



## RESEARCH ARTICLE

**UPDATE** **Cerebral lateralisation of first and second languages in bilinguals assessed using functional transcranial Doppler ultrasound [version 2; peer review: 1 approved, 1 approved with reservations, 1 not approved]**

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### Abstract

**Background:** Lateralised language processing is a well-established finding in monolinguals. In bilinguals, studies using fMRI have typically found substantial regional overlap between the two languages, though results may be influenced by factors such as proficiency, age of acquisition and exposure to the second language. Few studies have focused specifically on individual differences in brain lateralisation, and those that have suggested reduced lateralisation may characterise representation of the second language (L2) in some bilingual individuals.

**Methods:** In Study 1, we used functional transcranial Doppler sonography (fTCD) to measure cerebral lateralisation in both languages in high proficiency bilinguals who varied in age of acquisition (AoA) of L2. They had German (N = 14) or French (N = 10) as their first language (L1) and English as their second language. fTCD was used to measure task-dependent blood flow velocity changes in the left and right middle cerebral arteries during phonological word generation cued by single letters. Language history measures and handedness were assessed through self-report. Study 2 followed a similar format with 25 Japanese (L1) /English (L2) bilinguals, with proficiency in their second language ranging from basic to advanced, using phonological and semantic word generation tasks with overt speech production.

**Results:** In Study 1, participants were significantly left lateralised for

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both L1 and L2, with a high correlation ( $r = .70$ ) in the size of laterality indices for L1 and L2. In Study 2, again there was good agreement between LIs for the two languages ( $r = .77$  for both word generation tasks). There was no evidence in either study of an effect of age of acquisition, though the sample sizes were too small to detect any but large effects.

**Conclusion:** In proficient bilinguals, there is strong concordance for cerebral lateralisation of first and second language as assessed by a verbal fluency task.

### Keywords

Laterality, Bilingualism, FTCD

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Any reports and responses or comments on the article can be found at the end of the article.

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**REVISED Amendments from Version 1**

In this revised paper, the original experiment forms Study 1, and new data from Japanese-English bilinguals, again using functional transcranial Doppler Ultrasound, for Study 2. The second study was conducted by colleagues (now co-authors) from University College London and University of Essex. Clara Grabitz, who did study 1 as a research project, has given permission for a change of corresponding author to Dorothy Bishop.

Addition of study 2 allows us to confirm that there is high similarity between laterality indices for the two languages in proficient bilinguals across two different groups of bilinguals, and in one of these groups, across two word generation tasks. We make the case that the similarity is meaningful and not just a consequence of low power, as indicated by Bayes Factors for the comparison of means. Furthermore, although FTCD is not suitable for studying localisation of language within a hemisphere, we present evidence that it gives a reliable and sensitive measure of extent of lateralisation, that allows us to go beyond simple classification of language laterality as left or right, via a direct comparison of blood flow in the middle cerebral arteries.

We analysed data from both studies using our most recent analysis scripts; this ensures reproducibility as well as consistency with our other recent studies, and allows for identical analytic steps to be used for Studies 1 and 2. This change in approach (basing the measure of laterality index on mean difference over an interval rather than a region around a peak, and using prespecified criteria for removing outliers with noisy data) has little impact on the results, other than to improve reliability of one subset of data in Study 1.

**Any further responses from the reviewers can be found at the end of the article**

**Introduction**

The two cerebral hemispheres of the brain are neither structurally nor functionally identical. Hemispheric specialisation reflects a variety of factors influencing the brain, including genetics, development, experience and pathology. Language ability is particularly striking in this regard, since, at least in monolinguals, it is predominantly left lateralised in most people (Knecht *et al.*, 1998a). The representation of language in the bilingual brain has been a topic of controversy. On the one hand, differential recovery patterns for individual languages in stroke patients point towards separate neural representations (Paradis, 2004), yet on the other hand, neuroimaging of healthy individuals has mostly reported the involvement of overlapping cortical areas in the left hemisphere for first (L1) and second (L2) languages (Abutalebi *et al.*, 2005; Perani & Abutalebi, 2005; Sulpizio *et al.*, 2020).

The picture is complicated by the complex nature of bilingualism, with individuals varying in age of acquisition (AoA), proficiency, exposure to the different languages, and number of languages spoken. A recent review of brain structure and connectivity concluded that brain organisation was influenced by duration and extent of language use, and their combined effects (DeLuca *et al.*, 2019). In functional imaging, differential activation for L2 vs L1 has been reported for late acquisition or

low proficiency groups, though results have not always been consistent across studies, and the impact of these individual differences appears to be task dependent (Kim *et al.*, 1997; Klein, 2003; Klein *et al.*, 1995; Wartenburger *et al.*, 2003). More generally, studies on this topic tend to have relatively small sample sizes and hence low power to detect any but large effects.

