laterality quotient (LQ) was calculated using the formula $LQ = [(R - L)/(R + L)] \times 100$. A score of 100 reflects consistent right-handedness, while a score of −100 reflects consistent left-handedness. In the CG, there were 3 left-handers and 22 right-handers. In the WG, there were 5 left-handers and 45 right-handers. There were no significant differences in the frequency of left-handedness between the two experimental groups ($p = 0.79$). Additionally, we compared the EHI LQs for the two groups. In the CG, the mean LQ was 51.62 (SD = 54.06; range: −100 to 100). In the WG, the mean LQ was 47.62 (SD = 40.92; range: −71.43 to 100). There was no significant difference in EHI LQ between the two groups ($t_{(73)} = 0.36$; $p = 0.72$). We did include left-handed participants on purpose in the sample. Left-handers represent a substantial portion of the human population (10.6%) and it has recently been argued that they need to be included in laterality studies, as they are an important part of the normal range of human diversity [26]. Thus, excluding them would give a skewed picture of the actual laterality patterns for Silbo Gomero.

In order to assess the effects of experience with Silbo Gomero on language lateralization, we further subdivided the WG into two groups. First, a learners group (LG) (aged between 15 and 57 years, mean age: 37.82 years, SD: 9.91; 11 women; 14 men) that included individuals that had been practicing Silbo Gomero for 3 years or less (mean time whistling: 1.16, SD: 0.47). Second, an advanced group (AG) (age between 18 and 57, mean age: 38.73 years, SD: 10.90; 6 women; 19 men), who had active experience with Silbo Gomero for more than 3 years (mean time whistling: 6.08, SD: 5.00). Participants had no history of any neurological or psychiatric diseases that could affect language perception or production. All participants had unimpaired hearing capabilities according to self-report. The local ethics committee of the psychological faculty at Ruhr-University Bochum approved the procedure. All participants gave written informed consent and were treated in accordance with the Declaration of Helsinki. For the one 15-year-old participant, parental informed consent was also obtained.

2.2. Language Skills

A questionnaire regarding language skills was handed to the participants. Subjects were asked to declare their first language: mother tongue(s), second spoken languages: the language and approximated level of competency (subjects who did not know their level according to the Common European Framework were given a subjective measure: low, medium or advanced). In addition, the subjects in the WG were asked to indicate the amount of time since they had learned to whistle. Subjects in the CG were asked whether they were aware of the existence of Silbo Gomero. Most of the participants in the WG learned Silbo Gomero in courses and the majority of the whistlers in the AG were active Silbo teachers at the time point at which the study was conducted. In general, participants presented a wide range of language skills including early bilingualism and second spoken languages. In the CG, 14 people were bilingual speakers (Spanish-Catalán, Spanish-Gallego, Spanish-Asturiano, and Spanish-German). The mean number of second spoken languages was 2.2 (SD: 1.04). In the LG, there were 3 bilingual speakers (Spanish-German). The mean number of second spoken languages in this group was 0.92 (SD: 0.76). In the AG, there were no bilingual speakers. In this group, the mean number of second spoken languages was 0.84 (SD: 0.62).

2.3. Dichotic Listening Task

Language lateralization was assessed using an auditory dichotic listening paradigm programmed and presented using Presentation® software (Neurobehavioral Systems, Inc., Albany, USA). A similar task has been used before to assess whistle language lateralization in Turkish whistle language speakers [16].

For the dichotic listening task, syllable pairs consisting of two out of five different consonant-vowel (CV) syllables (ba [ba], ca [ka], cha [tʃa], ga [ga], ya [ya]) were used as stimuli. The syllables were chosen according to the five groups of distinguishable consonants [18] for learners of Silbo Gomero. Overall, there were 25 different syllable pairs, five homonyms (ba/ba, ca/ca, cha/cha, ga/ga and ya/ya) and 20 heteronyms (ba/ca, ba/cha, ba/ga, ba/ya, ca/ba, ca/cha, ca/ga, ca/ya, cha/ba, cha/ca, cha/ga, cha/ya, ga/ba, ga/ca, ga/cha, ga/ya, ya/ba, ya/ca, ya/cha, ya/ga). The spoken stimuli were recorded by a native male Spanish speaker. The whistled stimuli were recorded by a proficient male whistler. Syllable onset within each syllable pair stimuli was set at the beginning of the sound file using Audacity® software (Trademark of Dominic Mazzoni, Pittsburgh, PA, USA). Stimuli had a mean duration of 300 ms for the spoken syllables, and 750 ms for the whistled syllables. The stimuli were presented via headphones (Beyerdynamic GmbH, Heilbronn, Germany) at 80 dB.

