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Functional lateralization of tool-sound and action-word processing in a bilingual brain

BACKGROUND

The impact of bilingualism on lateralized brain functions such as praxis – the control of skilled actions – and language representations themselves, particularly in the auditory domain, is still largely unknown. Recent studies suggest that bilingualism affects both basic (fundamental frequency) sound and action-related speech processing. Whether it can impact non-verbal action sound processing is a question of debate.

PARTICIPANTS AND PROCEDURE

Here we examined twenty bilinguals using a dichotic listening paradigm, in which in addition to repeating the just heard action words, participants named – in Polish or English – one of two simultaneously presented tool sounds from attended ears. The results were compared with data from these same participants tested with reading the same words in a visual-half field paradigm.

RESULTS

In contrast to typical outcomes from monolinguals, the laterality indices of action-related sound processing (verbal and non-verbal) were not left lateralized but hemispherically balanced. Notably, despite similar organization of tool- and action-word sound processing, their auditory (balanced) and visual-language (left-lateralized) representations might be independent because there were no significant correlations between any of their laterality indices.

CONCLUSIONS

This indicates that bilingualism might involve reshuffling/reorganization of typically lateralized brain functions and such plasticity will have consequences for second language learning strategies, as well as for neurorehabilitation.

KEY WORDS

bilingualism; tool sounds; action words; praxis; language learning

BACKGROUND

Sounds are an important source of information for all mammals (Oertel, Cao, Ison, & Allen, 2017). They are mostly used for locating other animals, especially when visual information is limited (Clarke & Geiser, 2015). For people, sounds are not only a source of spatial information, but also of emotional experiences (Duffy, Waitt, & Harada, 2016). Furthermore, humans categorize sounds in many different ways, for example separating verbal from non-verbal sounds (even infants can do this, Wild et al., 2017), separating action-related sounds from action-unrelated sounds, or distinguishing vocalization sounds produced by living organisms and man-made items, such as tools (Lewis, Brefczynski, Phinney, Janik, & DeYoe, 2005, see also Crivelli, Rueda, & Balconi, 2018; Schneider, Sundararajan, & Mooney, 2018). Interestingly, when processing action-related sounds, including tool sounds, one can observe neural activity in motor-relevant areas of the human brain (Lewis, Phinney, Brefczynski-Lewis, & DeYoe, 2006; Bourquin, Simonin, & Clarke, 2013; Clarke & Geiser, 2015), and in areas related to recognition and performance of actions (Rizzolatti et al., 1996; D'Ausilio et al., 2009), such as Broca's area (Binkofski & Buccino, 2004; Corballis, 2010). Similar effects have also been observed in non-human primates. For example, when monkeys listen to sounds related to some type of action, the same neurons in area F5 (which is thought to be a homologue of human Broca's area) may fire as when they implement this very action (Kohler et al., 2002; Galati et al., 2008). This does not necessarily mean, however, that action-related sound processing and action performance rely on the same neural substrates; it merely indicates that there are some neural connections between areas involved in these functions in the primate brain (Helmich, Holle, Rein, & Lausberg, 2015; de Borst, Valente, Jaaskelainen, & Tikka, 2016).

Earlier studies by Lewis and collaborators (Lewis et al., 2005; Lewis et al., 2006) suggest that such links between tool sound representations and praxis representations can also be found in people. In right-handers who most often (in 96% of cases) have typically lateralized praxis skills (to the left hemisphere, e.g. Johnson-Frey, Newman-Norlund, & Grafton, 2005; Lewis, 2006; Bidula & Kroliczak, 2015; Corballis, 2017; see also Bornkessel-Schlesewsky, Schlesewsky, & von Cramon, 2009; Przybylski & Kroliczak, 2017; Styrkowiec, Nowik, & Kroliczak, 2019), tool sound processing is also most often left lateralized (Lewis et al., 2005). On the other hand, in left-handers, where an atypical lateralization of praxis, as well as language, often occurs (in over 30% of cases either balanced or right hemisphere lateralization is found: Knecht et al., 2000; Johnson-Frey, 2004; Vingerhoets et al., 2012; see also Kroliczak, Piper, & Frey, 2011; Vingerhoets et al., 2013; Somers et al., 2015; Joliot, Tzourio-Mazoyer,

& Mazoyer, 2016; Bidula, Przybylski, Pawlak, & Kroliczak, 2017), tool sound processing is also frequently atypically lateralized (more "towards" the right hemisphere, Lewis et al., 2006).The organization of many functions in the human brain, including praxis, may change, however, due to some experiences, especially those taking place at early stages of human development (Haberling, Corballis, & Corballis, 2016; Lane et al., 2017; see also Michel, 2017). One of the experiences of this type is bilingualism (Costa & Sebastian-Galles, 2014; Stein, Winkler, Kaiser, & Dierks, 2014; Garcia-Penton, Perez Fernandez, Iturria-Medina, Gillon-Dowens, & Carreiras, 2014; Kuhl et al., 2016). In the brains of bilingual people, changes are observed both at the subcortical level, in the context of brain morphology (Burgaleta, Sanjuan, Ventura-Campos, Sebastian-Galles, & Avila, 2016), and at the level of the organization of functions (Grundy, Anderson, & Bialystok, 2017). However, less is known about more specific neural consequences of bilingualism (Garcia-Penton et al., 2014). However, one might assume that bilingualism may result, for example, in a slightly different interhemispheric organization than in monolinguals (Hull & Vaid, 2007; Felton et al., 2017), which could then be reflected, for example, in a more balanced representation of functions, including language (Burgaleta et al., 2016), and its relation to praxis skills (Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Pulvermuller & Fadiga, 2010; Kroliczak et al., 2011; Haberling & Corballis, 2015; Kroliczak, Piper, & Frey, 2016; but cf. Poeppel, 2001). Moreover, a recent study (Skoe, Burakiewicz, Figueiredo, & Hardin, 2017) suggests that in the human brain the organization of basic sound processing, which refers to the auditory neuroaxis (ability to process sounds that are not speech-specific, such as the fundamental frequency), is influenced by bilingual experience. The latter demonstration is of particular interest because there is also evidence that orally mimicked tool sounds (and animal vocalizations) in monolingual contexts (and/or even monolingual individuals) engage left hemisphere structures (Lewis, Silberman, Donai, Frum, & Brefczynski-Lewis, 2018).

In one of our previous studies (Klichowski & Kroliczak, 2017), which utilized two paradigms aimed at studying functional lateralization (see Kimura, 2011) – dichotic listening (DL, see Hugdahl, 2012; Hund-Georgiadis, Lex, Friederici, & von Cramon, 2002) and visual-half field (VHF, see Hunter & Brysbaert, 2008; Van der Haegen, Cai, Seurinck, & Brysbaert, 2011; Verma & Brysbaert, 2011; for evidence for compatibility of DL and VHF tests, see Oltedal & Hugdahl, 2017) and stimuli in the form of words – we demonstrated that bilingualism (here: late bilingualism) could have also affected the processing of speech-specific sounds. (Note that we studied individuals who started second language learning as children, but typically well after the age of 6; in some ac-

Michal Klichowski,
Agnieszka Nowik,
Gregory Kroliczak,
James W. Lewis

counts early bilingualism takes place before the age of 6; see Reifegerste, Elin, & Clahsen, 2019). The bilinguals who we examined revealed hemispherically balanced speech sound processing (whether uttered in their first or second language), demonstrating a rather typical productive language lateralization at the same time. Because in that study participants listened to action words, these outcomes suggest that bilinguals may not only have an atypical (more balanced) hemispheric organization of word-sound processing but also of other (e.g., non-verbal) action-related sounds, including tool sounds. (Note that in the human brain there is some evidence for a link between areas involved in processing the meaning of actions and representations of action-related sounds, Buccino et al., 2005; Fischer & Zwaan, 2008; see also Bechtold et al., 2019).

In order to investigate whether or not bilinguals would also show atypical lateralization of non-verbal action-related sounds, we examined the majority of bilinguals from our previous study (Klichowski & Kroliczak, 2017), utilizing the same paradigm as the one used for studying the lateralization of sounds (DL). However, instead of words, the participants listened to tool sounds, namely, exactly the same stimuli as the ones used in previous studies by Lewis et al. (2005, 2006), because in DL, verbal as well as non-verbal sounds can be effectively studied (Kimura, 2011). In short, we compared the lateralization of language processing and lateralization of action-related sound processing, in the form of action words and tool sounds. The comparison of these data sheds new light on the organization of sound processing in the bilingual brain.

PARTICIPANTS AND PROCEDURE

The experiment was conducted in the Action and Cognition Laboratory in the Institute of Psychology at Adam Mickiewicz University in Poznan, Poland. The study complied with guidelines of the local Ethics Committee for Research Involving Human Subjects and was carried out in accordance with the ethical principles of the 2013 World Medical Association Declaration of Helsinki (for details, see: https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/).

The order of all tasks, performed either in English or Polish, and the majority of tests described here were counterbalanced across participants, except for tool sound processing, which was always presented last (but importantly, preceded equally often by the other tests and tasks; see below). Each test was taken on a different day (all the subjects visited the laboratory three times).