A range of methods has been used to assess anatomical and functional differences between cerebral hemispheres, depending on experimental aims as well as task constraints. Here our focus is on functional lateralisation, and the possibility that in bilingualism there may be a differential contribution from the right hemisphere for the two languages. This was suggested by a meta-analysis of behavioural studies by Hull & Vaid (2007), incorporating studies using dichotic listening, visual preference, and dual task methods; surprisingly, they found that proficient bilinguals who learned L2 in infancy had more bilateral language representation of L2 than those who acquired L2 after 5 years of age. Few fMRI studies have focussed on language lateralisation in bilinguals. An fMRI study of 16 bilingual people with epilepsy found excellent agreement between laterality indices for L1 and L2 on verb production tasks (Centeno *et al.*, 2014). In contrast, Dehaene *et al.*, 1997, found, consistent with other studies, that when listening to L1, there was consistency between participants in the locus of activation in the left hemisphere, but when listening to L2, there was substantial variability from person to person, not just within a hemisphere, but also in terms of which hemisphere was most activated. A recent study of basic and advanced L2 learners by Gurunandan *et al.* (2020) reported that, whereas language production tended to be left-lateralised in both languages, in receptive tasks, the two languages tended to lateralise to opposite hemispheres, with this effect increasing with language proficiency. For language production, the size of the laterality index showed only weak agreement between L1 and L2, regardless of proficiency. Taking these findings on language laterality together, we predict that on production tasks, we should find equivalent lateralisation for L1 and L2 in moderate-to-high proficiency bilinguals. Although there is suggestive evidence that laterality indices might show some dissociation between L1 and L2 in bilinguals, this tends to be seen on receptive tasks, and it is hard to know if such dissociations are reliable, as test-retest reliability of the laterality index is usually unknown.

Here we report two studies using functional transcranial Doppler ultrasonography (FTCD) to test the hypothesis that cerebral lateralisation is equivalent for first and second languages in proficient bilinguals. This method uses ultrasound to measure cerebral blood flow velocity (CBFV) in the left and right hemispheres. The change in CBFV reflects the task dependent contribution of each hemisphere due to neurometabolic coupling, i.e. brain areas showing task-dependent neuronal firing need to replenish metabolic resources, requiring increased blood flow (Aaslid *et al.*, 1982; Deppe *et al.*, 2004). In order to assess language lateralisation, CBFV is measured in the middle cerebral artery (MCA), which supplies extensive regions of the cortex, including frontal, temporal and parietal areas, (van der Zwan *et al.*, 1993). These cortical regions in the left

hemisphere contain areas that are necessary for language processing and production, including classical Broca's and Wernicke's areas in the inferior frontal and superior temporal lobes, respectively. FTCD is a reliable and valid measure of language lateralisation, (Bishop *et al.*, 2009; Groen *et al.*, 2012; Illingworth & Bishop, 2009; Stroobant *et al.*, 2011), giving good correlations with the gold standard intracarotid amobarbital test and functional MRI (fMRI) (Deppe *et al.*, 2004; Knake *et al.*, 2003; Knecht *et al.*, 1998a; Knecht *et al.*, 1998b; Rihs *et al.*, 1999; Somers *et al.*, 2011). Importantly, FTCD had moderate-to-good within-session (split half) and test-retest reliability (Woodhead *et al.*, 2020). We can therefore distinguish between true dissociations between LIs on different tasks and lack of agreement attributable to poor reliability of measurement.

FTCD lacks within-hemisphere spatial resolution, so is not suitable for identifying topographic differences in language representation within one hemisphere. However, it provides a measure of changes in blood flow velocity in the middle cerebral artery, which can give a direct index of the relative contribution of the two hemispheres, without any need to specify thresholds or regions of interest. Advantages of FTCD are that it is inexpensive, non-invasive, comfortable, easily applicable, mobile, and child-friendly and it has excellent resolution in the time domain (Bishop *et al.*, 2010; Knecht *et al.*, 1998b). FTCD has been used to study cerebral lateralisation in monolinguals, but it has not, to our knowledge, been used to compare lateralisation of two languages in bilingual participants, defined here as people who use more than one language on a regular basis (Grosjean, 1989).