The keyboard was customized: five buttons were labeled with the presented syllables (ba, ca, cha, ga, ya). After the stimulus presentation, participants had to press one of five keys to indicate which of the syllables they had perceived more accurately. The inter-stimulus interval was fixed at two seconds.

The task was divided into two conditions: a vocal condition and a whistled condition. Each condition had one practice block that was not included in the final analysis and two experimental blocks. Independently from the preferred hand, participants started with right or left hand alternatively in a randomized fashion and changed the hand in the middle of each block. In the second test block, the headphones were reversed to avoid the possible confounding effects of slightly different noise levels coming from the left and the right headphone speaker (which should not exist). The practice block for both the vocal and the whistled condition consisted of 20 trials to get participants accustomed to the task and the tone of the syllables. Afterwards, the two experimental blocks for each condition were presented. Here, all of the possible combinations of the syllables were presented: 5 homonyms and 20 heteronyms twice for each ear (one for every ear-hand combination). Thus, the total number of trials was 100 for each condition (80 heteronym and 20 homonym trials)

2.4. Statistical Analysis

Statistics were performed using IBM SPSS Statistics for Windows, Version 21.0. (IBM Corp., Armonk, NY, USA). The dichotic laterality index (LI) of the participants was calculated as LI = [(RE − LE)/(RE + LE)] * 100, (RE = number of right ear responses, LE = number of left ear responses). This index varies between −100 and +100, with positive values indicating a right ear advantage (REA) and negative values indicating a left-ear advantage (LEA) [16]. Performance on the dichotic listening task was analyzed parametrically using ANOVAs. Neyman–Pearson correlation coefficients were determined in order to investigate possible relationships between the variables.

3. Results

3.1. Dichotic Listening

Table 1 shows the results of the dichotic listening task.

Table 1. Results of the dichotic listening task: number of correct right ear (RE) and left ear (LE) answers on heteronym trials for the control group (CG) and the whistlers' group (WG) for vocal and whistled dichotic listening, as well as errors and laterality indexes (LIs).

Condition	Variable	CG	WG
Vocal	RE	48.40 ± 1.99	46.66 ± 1.41
	LE	23.88 ± 1.92	26.36 ± 1.36
	Error	7.72 ± 1.11	6.98 ± 0.82
	LI	27.71 ± 4.04	22.01 ± 2.97
Whistle	RE	21.00 ± 1.50	29.52 ± 1.06
	LE	21.20 ± 1.06	24.10 ± 0.75
	Error	37.80 ± 1.46	26.38 ± 1.03
	LI	−0.48 ± 2.03	7.21 ± 2.46

3.2. Error Rates

In order to check whether participants in the WG showed better recognition of whistled syllables than participants in the CG, we compared error rates between the groups using a 2 × 2 repeated measures ANOVA with the within-subjects factor condition (VOCAL, WHISTLE) and the between-subjects factor group (WG, CG). The main effect of condition reached significance ($F_{(1,73)} = 690.19$; $p < 0.001$; partial $\eta^2 = 0.90$), indicating that overall, participants made more errors during whistled dichotic listening (32.09 ± 0.89) than during vocal dichotic listening (7.35 ± 0.67). Moreover, the main effect of group reached significance ($F_{(1,73)} = 23.14$; $p < 0.001$; partial $\eta^2 = 0.24$). This effect indicated that overall, participants in the WG made fewer errors (16.68 ± 0.73) than participants in the CG (22.76 ± 1.03). In addition, the interaction condition × group reached significance ($F_{(1,73)} = 32.16$; $p < 0.001$; partial $\eta^2 = 0.31$) and Bonferroni-corrected post hoc tests were used to further investigate this effect. The analysis revealed that there was no significant difference between CG and WG for vocal dichotic listening ($p = 0.58$). In contrast, there was a significant difference in whistled dichotic listening ($p < 0.001$). Here, the CG made substantially more errors (37.8 ± 1.46) than the WG (26.38 ± 1.03).