PARTICIPANTS

Twenty healthy volunteers (10 women, age range: 20-45, mean = 27.75, SD = 5.96) took part in this study. The experiment was conducted with the understanding and written consent of each participant. All subjects had normal hearing and normal or corrected-to-normal visual acuity. Nineteen individuals declared themselves as right-handed (with mean *Laterality Quotient* [LQ] = 94.58, SD = 11.62, and *Laterality Score* [LS] = 61.84, SD = 10.57), and one individual declared herself as typically left-handed (LQ = −100, and LS = −70), as confirmed by the results of the revised – shorter – version of the Edinburgh Handedness Inventory (Dragovic, 2004; cf. Veale, 2014). All participants were native speakers of Polish (L1) who also declared their late bilingualism (i.e., they started second language learning typically well after the age of 6; see Reifegerste et al., 2019) but high fluency in English (L2). Participants' fluency in L2 was established in three ways: (1) on the basis of their field of study – English Philology and/or Pedagogy in English at Adam Mickiewicz University in Poznan (Poland), and/or (2) the possession of language certificates (e.g., at least Certificate in Advanced English – CAE, typically higher; as in the study by Krefta, Michalowski, Kowalczyk, & Kroliczak, 2015), and/or (3) the requirement of fluent command of English for performing a job in international companies.

STIMULI AND PROCEDURE

Visual half-field (VHF) tests. The stimuli were the following: 20 Polish action words, 20 English action words (see Klichowski & Kroliczak, 2017). The action words were in their infinitive forms in Polish, and typically in non-finite, gerund forms in English. The rationale was to minimize the difference in length between Polish and English action words. Note that Polish verbs are typically much longer than the corresponding English verbs. For the list of stimuli used in our VHF test, see Appendix A.

Participants were seated in front of a monitor at a viewing distance of ~57 cm (as in Klichowski & Kroliczak, 2017). Each trial started with a central fixation cross of a duration of 1000 milliseconds (ms). Next, two stimuli were presented in the left (LVF) and right visual field (RVF) with a central arrow pointing to the left or right. The role of the arrow was to indicate the target stimulus. The participants were instructed to read out loud the target stimulus, and to ignore the non-target stimulus. Each stimulus was presented as a target or non-target. All stimuli were displayed in Times New Roman font, with 50 points size – subtending 3.5 to 8.5 degrees of visual angle for the shortest and longest words, respectively, and 2 deg. for their heights, and were shown in black color on a white background.

After 217 ms[1], both stimuli were masked with strings of hash marks (the length of the presented string was always equal to the length of the masked stimulus). Then, only a central arrow pointing to the place where the target was shown remained on the screen and stayed there until a vocal response was registered. A blank screen of a variable (1250, 1500, or 1750 ms) duration was introduced between successive trials. Trial structure and timing are depicted in Figure 1.

The VHF test consisted of two pseudo-randomly presented blocks of trials, which for convenience will be called first and second. In the first block, action words were written in Polish and the participant was instructed to read them in this language, while in the second block, action words were written in English and the participant was instructed to read them in that language. At the beginning of a given block, participants were informed of its type. The language of instructions always corresponded to the language used in a given block. In total, each block consisted of forty trials. Note that before the actual experiment, a training session was administered. Stimuli used during the training session did not appear in the subsequent experiment.

Dichotic listening (DL) tests. The action words from VHF tests (*.wav files; recorded by an academic teacher of English pronunciation; see Klichowski & Kroliczak, 2017) and 20 unique tool sounds were used. The tool sounds (also *.wav files) were obtained from previous studies (Lewis et al., 2005, 2006) by selecting the most common twenty. For the list of stimuli used in DL tests,

see Appendix B. While only seven items from the action word and tool sound lists overlapped (as not all actions are associated with sounds, or can be easily identified by sounds), all of them are commonly known.

As before, participants were seated in front of a monitor at a viewing distance of ~57 cm. Each trial started with a central fixation cross of a duration of 1000 ms. Next, two stimuli with synchronized onsets were presented separately to the left (LE) and right ear (RE), via an 'HS-702' PC-Headset speaker, together with a central arrow displayed on the computer monitor and pointing either to the left or right. The role of the arrow was to indicate the target stimulus. The participants were instructed to repeat aloud the target action words, or to name the target tool sounds, and to ignore the non-target stimuli. Each stimulus was presented as a target and as a non-target, in the left and right ear. A blank screen with a central arrow pointing to one of the sides was displayed until a vocal response was registered. A blank screen of variable (1250, 1500, or 1750 ms) duration was introduced between successive trials. The trial structure is depicted in Figure 2.

Before the actual test, a training (action word processing) or learning (tool sound processing) session was administered. A training session consisted of two blocks similar to the actual test. During the learning session, participants listened to tool sounds and learned their names (action names). The training/learning session was repeated twice. Notably, before the training/learning session the participants – listening to various sounds – were asked to set the
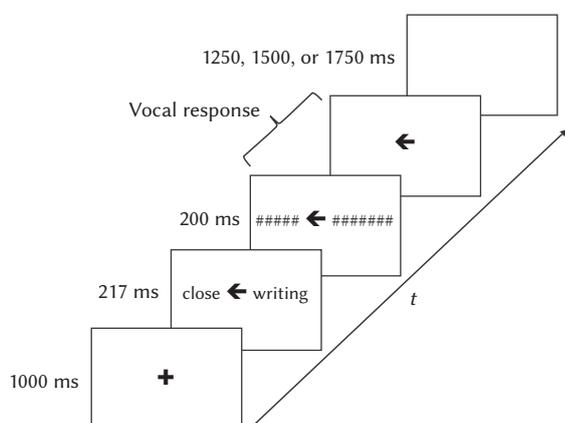
Figure 1. Trial structure and timing in visual half-field tests. After a fixation point was presented on a blank screen for 1000 ms, two stimuli (the target stimulus and the non-target stimulus) were shown bilaterally for 217 ms, with a central arrow pointing to the location of the target. 200-ms masks then covered the stimuli. After the onset of a participant's vocal response, a blank screen of variable duration (1250, 1500, or 1750 ms) was introduced and preceded the next trial.

Figure 2. Trial structure and timing in dichotic listening test. After a fixation point was presented on a blank screen for 1000 ms, two stimuli (the target stimulus and the non-target stimulus) were presented in the left and right ear (headset speaker), with a central arrow pointing to the location of the target. After the onset of a participant's vocal response, a blank screen of variable duration (1250, 1500, or 1750 ms) was introduced and preceded the next trial.
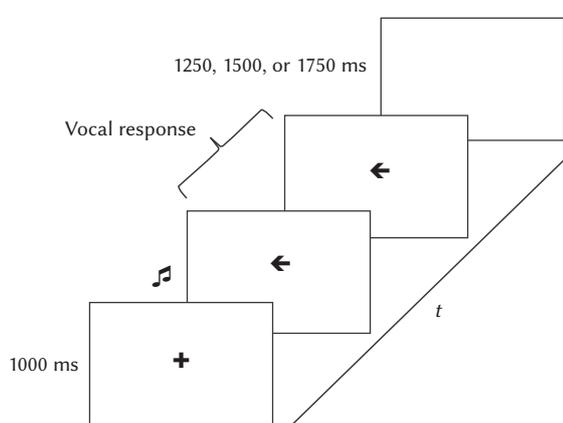
Michal Klichowski,
Agnieszka Nowik,
Gregory Kroliczak,
James W. Lewis

volume for each ear (each headset speaker), so that they had a subjective feeling of equal stimulus volume in both ears. The language of the training/learning session and instruction always corresponded to the language used in a given block.

Similar to the VHF test, the DL tests consisted of two pseudo-randomly presented blocks of trials, which again for convenience will be referred to as first and second. For action word processing in the first block the participant was instructed to repeat Polish action words, while in the second block, he/she was instructed to repeat English action words. For tool sound processing, in the first block the participant was instructed to name tool sounds in Polish, and in the second one, to name tool sounds in English. At the beginning of a given block, the participants were informed of its type. In total, each block consisted of forty trials.

All experiments (i.e., both VHF and DL tests) were implemented in SuperLab 4.5.4 for Mac by Cedrus (http://www.superlab.com/). The visual stimuli or cues were presented on a 21.5-inch Apple iMac monitor. Response times (RTs), as measured by the onset of the vocal reaction, were detected by the SV-1 Smart Voice Key (http://www.cedrus.com/sv1/). As only vocal reaction times are acquired by the voice key, the experimenter constantly monitored response accuracy (ACC).

DATA ANALYSES

To investigate the lateralization of stimulus processing, laterality indices (LIs) were obtained using the following formulae, separately for accuracy (LI_{ACC}) and response times (LI_{RT}):

$LI_{ACC} = ([R_{acc} − L_{acc}]/[R_{acc} + L_{acc}])*100$
$LI_{RT} = ([L_{rt} − R_{rt}]/[L_{rt} + R_{rt}])*100$

For LI_{ACC} calculations, R and L represent response accuracy (%) for stimuli presented in the RVF and LVF (VHF), or in the right and left ear, RE and LE, respectively (in DL). For LI_{RT} calculations, L and R represent mean response times (ms) in correct trials with stimuli presented in the LVF and RVF (VHF), or in the LE and RE (DL).

Positive values of LI_{ACC} and/or LI_{RT} indicate right visual field/ear advantage, thus left hemisphere dominance. A reversed effect (negative values) indicates left visual field/ear advantage, thus right hemisphere dominance. Finally, significant differences between LIs for different stimuli or languages might indicate that these stimuli/languages are differently lateralized in the brain. Consequently, correlational analyses of LIs for L1 and L2 or for stimuli from VHF and DL allowed us to examine whether or not representations of L1 are truly related to the representations of L2, and whether or not there are links between the representations of action-related sounds and the representations of languages.