### Study 1: Highly proficient French-English or German-English bilinguals

In Study 1, we used the cued word generation task, which is a well validated and commonly used productive language task (Knecht *et al.*, 1998a; Knecht *et al.*, 1998b), to test whether language lateralisation is equivalent for first and second languages in bilinguals. A secondary aim was to consider whether there is any impact of AoA. Participants were highly proficient bilinguals, all with English as a second language, who were working or studying in Oxford, UK at an advanced level. We predicted that the extent of left lateralisation of bilingual speakers would relate to their AoA of L2. On the basis of Hull & Vaid's (2007) behavioural meta-analysis we might expect to see weaker lateralisation for L2 in bilinguals with an early AoA. On the other hand, the convergence hypothesis (Green, 2003) predicts that as proficiency increases, the neural substrate of L1 and L2 become more similar. Green's hypothesis did not focus on lateralisation, but it might nevertheless be taken to suggest the opposite pattern to that predicted by Hull and Vaid, i.e., greater similarity in the neural basis of L1 and L2 in those with the longest experience of L2, i.e. those with early AoA.

### Methods

**Participants.** Participants were recruited through the Oxford University German Society and Oxford University French Society, as well as through posters in the Experimental Psychology building. Participants were aged over 18 years and were

either German-English (N = 14) or French-English (N = 10) bilinguals, with a self-reported high level of proficiency in English. All had normal or corrected to normal vision. Individuals with a diagnosis of any speech, language or learning impairment, affected by a neurological disorder or taking medication affecting brain function e.g. antidepressants, were not included in the study.

A total of 40 individuals were assessed for viability as study participants. In total, 14 participants were excluded for a range of reasons, including no suitable Doppler signal, due to the inability to find a suitable temporal window in the skull, or failure to stabilize the Doppler signal for the required amount of time (11 participants), or low quality data (3 participants). Data was analysed from 26 participants. During the analysis, 2 further participants were dropped because of an insufficient number of useable trials. All further analyses are based on the final sample of 24 participants (18 female; mean age = 23.04 years, sd = 3.64 years).

**Ethics statement.** The study was approved by the University of Oxford Central Research Ethics Committee (CUREC), approval number, MS-IDREC-C1-2015-126). All participants provided written informed consent.

**Apparatus.** A commercially available transcranial Doppler ultrasonography device (DWL, Multidop T2; manufacturer, DWL Elektronische Systeme, Singen, Germany) was used for continuous measurements of the changes in cerebral blood flow velocity (CBFV) through the left and right MCA. The MCA was insonated at ~5 cm (40–60 mm). Activity in frontal and medial cortical areas, supplied by the anterior cerebral artery, and inferior temporal cortex, supplied by the posterior cerebral artery, do not contribute to the measurements made in the MCA. Two 2-MHz transducer probes, which are relatively insensitive to participant motion, were mounted on a screw-top headset and positioned bilaterally over the temporal skull window (Deppe *et al.*, 2004).

**Handedness.** Handedness was not a selection criterion, and was assessed via the Edinburgh Handedness Inventory (EHI; Oldfield, 1971). The inventory consists of 10 items assessing dominance of a person's right or left hand in everyday activities. Each item is scored on a 5 step scale ("always left", "usually left", "both equally", "usually right", "always right"). A person can score between -100 and +100 for each item and an overall score is calculated by averaging across all items ("always left" -100; "usually left" -50; "both equally" 0).

**Language history.** The Language Experience and Proficiency Questionnaire (LEAP-Q; Marian *et al.*, 2007) was used to assess language history for all participants. The LEAP-Q is a self-assessment questionnaire consisting of nine general questions and seven additional questions per language that explore acquisition history, context of acquisition, current language use, and language preference and proficiency ratings across language domains (speaking, understanding and reading) as well as accent ratings. An overall self-reported proficiency

rating was calculated by taking the mean ratings for proficiency in speaking, reading and understanding English.

The main variable of interest from LEAP was age of acquisition of L2 (AoA), i.e. answer to the question ‘age when you began acquiring the language’; we subdivided into early AoA (before 6 years of age) and late AoA subgroups, to test the prediction from Hull & Vaid (2007) that language is more bilaterally represented when L2 is learned in early childhood. To characterise the sample, we also report the numbers of languages spoken; age of achieving fluency in English; self-reported strength of foreign accent when speaking English (on a scale from 0 [none] to 10 [pervasive]); and mean self-reported proficiency in English.

**Word generation task.** Tasks were programmed using Presentation® software (version 17.2; [www.neurobs.com](http://www.neurobs.com)). All instructions were presented centrally in white Arial font on a black background. Each participant was tested in English (L2) and their native language (L1; French or German) in a single session using two tasks, each consisting of 23 trials.

The order of the two languages was counterbalanced across participants and the entire testing session lasted between 75 and 90 minutes. The experimenter spoke English at all times. So that they were focussed on their native language, participants were asked to describe the Cookie Theft picture of the Boston Diagnostic Aphasia Examination in their native language prior to being tested in that language (Goodglass & Kaplan, 1983).