3.3. Laterality Index

In order to ensure comparability with a previous whistle language dichotic listening study in Turkish participants [16], we first compared dichotic listening LIs between the CG and WG, irrespective of experience (see Table 1). To this end, we used a 2 × 2 repeated measures ANOVA with the within-subjects factor condition (VOCAL, WHISTLE) and the between-subjects factor group (WG, CG). While there was no main effect of group ($F_{(1,73)} = 0.08$; $p = 0.77$), the main effect of condition reached significance ($F_{(1,73)} = 56.82$; $p < 0.001$; partial η^2=0.44), indicating a stronger REA for spoken syllables (LI = 24.86 ± 2.54) than for whistled syllables (LI = 3.37 ± 1.89). Moreover, the interaction condition × group reached significance ($F_{(1,73)} = 5.50$; $p < 0.05$; partial $\eta^2 = 0.07$) and Bonferroni-corrected post hoc tests were used to further investigate this effect. The analysis revealed that there was no significant difference between the CG and WG for vocal dichotic listening ($p = 0.27$). In contrast, there was a significant group difference for whistled dichotic listening ($p < 0.05$). Here, the CG showed a slight negative LI that was close to zero (−0.48 ± 2.03), indicating no lateralization in this group (one-sample *t*-test against zero, $p = 0.82$, no difference from zero). In contrast, the WG showed a positive LI (7.21 ± 2.46), indicating a significant REA (one-sample t-test against zero, $p = 0.01$).

3.4. Right-Ear Advantage

To test whether the percentages of individuals with a REA during vocal and whistled dichotic listening differed between CG and WG, we determined for each participant whether they showed a REA (positive LI) or a LEA (negative LI) during vocal and whistled dichotic listening. We then compared the numbers of left- and right-preferent individuals between the CG and WG using Mann–Whitney U-tests. For vocal dichotic listening, there was no significant difference between the CG and WG ($p = 0.37$). Here, participants from both groups were much more likely to show a REA than a LEA (CG: REA: 96%, LEA: 4%; WG: REA: 90%, LEA: 10%). However, the effect reached significance for whistled dichotic listening ($p < 0.01$). Here, participants in the CG showed a LEA more often than a REA (REA: 36%, LEA: 64%). In contrast, participants in the WG showed a REA more often than a LEA (REA: 68%, LEA: 32%).

3.5. Association between Whistled and Vocal Dichotic Listening

In order to investigate the association between whistled and vocal dichotic listening, we calculated Neyman–Pearson correlation coefficients between the LIs for vocal and whistled dichotic listening. In the CG, the effect failed to reach significance (r = −0.02; $p = 0.91$). In the WG, the correlation coefficient also failed to reach significance (r = 0.26; $p = 0.07$).

3.6. Association between Dichotic Listening and Handedness

In order to investigate the associations between whistled and vocal dichotic listening and handedness, we calculated Neyman–Pearson correlation coefficients between the LIs for vocal and whistled dichotic listening and EHI LQ. In both the CG and the WG, all effects failed to reach significance (all p's > 0.10).

3.7. The Effect of Experience with Silbo Gomero

In order to investigate whether the extent of experience with Silbo Gomero affected language lateralization, we re-analyzed the data from the WG by splitting it into a learner's groups (LG) and an advanced group (AG). We then compared dichotic listening LIs between LG and AG, using a 2 × 2 repeated measures ANOVA with the within-subjects factor condition (VOCAL, WHISTLE) and the between-subjects factor group (LG, AG). The main effect of condition reached significance ($F_{(1,48)} = 19.45$; $p < 0.001$; partial $\eta^2 = 0.29$), indicating a stronger right-ear advantage during spoken dichotic listening (LI = 22.01 ± 3.00) than during whistled dichotic listening (LI = 7.21 ± 2.48). All other effects failed to reach significance (all p's > 0.65).

In order to test whether the age of acquisition of Silbo Gomero had an impact on whistle language lateralization, we calculated Neyman–Pearson correlation coefficients between the age of acquisition on whistle language LI for both the LG and the AG. Both effects failed to reach significance (LG: r = 0.22; $p = 0.34$; AG: −0.36; $p = 0.104$). In addition, there were no significant correlations either between the LI and the number of years whistling (LG: r = 0.266; $p = 0.20$; AG: r = 0.091; $p = 0.67$).