For each test, two separate (1 for response accuracies and 1 for response times) 2×2 repeated-measures analyses of variance (rm-ANOVA) were conducted, with the following within-subjects factors: language (L1, L2) and target location (RVF, LVF or RE, LE). To compare differences between LIs, t-tests for dependent samples were also used. When LIs from different tests were contrasted, supplemental 3×2 rm-ANOVAs were run with test type (VHF: action word processing, DL: action word processing, DL: tool sound processing) and language (L1, L2) as within-subjects factors. Where necessary, the required post-hoc tests of simple main effects were Bonferroni corrected. Finally, to investigate whether or not representations of L1 and L2, or representations of language and action-related sounds (or each other), share any common organizational features, we performed correlational analyses of LIs using Pearson correlations method (r).

The adopted level of significance was α = .05. For reaction times accompanying correctly recognized stimuli, outliers greater than two standard deviations above or below the mean (calculated for each condition) were removed due to the possibility of an equipment malfunction and/or participants guessing the answer. All statistical analyses were carried out using IBM SPSS Statistics 24.0.

RESULTS

VISUALLY PRESENTED ACTION WORD PROCESSING

Figure 3A shows that for ACC there was no main effect of language ($F(1, 19) = 0.90$). However, we observed a main effect of target location ($F(1, 19) = 66.27$, $p < .001$), such that ACC was significantly better for action words presented in RVF (72.2%), as compared to LVF (44.0%) (difference between means = 28.2%, SE = 3.5%, Bf-p < .001). Although we observed language by target location interaction ($F(1, 19) = 7.55$, $p < .05$), this effect, as Figure 3C shows, occurs both for L1 (difference between means = 33.5%, SE = 4.3%, Bf-p < .001) and L2 (difference between means = 23.0%, SE = 3.6%, Bf-p < .001), with the latter difference being slightly smaller.

For RT the main effect of language was significant ($F(1, 19) = 21.50$, $p < .001$), and it was such that participants read action words faster in L1 (mean = 1061 ms), as compared to L2 (mean = 1179 ms) (difference between means = 118 ms, SE = 25 ms, Bf-p < .001). This effect is depicted in Figure 3B. We also observed a main effect of target location ($F(1, 19) = 15.08$, $p = .001$), such that participants read action words presented in RVF faster (mean = 1067 ms), as compared to LVF (mean = 1173 ms) (difference between means = 106 ms, SE = 27 ms, Bf-p < .01). While the language by target location interaction was not significant ($F(1, 19) = 1.59$,

$p = .077$), a priori comparisons revealed, as Figure 3D shows, that responses towards action words presented in RVF both for L1 were substantially faster (difference between means = 124 ms, *SE* = 22 ms, *Bf-p* < .001) than those for L2 (difference between means = 87 ms, *SE* = 38 ms, *Bf-p* < .05), as compared to LVF.

Finally, there were no significant differences between lateralization of action word processing (or more precisely, between action word LIs) for L1 and L2.

Figure 4A-B shows that this effect (a right visual-field/left hemispheric domination) occurs neither for ACC-based LIs (difference between means = 6.48, *SE* = 4.01, $t(19) = 1.62$, $p > .05$) nor RT-based LIs (difference between means = 2.12, *SE* = 1.13, $t(19) = 1.88$, $p > .05$). However, we found strong significant correlations between individuals' L1 and L2 LIs, for both ACC-based LIs ($r = .56$, $p = .010$) and RT-based LIs ($r = .60$, $p < .01$). These effects are shown in Figure 4C-D.
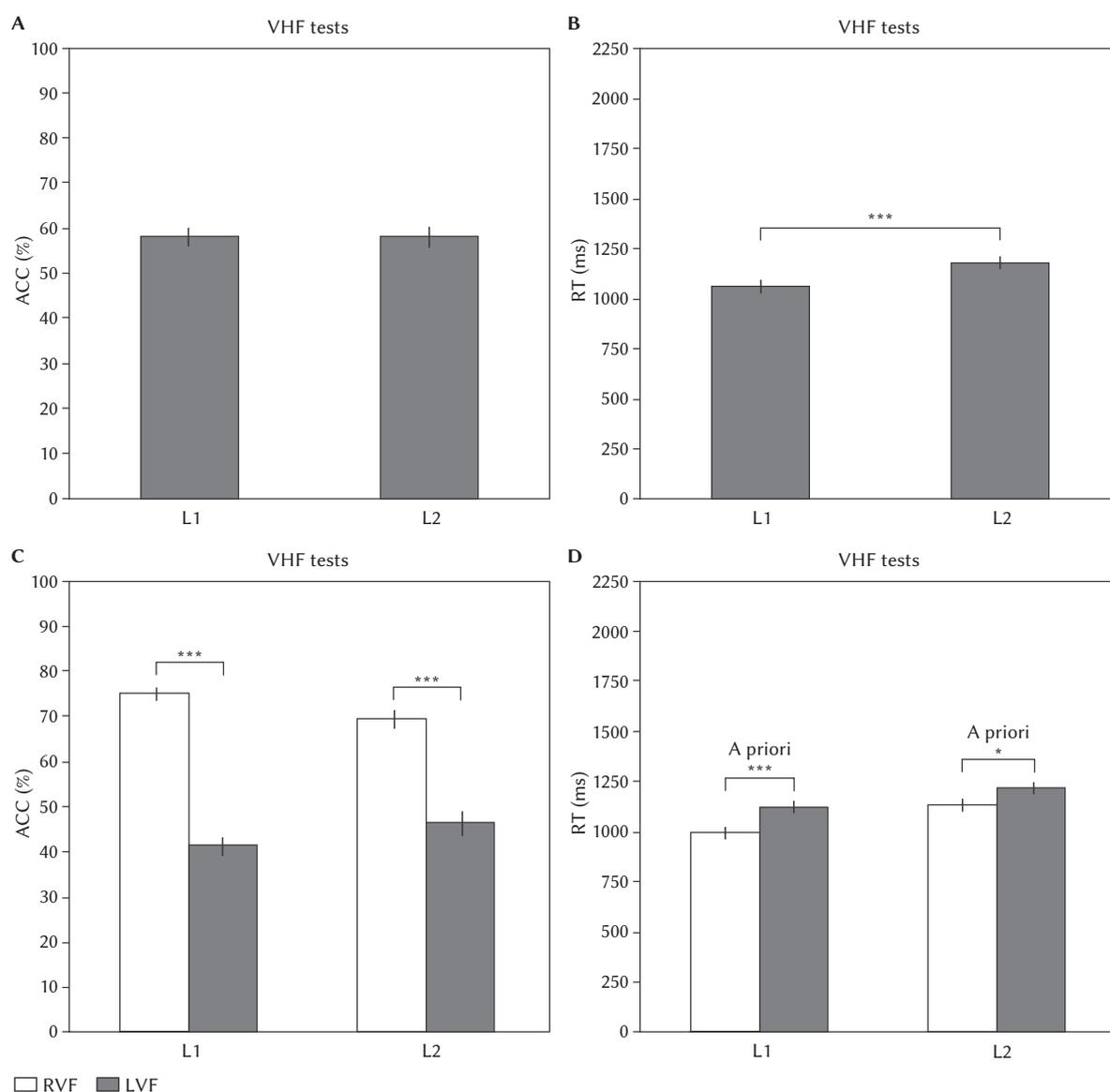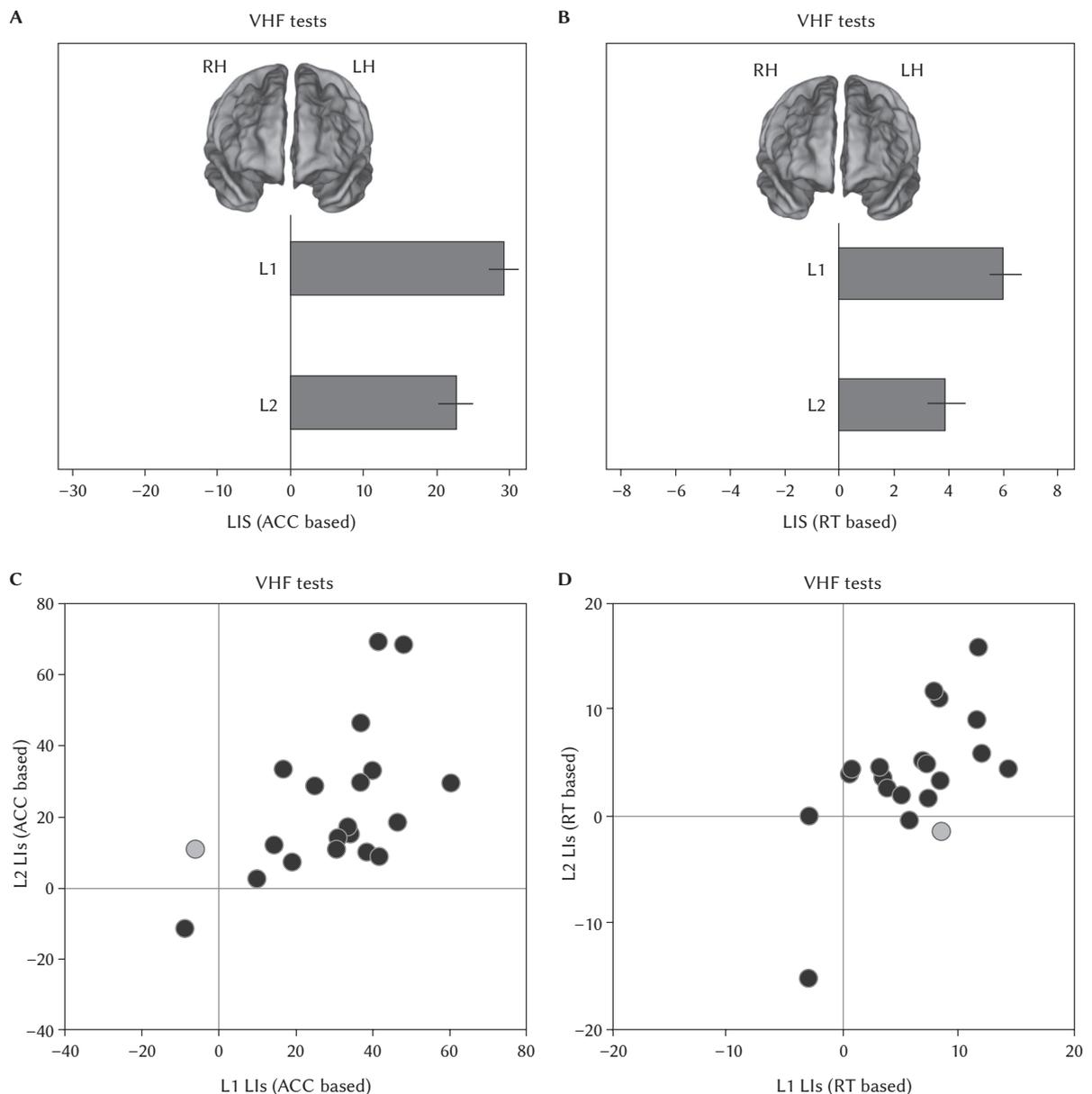
Figure 3. Visual half-field (VHF) processing of action words. (A) Differences between accuracy (ACC) for action word reading in the first language (Polish, L1) and second language (English, L2): No significant effects. (B) Differences between response times (RTs) for correctly read action words in L1 and L2: RTs were significantly faster for L1. (C) Differences between ACC for reading action words presented in right visual field (RVF) and left visual field (LVF): ACC was significantly better for RVF both in L1 and in L2. (D) Differences between RTs for correctly read action words presented in RVF and LVF: RTs were significantly faster for RVF (as compared to LVF) both in L1 and in L2, with the difference for the former tending to be substantially greater. Only significant results are indicated here. Asterisks indicate significant *p*-values: *$p < .05$, ***$p < .001$. Error bars depict standard errors of the means.