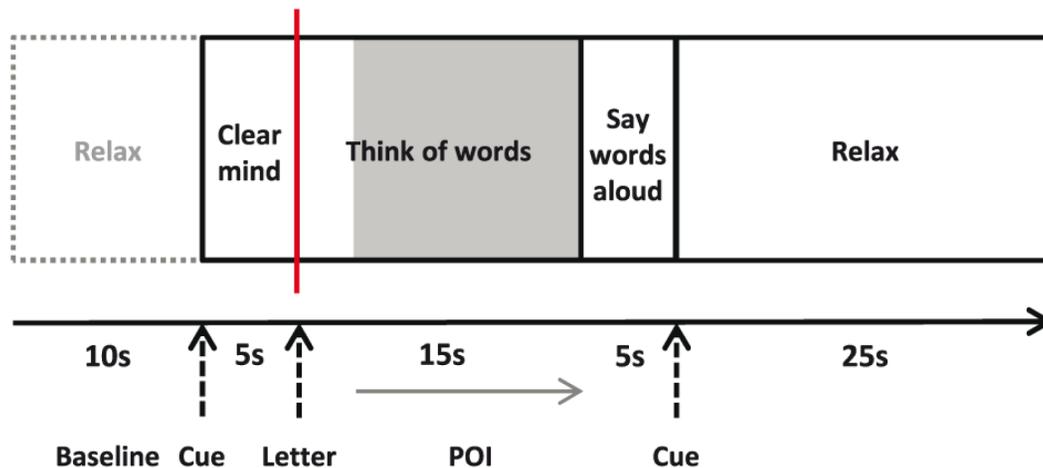
The cued word generation paradigms were based on Knecht and colleagues’ 1998 paradigm (Knecht *et al.*, 1998b). For each trial, the participant is shown a letter and is asked to silently generate words starting with that letter. Each task comprised 23 trials and lasted for around 20 minutes. We excluded

the three letters with the lowest first letter word frequency: Q, X and Y in English; Q, X and Z in German; and W, X and Y in French. Written task instructions for the German and French word generation tasks were translated into German and French by the experimenter (CG).

Each trial started with an auditory tone and the written instruction “Clear Mind” (5 s), followed by the letter cue to which the participant silently generated words (15 s), and then overt word generation (5 s) (Figure 1). To restore baseline activity, participants were instructed to relax (25 s) at the end of each trial. Event markers were sent to the Multi-Dop system when the letter cue appeared, denoting trial onset for subsequent analysis of the Doppler signal.

**Data pre-analysis and calculation of asymmetry indices.** The cerebral blood flow velocity data were analysed using custom scripts in R Studio (R Core Team, 2020), which are available in the *Underlying data* (Bishop *et al.*, 2021a). The data preprocessing followed conventional methods (Deppe *et al.*, 2004), and included the following steps:

- Downsampling from 100 Hz to 25 Hz.
- Epoching from -11 s to 30 s relative to the onset of the ‘Clear Mind’ cue.
- Manual exclusion of trials with obvious spiking or dropout artefacts.
- Automated detection of data points with signal intensity beyond 0.0001-0.999 quantiles. If a trial contained one of these extreme data points, it was replaced by the mean for that epoch; if it contained more than one, the trial was excluded from further analysis
- Normalisation of signal intensity by dividing CBFV values by the mean for all included trials and multiplying by 100.



**Figure 1.** A schematic diagram of the word generation task. Period of interest (POI) is marked in grey from 8 to 20 s, and the event marker is displayed in red.

- Heart cycle integration by averaging the signal intensity from peak to peak of the heartbeat.
- Baseline correction by subtracting the mean CBFV across the baseline period (-10s to 0s relative to the 'Clear Mind' cue) from all values in the trial.
- Automated detection and rejection of trials containing normalized values below 60 or 140.

Participants with fewer than 15 usable trials for either language were excluded from all further analyses. For each participant that was included in the analysis, a grand mean was calculated over all of their included trials. A laterality index (LI) was calculated by taking the mean of the difference between left and right CBFVs (L-R) within a period of interest (POI) that started 8 s after the 'Clear Mind' cue (i.e. 3 s after the word generation task had begun) and ended at 20 s (i.e. when the covert generation task ended). The start time of the POI was chosen to allow time for the blood flow to respond to the task; and the end time was chosen to prevent capturing the response to the overt speech generation phase.