4. Discussion

The aim of the present study was to investigate the brain lateralization of whistled Spanish. We hypothesized that contrary to spoken Spanish, Silbo Gomero is more bilaterally represented, as both the left and right hemispheres are needed to process whistled stimuli correctly. This hypothesis was confirmed by the data. For vocal dichotic listening, both groups showed a pronounced REA, replicating the main finding of a substantial body of evidence for this task [21,27–33]. Thus, both participants in the CG and participants in the WG on average showed leftward lateralization for the processing of vocal Spanish. As was to be expected, the two groups did not differ from each other in this condition, as participants in both groups were native Spanish speakers.

There was, however, a group difference in the whistled condition. Here, participants in the CG did not show any lateralization, indicating that they did not process the whistled syllables as language. In contrast, participants in the WG still showed a significant REA in this condition, which was, however, substantially decreased compared to vocal dichotic listening. This indicates that in the whistled condition, the right hemisphere likely played a more important role in stimulus processing than during vocal dichotic listening.

This reduction in the REA is in line with the main finding of a previous dichotic listening study in proficient Turkish whistlers [16]. Here, the authors reported that whistled language comprehension relies on symmetric hemispheric contributions, associated with a decrease in left and a relative increase in right hemispheric encoding mechanisms. While we did not find a completely symmetrical pattern for whistled Silbo Gomero, the LI of the WG in the whistle condition was substantially reduced compared to the vocal condition, indicating a similar principle to that observed in the Turkish study. Why whistled Silbo Gomero still elicits a slight REA in the present study might be explained by differences in cohort characteristics or differences between Turkish and Spanish. Interestingly, it has been shown that most participants show a LEA for musical stimuli [30,31]. It could be conceived that whistled languages present a system of communication with processing demands somewhere between that of languages and that of music, explaining the reduced REA in processing whistled stimuli.

Our findings are also in line with the only neuroimaging study on Silbo Gomero that has been conducted so far [23]. While it is difficult to directly compare the results of the two studies, as we did not perform fMRI scans, our results are largely in line with the overall findings of the previous work. Specifically, the authors showed that in proficient whistlers, left temporal brain areas commonly associated with language are also activated during the processing of Silbo Gomero. However, activation in the right temporal lobe also increased during whistle processing. The authors assumed that this is due to the need to process to non-linguistic pitch changes, tones, and complex sounds when listening to Silbo Gomero. This agrees with our finding of a reduced REA in the WG in the whistle condition. The idea that different cognitive processes are involved in whistle and vocal dichotic listening is also supported by the lack of significant correlation between spoken LI and whistled LI, which makes it likely that non-verbal processes are involved in understanding whistled dichotic listening.

Our finding that whistlers still show a REA for the processing of whistled dichotic listening is also in line with previous studies in non-verbal languages. Generally, it has been shown that independent of language modality, a left-lateralized pattern can be observed for both signed and spoken languages [34,35]. Similar results were also found for Morse code. Experienced Morse code operators show a significant REA, indicating left hemisphere lateralization, for the perception of dichotically presented Morse code letters [36].

We assumed that whistle experience could affect overall performance in the whistled dichotic listening task, as well as the lateralization pattern. However, both the direct statistical comparison of the two groups and the correlation analyses indicated that experience with Silbo Gomero did not significantly affect language lateralization. This indicates that the critical period in which individuals that learn Silbo Gomero switch from internally translating whistles to vocal language to natively understanding the whistle language might be outside the time range we tested.

Interestingly, our findings are also largely in line with a recent meta-analysis on language lateralization in bilinguals [37]. Here, it was shown that language lateralization differed between bilinguals who acquired both languages by 6 years of age and those who acquired the second language later. While the early bilinguals showed bihemispheric processing for both languages, the late bilinguals showed a left-hemispheric dominance for both languages. In our sample, both the LG and the AG acquired Silbo Gomero decidedly later in life than by 6 years of age. Thus, both groups could be considered late bilinguals, which would explain why they did not differ from each other. Since Silbo Gomero is a whistled communication system based on Spanish, it is somewhat unclear whether or not Spanish-speaking individuals able to communicate in Silbo Gomero could be considered truly bilingual or not. Nevertheless, these findings on language lateralization in bilinguals clearly suggest that for future studies on lateralization of Silbo Gomero processing, it would be meaningful to tests participants that acquired Silbo Gomero before their sixth birthday.