AUDITORILY PRESENTED ACTION WORD PROCESSING

Figure 5A shows that for ACC there was a main effect of language ($F(1, 19) = 8.37$, $p < .01$), such that ACC was significantly higher for action words repeated in L1 (83.1%), as compared to L2 (75.0%) (difference between means = 8.1%, SE = 2.8%, Bf-p < .01). However, as Figure 5C shows, there was no main effect of target location ($F(1, 19) = 0.45$, $p > .05$) and the language by target location interaction was not significant, either ($F(1, 19) = 0.48$, $p > .05$). Figure 5B-D shows that for RT there were no significant effects (all $p > .05$).

Michal Klichowski,
Agnieszka Nowik,
Gregory Kroliczak,
James W. Lewis

Figure 4. Hemispheric organization (laterality indices, LIs) of processing for visually presented action words in the first language (Polish, L1) and second language (English, L2). (A) Accuracy (ACC)-based LIs: No significant differences between lateralization of action word processing in L1 and L2. (B) Response-time (RT)-based LIs: No significant differences between lateralization of action word processing in L1 and L2. (C) Individual ACC-based LIs: There were significant correlations between lateralization of action word processing in L1 and L2. (D) Individual RT-based LIs: There were significant correlations between lateralization of action word processing in L1 and L2. LH – left hemisphere, RH – right hemisphere; VHF – visual half-field; black dots – right-handed participants; gray dot – left-handed participant. Error bars depict standard errors of the means.

There were no significant differences between lateralization of action word processing (or more precisely, between action word LIs) for L1 and L2, either. Figure 6A-B shows that this effect (no ear/ hemispheric dominance) occurs both for ACC-based LIs (difference between means = 2.25, SE = 3.24, $t(19) = -0.69$, $p > .05$) and RT-based LIs (difference between means = 2.41, SE = 1.39, $t(19) = 1.74$, $p > .05$). Nevertheless, as Figure 6C-D shows, there were no significant correlations between individuals' L1 and

L2 LIs, for both ACC-based LIs ($r = .27$, $p = .252$) and RT-based LIs ($r = .27$, $p = .253$).

TOOL SOUND PROCESSING

Figure 7A shows that for ACC there was a main effect of language ($F(1, 19) = 6.47$, $p < .05$), such that participants were better in processing tool sounds in L1 (59.7%), as compared to L2 (50.4%) (difference
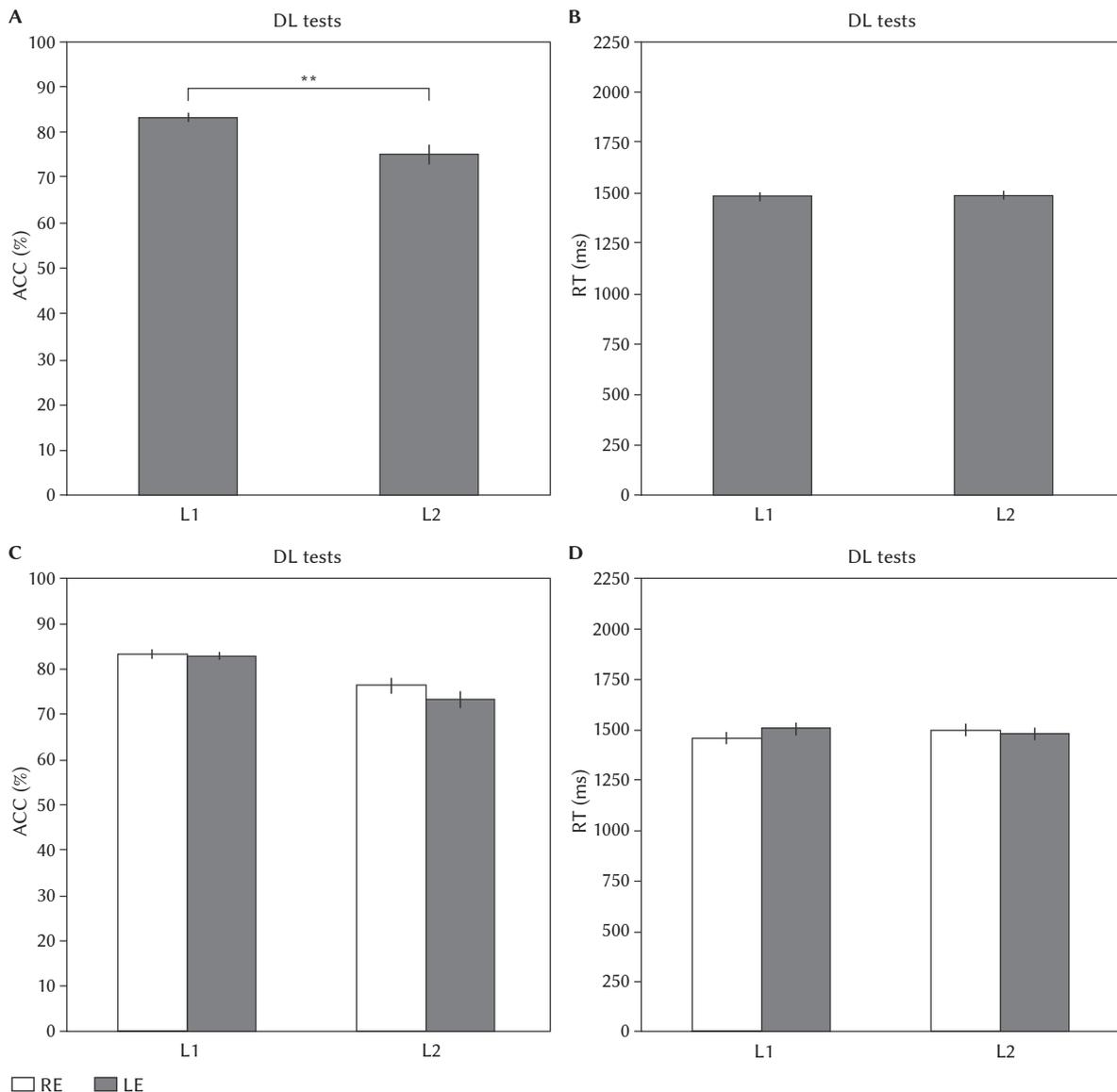
Figure 5. Dichotic listening (DL) involving action words. (A) Differences between accuracy (ACC) for action word processing in the first language (Polish, L1) and second language (English, L2): ACC was significantly higher for L1. (B) Differences between response times (RTs) for correctly repeated action words in L1 and L2: No significant effects. (C) Differences between ACC for action words presented in right ear (RE) and in left ear (LE): No significant effects. (D) Differences between RTs for correctly repeated action words presented in RE and LE: No significant effects. Asterisks indicate significant p-values: ** $p < .01$. Error bars depict standard errors of the means.

between means = 9.4%, *SE* = 3.7%, *Bf-p* < .05). Nevertheless, there was no main effect of target location (*F*(1, 19) = 0.33, *p* > .05). Figure 7C shows that the language by target location interaction was not significant either (*F*(1, 19) = 4.06, *p* > .05).