This method of calculating LI using the mean L-R difference across the whole of the POI (the 'mean' method) deviates from the conventional method that we had used in the first version of this paper (<https://doi.org/10.12688/wellcomeopenres.9869.1>). The original 'peak' method, popularised by Deppe *et al.* (1997) takes the mean of a narrow time window around the peak difference within the POI. This method forces the LI to be either left or right - even if the waveform is close to zero with no clear lateralised peak, the highest absolute value in the POI will be treated as a peak. This creates a bimodal distribution of LIs. We have compared the 'peak' method with our 'mean' method, and shown that, while they give high agreement, the mean method is at least as reliable and gives normally distributed LI values, albeit with lower values, due to averaging over the whole POI (Woodhead *et al.*, 2020). We have therefore moved to using the mean method in our current research. Nonetheless, peak LI values were computed in case they are required for comparison with other studies, and are available on the online data repository: <https://osf.io/4pm76/>.

In a final step, to bring our methods in alignment with Woodhead *et al.* (2019), we identified and excluded datasets with unusually high trial-by-trial variability using the Hoaglin & Iglewicz (1987) outlier detection method. For this analysis, LI was calculated for each trial, rather than just for the grand average. The standard error of these single-trial LI values was then calculated. Outliers were defined as datasets where the standard error was above an upper threshold, calculated as:

$$\text{Upper threshold} = Q3 + 2.2 * (Q3 - Q1)$$

where Q1 is the first quantile of the standard errors among all participants, and Q3 is the third quartile. Participants who had standard error above the upper threshold for either L1 or L2 were excluded from all further analyses.

**Statistical analysis.** All analyses were conducted using the R Programming Language (R Core Team, 2020). We first checked for a leftward bias in the overall laterality index, using a one-group t-test, and also categorised each participant as left-biased, right-biased or bilateral. The bilateral group were those whose confidence interval around the LI included zero. Split half reliability of the LI was estimated using LIs computed from odd or even trials only. Spearman correlations were computed between LIs for L1 and L2.

To test our main hypothesis, the association between strength of lateralization (LI values) for L1 and L2 was first visualized using a scatterplot, with the strength of association computed as Spearman's correlation coefficient. Following Woodhead *et al.* (2020), we adopted an approach based on Bland & Altman (1986) to determine whether the individual LIs for L1 and L2 were equivalent. This involves specifying boundaries for the expected distribution of difference scores, which should contain 95% of bivariate points, if the two values are equivalent. The expected range can be computed from knowledge of the task reliability. We adopted the range specified by Woodhead *et al.* (2020); they computed difference scores by LIs for odd vs even trials, and set boundaries corresponding to expected mean of zero +/-1.96 standard deviations. If the two measures are equivalent, 95% of difference scores, the repeatability coefficient, between LIs for L1 and L2 should fall in this range (from -2.5 to 2.5).

For our second hypothesis, that laterality for L2 would be associated with AoA, we used a t-test to compare laterality for L2 between those with early vs late AoA. A two-tailed test was used because the literature does not give clear predictions about direction of effect.

In addition, we report the correlation between LI values and strength of handedness (EHI quotient), and the impact of testing order (L1 then L2, or L2 then L1).

## Results

**Handedness.** Summary statistics for the EHI handedness measure can be seen in Table 1. Of 24 participants included in the data analysis, 23 had EHI values above 0, indicating right handedness. The remaining participant had an EHI of -20, indicating weak left handedness. Correlations between LI from FTCD and handedness scores on the EHI, were not statistically distinguishable from zero for either L1 ( $r = -0.145$ ) or L2 ( $r = 0.137$ ).

**Language history.** Summary statistics for the language history questionnaire can be seen in Table 1. Self-reported proficiency in speaking, reading and understanding English were all generally high (all around 9/10), with a minimum for any individual rating of 6/10. Age of acquisition, defined as age when first started acquiring the language, was more variable, ranging from 0 to 15 years. Binary categorisation of AoA, using Hull & Vaid's (2006) criteria gave 7 cases of early AoA (below 6 years of age), and 17 cases of late AoA.

**FTCD data quality and reliability.** As mentioned in the Methods, two participants were excluded from the analysis because of insufficient number of usable trials. For the remaining 24 participants, 5.98% of trials were excluded for L1, and 6.34% for L2.