In addition to this meta-analysis, there is also an empirical study on language lateralization in bilinguals that might be of relevance for the understanding of the present results [38]. Here, the authors analyzed language lateralization assessed with the dichotic listening task for both the first and the second language in two groups of bilinguals. In the first group, both languages the bilingual participants spoke came from the same linguistic root. In the second group, the two languages the bilingual participants spoke came from different linguistic roots. Here, the authors found that when the second language came from a different linguistic root than the first language, the participants showed comparable brain lateralization for both languages. However, in the group were the two languages came from the same linguistic root, the second language showed a stronger REA than when the two languages came from different linguistic roots. As spoken Spanish and Silbo Gomero clearly have the same linguistic roots, this effect might explain why we found partly left-hemispheric processing for Silbo Gomero.

One effect of note we found was the above-chance recognition rates of the CG for whistled stimuli. It is, however, not unlikely that the participants in the CG correctly identified some syllables in the whistle condition despite having no knowledge of Silbo Gomero. For example, it was shown that native speakers of French and Spanish understood whistled vowels above chance, even if they did not speak any whistle language [39]. Moreover, the findings that the recognition rates of the CG for whistled stimuli were above-chance might also be related to phonetic symbolism. For example, it has been shown that participants are able to guess the meaning from word sounds of languages unknown to them based on the processing of phonetic symbolism [40]. Still, participants in the WG understood a significantly higher number of syllables than those in the CG in this condition, as evidenced by the analysis of the error rates.

Concerning methodological issues, a potential drawback of the present study was the impossibility to use the exact same syllables as in the whistled Turkish dichotic listening study [16], since the syllables "ba" and "pa" used in the Turkish experiment are not distinguishable in Silbo Gomero. As a result, the possible mechanisms involved in the two studies are very likely similar but possibly not identical. Moreover, due to the high relevance of context for understanding whistled languages, it is somewhat difficult to test a whistled language using just syllables as stimuli, especially CV syllables. The problem lies in the fact that the whistled language needs a context to be understood and some parts of the word or sentence are not intelligible for the receptor but are clarified thanks to the rest of the sentence. Furthermore, some syllables sound very similar to each other (like "ga" and "ya") and are thus potentially difficult to distinguish from one another without any other extra information. This explains the somewhat high error rate of the WG for whistled dichotic listening. In future studies, this issue could be remedied by using syllables VCV (vowel-consonant-vowel) that according to the comments of several participants in the WG would be easier to understand for them. Moreover, it was not optimal that potential hearing issues were assessed by self-report. Future dichotic listening studies on Silbo Gomero should include detailed audiometric testing prior to data collection. Another point that could be optimized in future studies is a stronger control of language background between the groups, specifically regarding bilingualism. In our study, a higher number of bilingual individuals were found in the CG than in the WG, which could potentially have affected results. Additionally, it needs to be mentioned is that handedness can be measured as both hand preference [25] and hand skill [41]. In our study, we only measured hand preference using the EHI. Future studies should also include a measure of hand skill, as the two variables can differ to some extent [42].

Our study has several interesting implications for future studies. For example, outside of the Carreiras et al., 2005, study, no neuroimaging studies have been conducted with Silbo Gomero speakers. Thus, using modern neuroimaging techniques to further unravel the brain networks involved in the understanding and production of whistled languages is a crucial next step. Moreover, using EEG to understand the electrophysiological correlates of Silbo Gomero would be a meaningful aim for future studies. Furthermore, a previous study has used transcranial electrical stimulation of the auditory cortex to modulate the REA in dichotic listening [43]. Similar study designs could help to disentangle differences between language lateralization for spoken and whistled languages. In addition, studies with people who suffered from damage in left hemisphere language areas could yield promising results for using whistled languages as a means of rehabilitation for communication impairments.

In conclusion, the processing of Silbo Gomero leads to a reduced REA compared to spoken Spanish. This is in line with previous findings for whistled Turkish, implying that processing of whistled languages occurs more bihemispherically, independently of which language is whistled. This shows that if left-hemispheric functions like fast temporal processing are less relevant for processing a specific form of language, leftward language lateralization decreases.

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