A similar pattern of results was observed for RTs. As Figure 7B shows, we found a main effect of language (*F*(1, 19) = 5.72, *p* < .05), such that participants named tool sounds faster in L1 (2027 ms), as compared to L2 (2181 ms) (difference between means = 154 ms, *SE* = 64 ms, *Bf-p* < .05). There was no main effect of target location (*F*(1, 19) = 0.07, *p* > .05), and, as Figure 7D shows, the language by target location interaction was not significant, either (*F*(1, 19) = 0.98, *p* > .05).

Michal Klichowski,
Agnieszka Nowik,
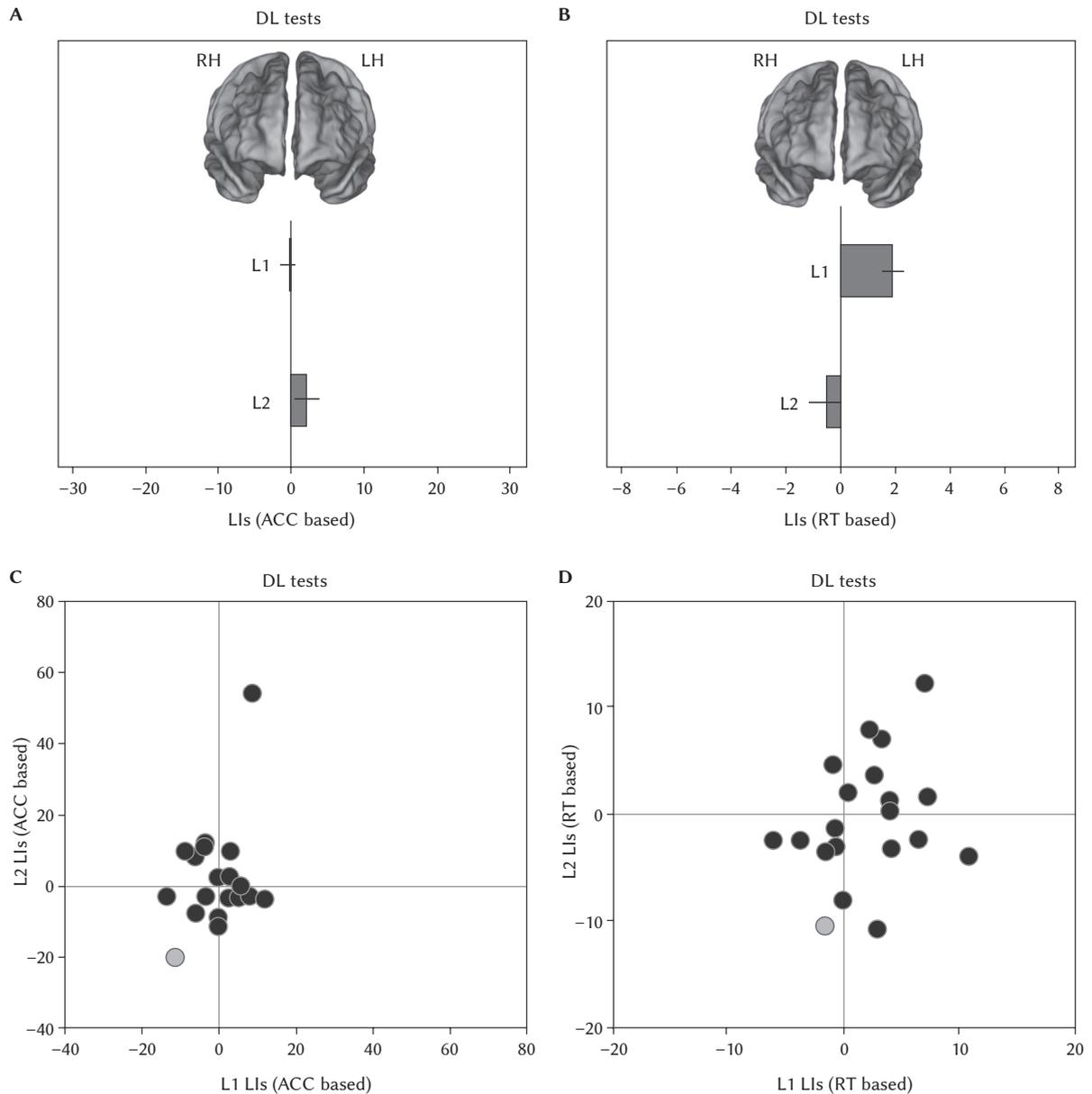Gregory Kroliczak,
James W. Lewis

Figure 6. Hemispheric organization (laterality indices, LIs) of processing for auditorily presented action words in the first language (Polish, L1) and second language (English, L2). (A) Accuracy (ACC)-based LIs: No significant differences between lateralization of action word processing in L1 and L2. (B) Response-time (RT)-based LIs: There is a trend, rather than a significant difference between lateralization of action word processing in L1 and L2. (C) Individual ACC-based LIs: There were no significant correlations between lateralization of action word processing in L1 and L2. (D) Individual RT-based LIs: There were no significant correlations between lateralization of action word processing in L1 and L2. LH – left hemisphere, RH – right hemisphere; DL – dichotic listening; black dots – right-handed participants; gray dot – left-handed participant. Error bars depict standard errors of the means.

Figure 8A-B shows a significant right ear/left hemispheric advantage for tool sounds named in L1, as compared to L2, but only for ACC-based LIs (difference between means = 8.13, *SE* = 3.54, *t*(19) = 2.30, *p* < .05; for RT-based LIs *t*(19) = 1.00, *p* > .05). Moreover, as Figure 8C-D shows, there were non-significant trends, but no significant correlations between individuals' L1 and L2 LIs, for both ACC-based LIs (*r* = .15, *p* = .542) and RT-based LIs (*r* = .29, *p* = .214).

LATERALITY OF VISUALLY PRESENTED ACTION WORD PROCESSING VERSUS AUDITORILY PRESENTED ACTION WORD AND TOOL SOUND PROCESSING

Figure 9A shows that for ACC there was a main effect of test type (*F*(2, 38) = 24.95, *p* < .001), such that we observed a significant left hemispheric advantage for VHF, as compared to both DL tests (i.e., for visually presented action word processing vs. auditorily pre-
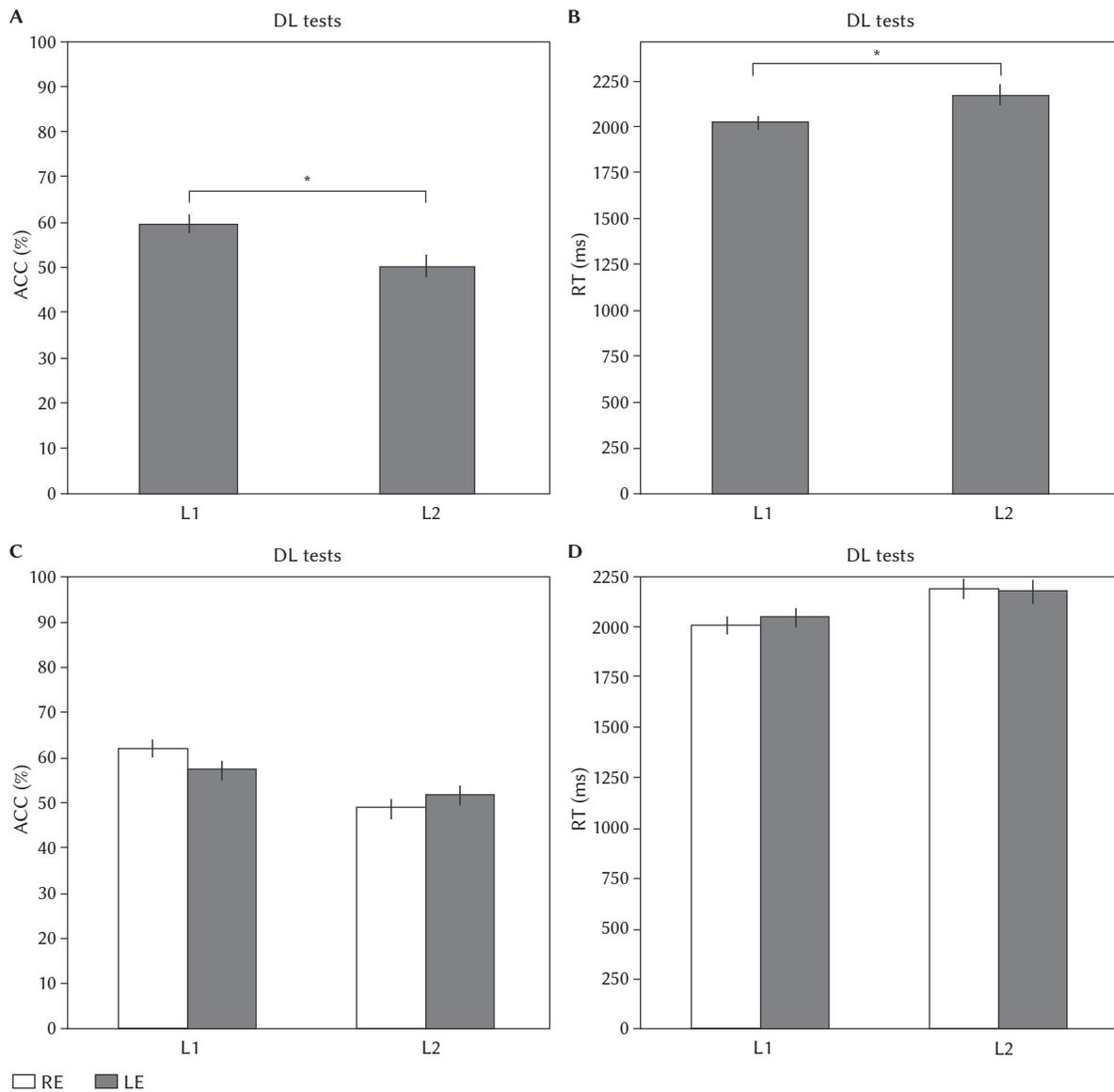
Tool-sound processing in a bilingual brain