**Table 1. Demographics for the Study 1 participants, N=24 (18 female).**

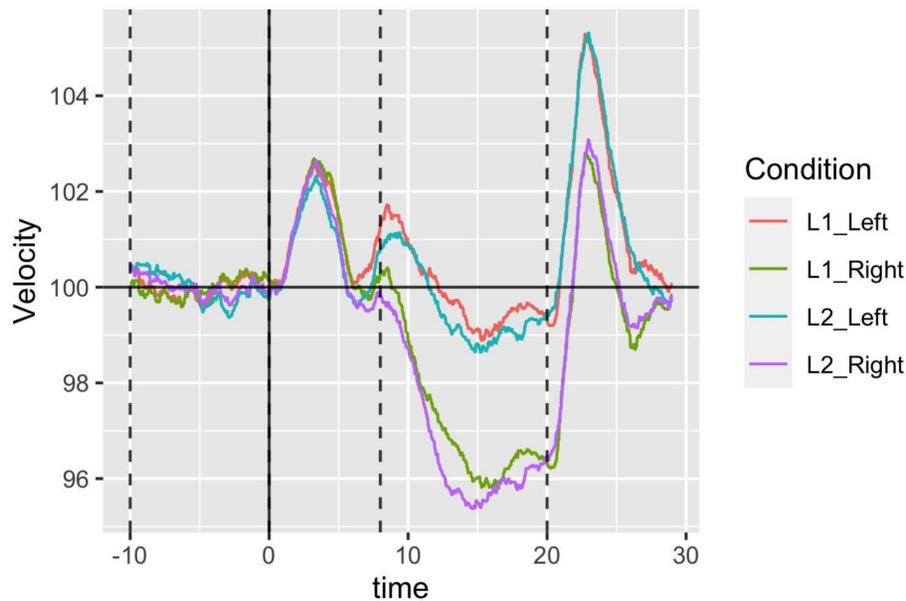
Characteristic	Mean (sd)
Age, years	23.04 (3.64)
EHI/100	73.67 (26.74)
Languages spoken	3.71 (0.95)
Age of English acquisition, years	7.54 (4.41)
Age of English fluency, years	12 (6.83)
English accent/10	2.58 (2.41)
English overall rating/10	9.1 (1)
English speaking rating/10	8.92 (1.1)
English listening rating/10	9.12 (1.08)
English reading rating/10	9.25 (0.94)

Normality of the LI values was assessed using Shapiro-Wilk tests. Distributions of LIs were unimodal for both L1 and L2. Data for L1 did not significantly deviate from normality ( $W = 0.88$ ,  $p = 0.009$ ), whereas data for L2 were significantly non-normal ( $W = 0.96$ ,  $p = 0.514$ ), showing a rightward skew.

Split-half reliability was assessed by correlating the LI values from odd and even trials. The Spearman's correlation for the L1 data was 0.58, and for the L2 data it was 0.7, indicating medium to good within-session reliability.

Normalized blood flow velocities for the left and right middle cerebral arteries are presented for each task in [Figure 2](#).

[Table 2](#) shows summary statistics for the LI values for L1 and L2. The Bayes factor was computed to check the equivalence of the mean LI for the two languages using the R package 'BayesFactor' with default settings ([Morey & Rouder, 2018](#)), and gave a value of 0.234, which may be interpreted as moderate evidence for the null hypothesis ([Lee & Wagenmakers, 2014](#)). The percentage of participants in each group categorised as left lateralised, bilateral or right lateralised is also shown. The majority of participants were left lateralised, with only around 10% showing bilateral activation. No participants showed right lateralisation for either L1 or L2. T-tests showed that



**Figure 2.** Left and right hemisphere activation is displayed as a function of epoch time in seconds for the word generation task for L1 (French or German) and L2 (English) in Study 1. Dotted lines indicate the start and end of the baseline period (from -10 to 0 seconds) and the period of interest (from 8 to 20 seconds). L1, first language; L2, second language.

**Table 2. Summary statistics for Study 1 laterality indices (N = 24).**

Language	Mean trials	mean LI	se LI	% left	% bilateral	% right
L1	21.62	2.72	0.36	92	8	0
L2	21.54	2.82	0.28	88	12	0

there were no significant effects of testing order on LI values, either for L1 ( $p = 0.113$ ) or L2 ( $p = 0.712$ ).

As can be seen in the scatterplot in [Figure 3](#), laterality indices for L1 and L2 were similar, with Spearman's  $R = 0.703$ . Furthermore, the points cluster around the continuous grey line, which shows the point of equivalence between L1 and L2, and all but one point falls within the Bland-Altman bounds (dotted grey lines), as would be expected if L1 and L2 were equivalent.

**Effect of age of acquisition.** One can see by inspection of [Figure 3](#) that there is no evidence of a trend for lower LI for L2 in those with early AoA, and a t-test of differences in L2 LI for those with early and late AoA revealed no differences:  $t = 0.84$ ,  $p = 0.419$ . For a more quantitative assessment of association, we computed Spearman's correlations between the LI values for L2 (English) and the age of acquisition of English. This was not statistically different from zero ( $r = 0$ ,  $p = 0.99$ ).

## Discussion

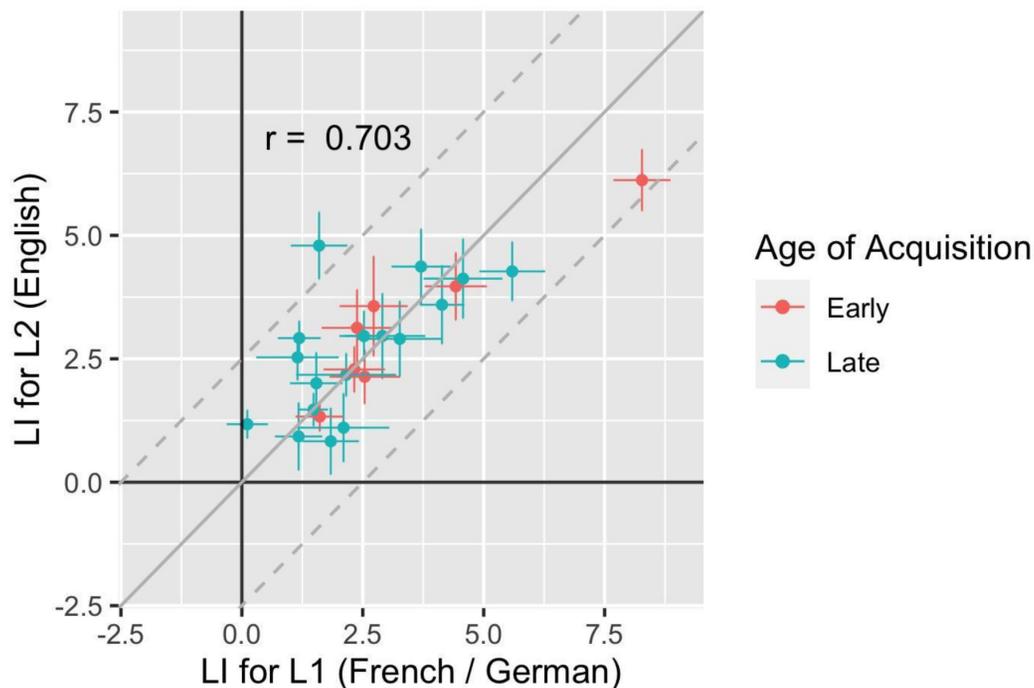
Nearly all participants showed significant left lateralised blood-flow for both L1 and L2 during the word generation task. Only 5 participants were classified as bilateral for one language, and for 3 of these it was L1 that was bilateral. Furthermore, laterality indices for L1 and L2 were highly related and similar in magnitude, indicating good reliability of the measure.

Proficiency was generally high in this sample, so it was not possible to assess the impact of variation in proficiency on lateralisation. The sample was small, and so lacking in power to detect small effects, but there was no indication of support for the hypothesis that AoA affected absolute levels of language lateralisation or was related to a difference in lateralisation between the two languages.

## Study 2: Japanese-English bilinguals with moderate-high proficiency

In Study 1 we found no difference in laterality patterns for L1 and L2 between French-English and German-English bilinguals, but it is possible that differences might be more apparent with languages that are more different from one another, in grammatical structure, lexical items and/or phonology. These factors have been shown to influence the ease with which a second language is learned, and might plausibly affect the extent to which language representations are shared or distinct ([Schepens et al., 2016](#)). Study 2 provided the opportunity to assess this idea in a sample of adults whose native language was Japanese, with English as the L2.

Study 2 was run independently of Study 1, at a different institution by different experimenters, to address similar questions to Study 1, but with Japanese-English bilinguals. We report the two studies together here as they make it possible to test generalisability of the Study 1 findings in a different language, and with some methodological modifications. In addition,



**Figure 3.** Scatterplot showing individual mean LIs in L1 and L2, with horizontal and vertical error bars denoting standard errors. The continuous grey line corresponds to the point of equality of the two measures, and the dotted lines show the limits where difference between LIs is  $\pm 2.5$ .

Study 2 included bilinguals with a wider range of proficiency than Study 1, making it possible to consider the effect of this variable on lateralisation.

An additional aim of Study 2 was to test whether a language that uses both logographic and syllabic orthographic systems would show a more pronounced difference between phonological and semantic processing in the strength of lateralisation (cf, [Gutierrez-Sigut et al., 2015](#)). Japanese Kana carry phonological information, but Kanji are more strongly linked to semantic information. We expected that phonological fluency would stimulate typically left-lateralised pre-motor articulatory planning processes more strongly than semantic fluency, and therefore be more strongly left-lateralised.

## Methods

**Participants.** We recruited participants through the UCL psychology participant pool, research posters around the University, and through email communication to contacts within Japanese communities in London. We initially recruited 32 adult native speakers of Japanese, who reported using English on a daily basis. None of the participants had a history of reading or language difficulties. All had normal or corrected to normal vision.

Seven participants were excluded from the study. This was due to inability to find a suitable temporal window (6 participants), or an insufficient number of usable trials after preprocessing (1 participant). All analyses are based on the final sample of 25 participants] (19 female, mean age = 29.32 years, sd = 6.73 years).