Figure 7. Dichotic listening (DL) processing of tool sounds. (A) Differences between accuracy (ACC) for tool sound naming in the first language (Polish, L1) and second language (English, L2): ACC was significantly better for L1. (B) Differences between response times (RTs) for correctly named tool sounds in L1 and L2: RTs were significantly faster for L1. (C) Differences between ACC for tool sound naming presented in right ear (RE) and left ear (LE): No significant effects both for L1 and in L2. (D) Differences between RTs for correctly named tool sounds presented in RE and LE: No significant effects both for L1 and in L2. Asterisks indicate the only significant results, with * referring to *p* < .05. Error bars depict standard errors of the means.

sented action word processing: difference between means = 25.10, SE = 4.38, Bf-p < .001; visually presented action word processing versus tool sound processing: difference between means = 25.35, SE = 4.66, Bf-p < .001; auditorily presented action word processing versus tool sound processing: no significant differences, Bf-p > .05). Nevertheless, there was no main effect of language (F(1, 19) = 3.50, p > .05) and the test type by language interaction was not significant, either (F(2, 38) = 2.53, p > .05).

Figure 9B shows that for RT there was also a main effect of test type (F(2, 38) = 7.77, p < .01), such that (similarly to ACC) we observed a significant left hemispheric advantage for VHF, as compared to both DL

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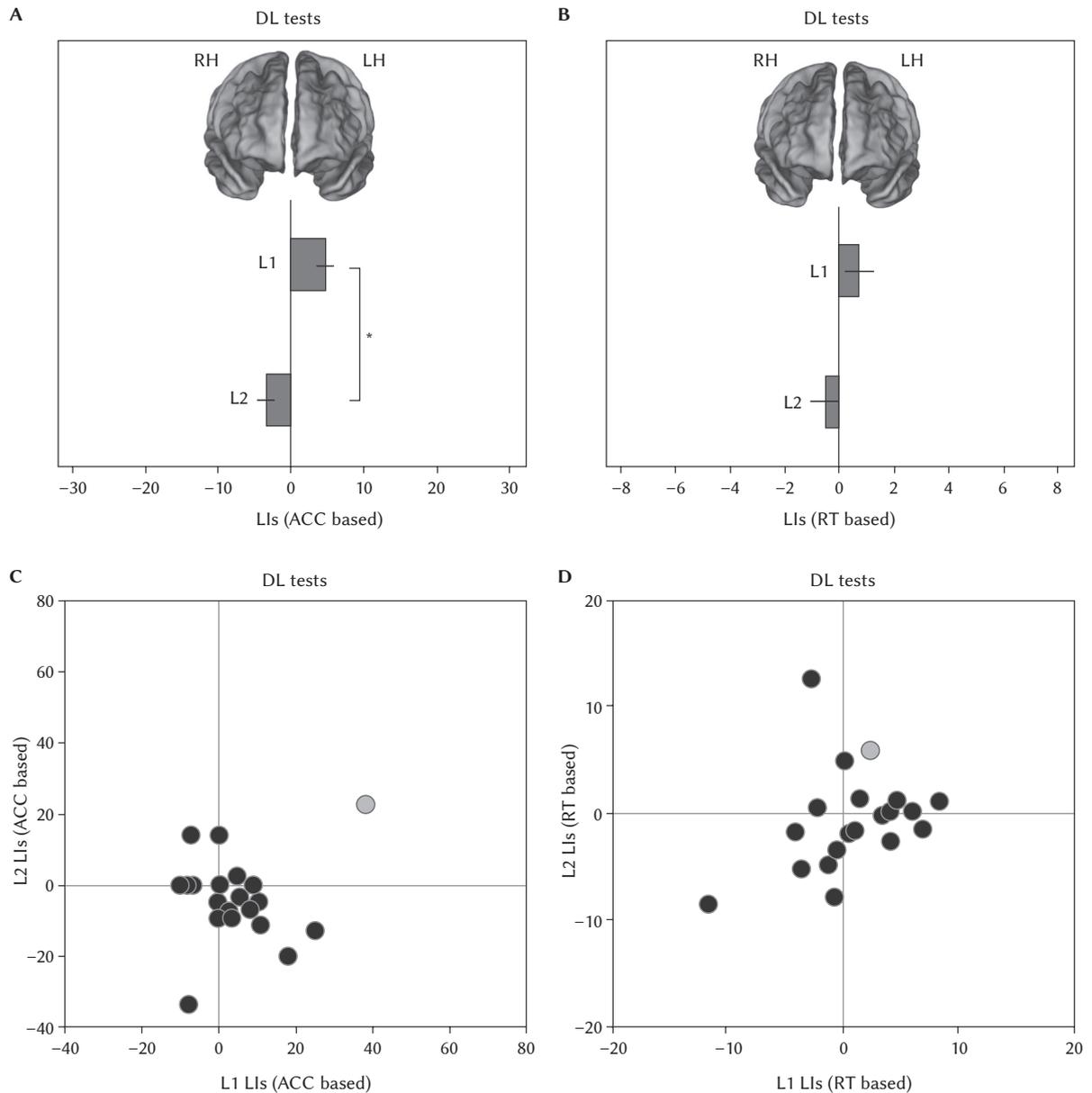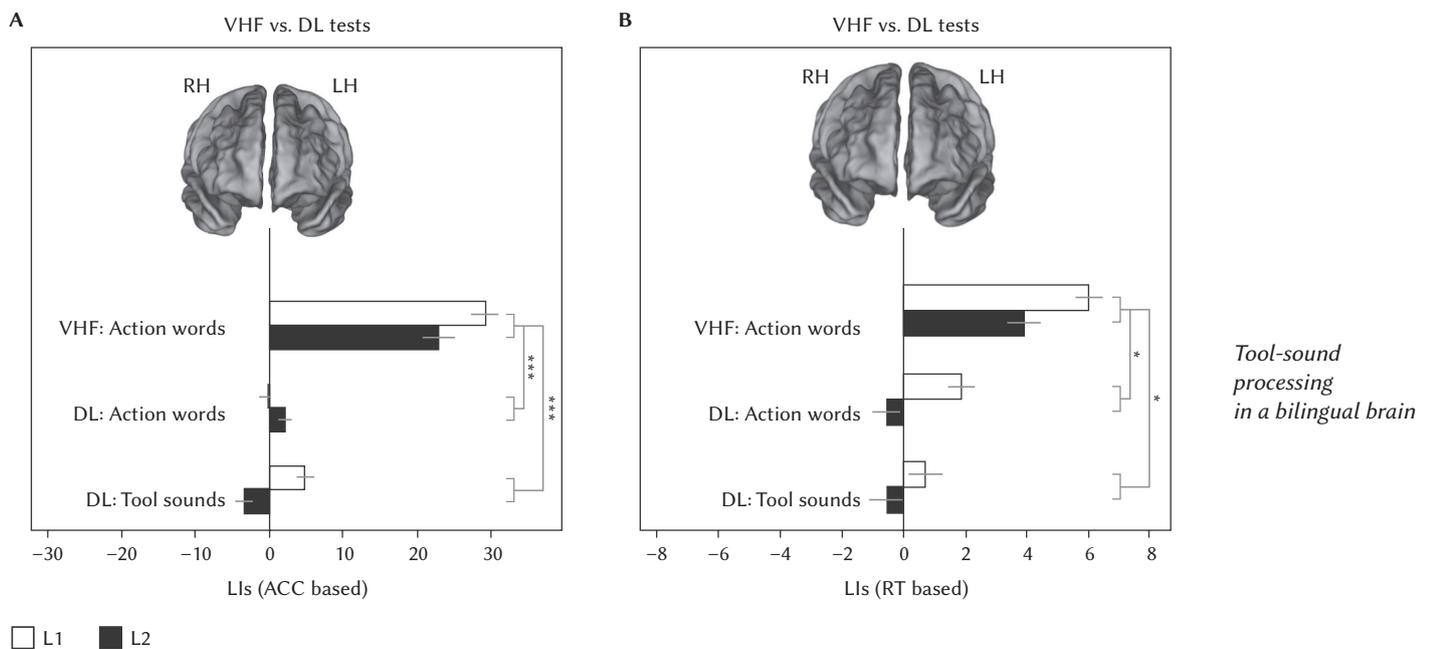Agnieszka Nowik,
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Figure 8. Hemispheric organization (laterality indices, LIs) of processing tool sounds. (A) Accuracy (ACC)-based LIs: There was a significant left hemispheric (LH) advantage for tool sound naming in the first language (Polish, L1), as compared to second language (English, L2). (B) Response-time (RT)-based LIs: No significant differences between lateralization of tool sound naming in L1 and L2. (C) Individual ACC-based LIs: There were no significant correlations between lateralization of tool sound naming in L1 and L2. (D) Individual RT-based LIs: There were no significant correlations between lateralization of tool sound naming in L1 and L2. LH – left hemisphere, RH – right hemisphere; DL – dichotic listening; black dots – right-handed participants; gray dot – left-handed participant. Asterisks indicate significant *p*-values: *p* < .05. Error bars depict standard errors of the means.

Figure 9. Hemispheric organization (laterality indices, LIs) of processing for visually presented action words versus auditorily presented action words and tool sounds. (A) Accuracy (ACC)-based LIs: There was a significant left hemispheric (LH) advantage for visually presented action word processing, as compared to auditorily presented action words, and also as compared to tool sounds, both in the first language (Polish, L1) and second language (English, L2). There were no significant differences between lateralization of processing for auditorily presented action words and tool sounds. (B) Reaction-time (RT)-based LIs: There was also a significant left hemispheric (LH) advantage for visually presented action word processing, as compared to auditorily presented action words, and also as compared to tool sounds, both in L1 and L2. However, there were no significant differences between lateralization of processing for auditorily presented action words and tool sounds. (C) Individual ACC-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L1 and auditorily presented action word processing in L1. (D) Individual RT-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L1 and auditorily presented action word processing in L1. (E) Individual ACC-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L1 and tool sound naming in L1. (F) Individual RT-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L1 and tool sound naming in L1. (G) Individual ACC-based LIs: There were no significant correlations between lateralization of auditorily presented action word processing in L1 and tool sound naming in L1. (H) Individual RT-based LIs: There were no significant correlations between lateralization of auditorily presented action word processing in L1 and tool sound naming in L1. (I) Individual ACC-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L2 and auditorily presented action word processing in L2. (J) Individual RT-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L2 and auditorily presented action word processing in L2. (K) Individual ACC-based LIs: There were no significant correlations between lateralization of visually presented action word processing in L2 and tool sound naming in L2. (L) Individual RT-based LIs: There were significant correlations between lateralization of visually presented action word processing in L2 and tool sound naming in L2. (M) Individual ACC-based LIs: There were no significant correlations between lateralization of auditorily presented action word processing in L2 and tool sound naming in L2. (N) Individual RT-based LIs: There were no significant correlations between lateralization of auditorily presented action word processing in L2 and tool sound naming in L2. LH – left hemisphere, RH – right hemisphere; VHF – visual half-field; DL – dichotic listening; black dots – right-handed participants; gray dot – left-handed participant. Asterisks indicate significant *p*-values: **p < .05, ***p < .001. Error bars depict standard errors of the means. *(Figure 9 continues)*

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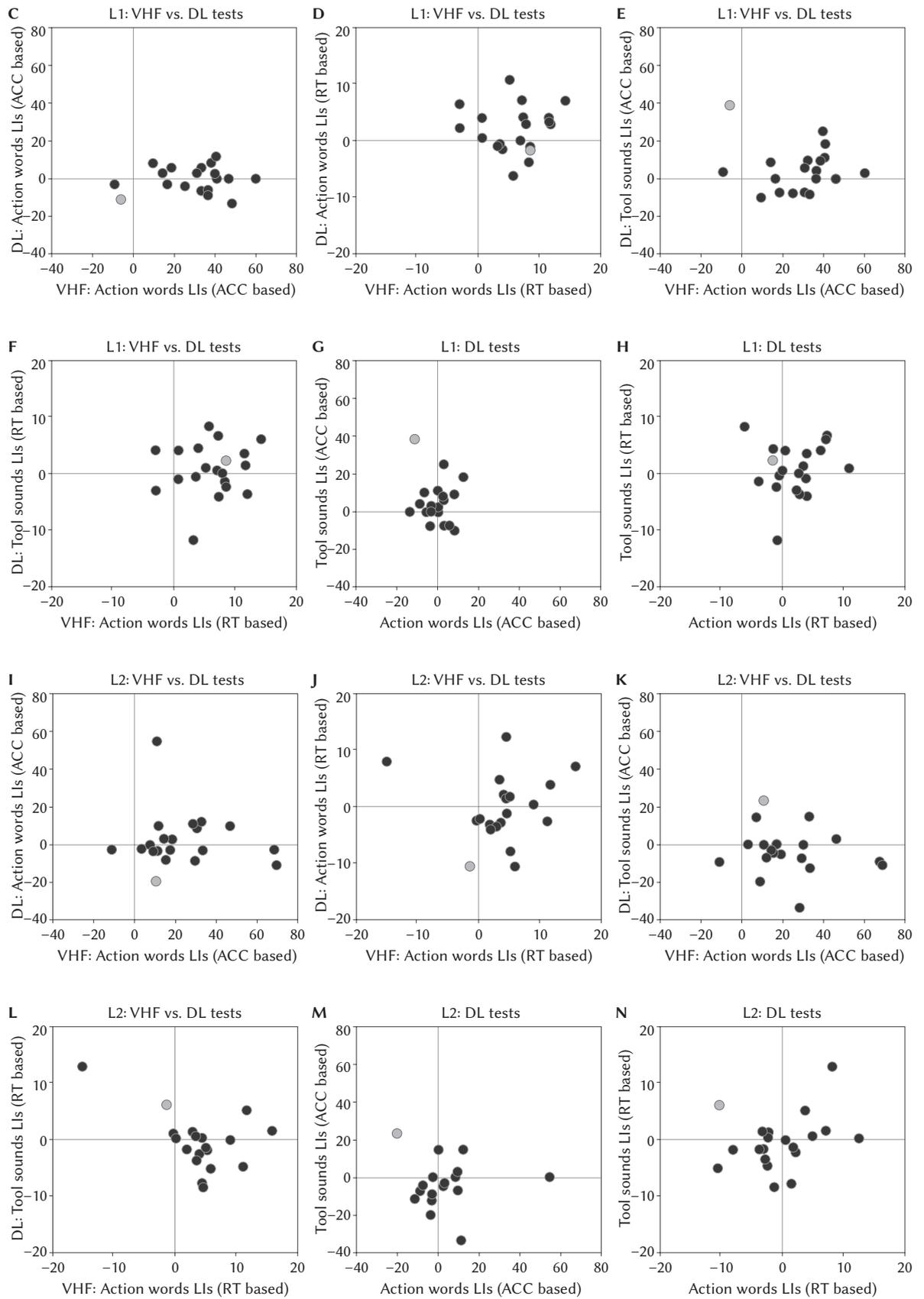Gregory Kroliczak,
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Figure 9.
(Figure 9 continued)

tests (i.e., for visually presented action word processing vs. auditorily presented action word processing: difference between means = 4.22, *SE* = 1.39, *Bf-p* < .05; visually presented action word processing versus tool sound processing: difference between means = 4.84, *SE* = 1.50, *Bf-p* < .05; auditorily presented action word processing versus tool sound processing: no significant differences, *Bf-p* > .05). However, for RT we also observed a main effect of language ($F(1, 19) = 7.60$, $p < .05$), such that L2 was less left lateralized as compared to L1 (difference between means = 1.93, *SE* = 0.70, *Bf-p* < .05). Nevertheless, the test type by language interaction was not significant ($F(2, 38) = 0.22$, $p > .05$).

Moreover, we found that there were no significant correlations between individuals' LIs for visually presented action-word processing and all kinds of processing for auditorily presented stimuli, and even for auditorily presented action-word processing and tool-sound processing. This effect was found for both ACC-based LIs ($r < .17$ in all cases, all *p*-s > .05) and RT-based LIs ($r < .29$ in all cases, all *p*-s > .05, with the exception of one situation when $r = .49$ and $p = .027$: LIs for visually presented action word processing in L2 and LIs for tool sound naming in L2, see Figure 9L) and these results are shown in Figure 9C-N.

DISCUSSION

Consistent with numerous fMRI studies (e.g. Hunter & Brysbaert, 2008) showing that the VHF paradigm is a good measure of cerebral language dominance, our current study demonstrated that, despite some variability, bilinguals have productive language typically lateralized (to the left hemisphere), and in line with the results of our previous study (Krefta et al., 2015) that both languages (L1 and L2) have similar organization in their brains (there is clear co-lateralization). As expected, though, bilinguals showed atypical (hemispherically balanced) organization of processing action-related sounds, that is both in the form of action words as such, and tool sounds (irrespective of the language that they used to identify a given sound). However, there were no correlations between LIs for language processing and LIs for action-related sound processing. What is more surprising, though, is that there were no correlations between LIs for auditory processing of action words and LIs for tool sound processing, either. It thus seems that in the bilingual brain these three functions might be neurally independent.

CO-LATERALIZATION OF LANGUAGES
IN THE BILINGUAL BRAIN

Neuroimaging studies on language processing in the bilingual brain show many contradictions (Liu & Cao, 2016). On the one hand, there is some evidence that

L2 is organized in the brain like L1, i.e. that L2 uses the same brain network that L1 does (e.g. Nakada, Fujii, & Kwee, 2001; Tan et al., 2003). On the other hand, there is also evidence that L2 processing can take place in a different cortical network than L1, and that for processing of L2 there is weaker lateralization as compared to L1 (Nelson, Liu, Fiez, & Perfetti, 2009; Huang, Itoh, Kwee, & Nakada, 2012; Park, Badzakova-Trajkov, & Waldie, 2012). Our results for language production (reading words in VHF tests) are thus in line with the first group of reports which suggest a common brain network for L1 and L2, and unambiguously corroborate the existence of the co-lateralization of L1 and L2 in the bilingual brain demonstrated in our previous study (Krefta et al., 2015). This is at variance with reports showing that the processing of L2 is more hemispherically balanced than that of L1. In a somewhat differently designed VHF experiment with bilinguals (Willemin et al., 2016) similar results were obtained, yet there was a right hemisphere shift observed in early, as compared to late bilinguals. These outcomes then suggest that our observations are characteristic for late bilingualism.

Nevertheless, in spite of the lack of significant differences between the LIs of L1 and L2, and a strong correlation between them, we found that bilinguals processed words in L2 more slowly (on average, 118 ms slower) as compared to L1. It was definitely not a consequence of lower fluency because for VHF tests there were no differences between ACC for L1 and L2 (ACC asymmetry would indicate a mediating role of proficiency; see Felton et al., 2017). This is in line with the Inhibitory Control Model. It shows that before using L2 in the bilingual brain, stronger control mechanisms occur as compared to L1, which makes the reaction time longer (Wu & Thierry, 2017; Felton et al., 2017). It is linked to the fact that before using L2, the language control network has to hinder (automatically activated) L1 (Grundy et al., 2017).

FUNCTIONAL ORGANIZATION
OF ACTION-RELATED SOUND PROCESSING
IN THE BILINGUAL BRAIN

In DL experiments where verbal material is used, left-hemispheric dominance is commonly observed, irrespective of sex, age or language (for example, see the study by Bless et al., 2015, on over 4000 participants with more than 60 different language backgrounds, or the meta-analysis by Kimura, 2011). A general model of processing speech sounds also shows that this mechanism should be strongly left-lateralized (Friederici, 2002, 2011; Friederici & Alter, 2004; Dotan & Friedmann, 2015). Thus, our study on processing auditorily presented action words suggests that bilinguals have a different (more hemispherically balanced) organization of speech-specific sounds from

Michal Klichowski,
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Gregory Kroliczak,
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monolinguals. This observation is in line with the neuroimaging study by Kuhl et al. (2016) where the participants were Spanish-English bilingual and native English-speaking monolingual adults.

However, despite the lack of significant differences between the LIs of L1 and L2 for processing auditorily presented action words (with some non-significant tendencies, though), there was no correlation between them. This suggests that bilinguals process speech-specific sounds in L1 and L2 differently, and that the functional organization of speech sound processing (see Hickok & Poeppel, 2000, 2007; see also Hickok & Poeppel, 2015) in the bilingual brain is influenced by the language used. It is probably not due to the structure of L1 and L2 or distance between L1 and L2 (which can influence the level of lateralization; see van der Noort et al., 2014; Kim et al., 2016), because, as our VHF tests show, there was co-lateralization of L1 and L2 representations. In the bilingual brain, different languages are thus probably not organized differently (see Hull & Vaid, 2007; Peng & Wang, 2011), whereas sounds of different languages are.

The case is similar for tool sounds. Although processing these sounds should be lateralized (see Lewis et al., 2005, 2006), in bilinguals their processing (irrespective of the language of response) was hemispherically balanced (yet, with some trends). Moreover, the LIs for L1 and L2 for tool sounds were not correlated. The functional organization of tool sound processing in the bilingual brain, therefore, also seems to depend on the language in use.

Our study then shows that the functional lateralization of action-related sound (whether verbal, e.g. action words, or non-verbal, e.g. tool sounds) processing is influenced by bilingual experience. This conclusion thus supports the thesis that bilingualism changes the functional organization of sound processing in the brain (Skoe et al., 2017), as well as a broader hypothesis that bilingualism causes neuroplastic (adaptive) changes in the human brain (Garcia-Penton et al., 2014; Burgaleta et al., 2016; Grundy et al., 2017), and that there are cortical correlates of bilingualism that can be observed (Felton et al., 2017).

FUNCTIONAL INDEPENDENCIES IN THE BILINGUAL BRAIN

The comparison of LIs for visually presented action words with LIs for auditorily presented action words and tool sound processing shows that these functions might be neurally independent to some extent, as there are no correlations whatsoever. (High variability, but in some cases also little variability, might be other contributing factors.) Thus, unless both of these tasks are more linguistic in nature, these findings are not in line with neuropsychological and neuroimaging evidence that shows a close link between the representa-

tions of praxis and language in the human brain (Fadiga et al., 2002; D'Ausilio et al., 2009; Kroliczak et al., 2011; see also Kroliczak, Westwood, & Goodale, 2006). This suggests that bilinguals, unlike monolinguals (see Bernardis & Gentilucci, 2006; Gentilucci & Corballis, 2006; Gentilucci, Campione, Dalla Volta, & Bernardis, 2009; Pulvermuller & Fadiga, 2010), when processing different action-related sounds, use different brain networks which to some extent are independent from the language production brain network.

The paradigms used in this study, however, only serve the purpose of measuring hemispheric asymmetry (Kimura, 2011). We thus do not know if an atypical lateralization of sound processing in the bilingual brain means a larger share of homologous traditional areas from the right hemisphere (Friederici, 2002; Friederici & Alter, 2004; Pulvermuller & Fadiga, 2010), as is the case, for example, when the right hemisphere takes over (in a mirror-image fashion) the functions of language areas in the left hemisphere if they are injured or destroyed in early childhood (Tivarus, Starling, Newport, & Langfitt, 2012; cf. Liegeois, Connelly, Baldeweg, & Vargha-Khadem, 2008). This may mean that the representations of sound processing in the bilingual brain have unique neural characteristics, similarly to unique organization of productive language in atypical cases (Bidula et al., 2017; see also Corballis, 2003; Vingerhoets et al., 2013; Gainotti, 2015; Haberling & Corballis, 2015; Badzakova-Trajkov, Corballis, & Haberling, 2016), or representations of praxis in people who use a tool professionally, e.g. in tennis players (Biggio, Bisio, Avanzino, Ruggeri, & Bove, 2017). We could then talk about the existence of many unique sound brain networks in the bilingual brain. In order to settle this issue, it is necessary to conduct further studies that use neuroimaging methods (and such a continuation of VHF and DL studies is also suggested by the authors of these paradigms, see Kimura, 2011). Furthermore, only neuroimaging studies may corroborate that behavioral effects observed in our experiment are indeed related to unique organization of the bilingual brain. Of course, bilingual experience might also benefit a plethora of other cognitive processes, including executive functions, particularly the control and inhibition mechanism (Hartanto & Yang, 2019).

CONCLUSIONS AND POSSIBLE CLINICAL IMPORTANCE

Our findings show that action-related sound processing (whether verbal or non-verbal) in bilinguals is not (as is the case in monolinguals) left-lateralized, but it is hemispherically more balanced. Furthermore, for sound processing bilinguals use many diverse neural networks, to some extent independent of the language production brain network. The functional organiza-

tion of sound processing in the bilingual brain thus seems to be rather more complex and plastic than that in the monolingual brain. Therefore, the bilingual brain should more easily (than the monolingual one) adapt in patients with damage in brain areas associated with sound-related functions (apart from those associated with speech production). Such a conclusion is in line with a study by Alladi et al. (2016), who found that post-stroke, cognitive functions remain intact considerably more often in bilinguals than in monolinguals (with the exception of aphasia). Thus, our findings support the broad thesis that bilingualism, as well as intensive new/second language learning, may protect one from the development of some post-stroke cognitive impairments (Alladi et al., 2016) and in ageing healthy elderly people may, for example, delay the onset of dementia symptoms (Bak, Long, Vega-Mendoza, & Sorace, 2016; Bialystok, Abutalebi, Bak, Burke, & Kroll, 2016). In sum, our findings shed new light not only on the functional organization of the bilingual brain, but also on general mechanisms of brain plasticity and emphasize even more the potential of non-native language learning for brain health and neurorehabilitation.

ACKNOWLEDGMENTS

ENDNOTE

1 Hunter and Brysbaert (2008) suggested that in VHF studies the stimuli should not be visible for more than 200 ms. Earlier studies from our laboratory (Klichowski & Kroliczak, 2017; Krefta et al., 2015) have demonstrated that, with the adopted parameters of the procedure and stimulus characteristics, a target duration of 217 ms leads to the required response accuracy of approximately 75% (see also McNair & Harris, 2012; but cf. Helon & Kroliczak, 2014).

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Tool-sound processing in a bilingual brain

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Appendix A: Stimuli used in VHF tests

Polish action words: *celować; czyścić; fotografować; kroić; malować; masować; mieszać; odkurzać; pakować; pisać; podkreślać; podlewać; prasować; rysować; strzelać; szczotkować; szlifować; wycinać; zmywać; zamykać.*

English action words: *aiming; brushing; cleaning; close; cutting; drawing; grinding; highlight; ironing; massaging; mixing; packaging; painting; photograph; shooting; slicing; vacuuming; washing; watering; writing.*

Appendix B: Stimuli used in DL tests

Polish action words: *celować; czyścić; fotografować; kroić; malować; masować; mieszać; odkurzać; pakować; pisać; podkreślać; podlewać; prasować; rysować; strzelać; szczotkować; szlifować; wycinać; zmywać; zamykać.*

English action words: *aiming; brushing; cleaning; close; cutting; drawing; grinding; highlight; ironing; massaging; mixing; packaging; painting; photograph; shooting; slicing; vacuuming; washing; watering; writing.*

Polish names of tool sounds: *czyścić; grabić; kleić; kopać; kroić; malować; ostrzyć; piłować; pisać; pompować; przepychać; rąbać; rysować; spiłowywać; spłukiwać; stemplować; szlifować; wbijać; wycinać; zszywać.*

English names of tool sounds: *chop; clean; cut; dig; draw; file off; grind; hammer; paint; pump; rake; rinse; saw; sharpen; slice; stamp; staple; tape; unclog; write.*