**Ethics statement.** Ethical approval for the study was granted by the UCL Research Ethics Committee (ID:3612/001). Participants gave written informed consent and were aware they could withdraw at any time.

**Language history and ability.** Age of acquisition of English and number of years of using English were evaluated via self-report. As with Study 1, a binary age of acquisition (AoA) variable was created by subdividing participants into early (below 6 years) and late (6 years or over) subgroups.

English language ability was measured using the Quick Placement Test ([University of Cambridge Local Examinations Syndicate, 2001](#)), which assesses English reading, vocabulary, and grammar. The test is scored out of 60. Those who scored under 40 were classed as having basic level proficiency (N = 4); between 40 and 48 were classed as having intermediate level proficiency (N = 3); and above 48 were classed as having advanced level proficiency (N = 17). The test data was not available for one participant.

**FTCD apparatus.** Blood flow velocity through the left and right MCAs was examined using a DopplerBox ultrasonography device and DiaMon headset (manufactured by DWL Elektronische Systeme, Singen, Germany). Two 2-MHz transducer monitoring probes were mounted on the headset and placed at each temporal skull window.

**Word generation tasks.** Stimuli were presented using Cogent toolbox (<http://www.vislab.ucl.ac.uk/cogent>) for MATLAB (Mathworks Inc., Sherborn, MA). Triggers time locked to the onset of the stimulus were sent from the presentation PC to the Doppler Box set-up.

The task was based on [Gutierrez-Sigut et al. \(2015\)](#), and involved phonological and semantic word generation tasks in English and Japanese, with order counterbalanced across participants. Task instructions were delivered to correspond to the tested language. Unlike in Study 1, there was no silent interval for covert word generation: participants spoke the words aloud as they thought of them. Gutierrez-Sigut et al. had previously shown that LIs were similar regardless of whether overt or covert responses were given, and they noted a benefit of overt production was that the experimenter could record the participants' responses as they occurred. For each trial, participants saw "Clear Mind" presented on the screen for 3 seconds. The cue stimulus was then presented, and participants had 17 seconds to overtly generate as many words as possible. Participants were then instructed to relax for 16 seconds to restore baseline activity. Each trial lasted a total of 36 seconds.

## Stimuli

**Phonological word generation - Japanese and English.** In Japanese, participants were presented with a cue in Hiragana, one of the Japanese phonological scripts. Following the Japanese mora frequency analysis conducted by [Dan et al. \(2013\)](#) based on the familiarity ratings in [Amano & Kondo \(1999\)](#), 10 of the 12 most frequent moras that are positioned at the beginning of words were selected (あ/a/, い/i/, お/o/, か/ka/, き/ki/, こ/ko/, さ/sa/, し/shi/, た/ta/, ふ/fu/). The two moras omitted were は/ha/ and じ/ji/. は was omitted because it would be pronounced /wa/ when it was the subject-marker and じ was omitted because it was the voiced sound of し (/shi/) that was included in the stimuli. Participants had to produce as many words as possible that began with the specified Kana. Each Kana was presented twice, and the 20 trials were presented in a pseudo-randomised order to ensure all 10 cues had been presented once before a cue was repeated.

In the English phonological word generation task, participants were presented with 10 alphabetic letters (A, B, C, F, H, M, O, S, T, W) and asked to produce as many words as possible that began with the specified letter. Trials were presented in the same manner as the Japanese task.

**Semantic word generation - Japanese and English.** Ten Japanese words representing semantic categories were presented in the standard written form, i.e. the mixture of Kanji and Kana: 家畜 farm animals, 動物園の動物 zoo animals, 野菜 vegetables, 果物 fruits, 飲み物 drinks, 色 colours, スポーツ sports, ペット pets, 道具 tools, and 乗り物 transport. The same semantic categories were presented in English. Participants had to report as many words that matched these categories as possible. Each category was repeated twice in the semantic fluency blocks. Categories were presented in a pseudo randomised order.

**FTCD analysis.** The same FTCD analysis method was used as in Study 1, except that the epoch lengths were changed to match timings for Study 2. The POI started at 6 s after the onset of the ‘Clear Mind’ stimulus (i.e., 3 s after the word generation task had begun) and ended at 20 s (i.e., at the end of the word generation task).

## Results

**Language history and task performance.** Summary statistics of language history can be seen in Table 3. Age of English acquisition ranged from 0 to 13 years. In contrast to Study 1, where there was little variation in proficiency: Study 2 included 4 cases with basic proficiency, 3 cases with intermediate proficiency, and 17 cases with advanced proficiency, according to the Quick Placement Test. The usage of English was assessed using the question “how much English and Japanese (and other languages if you have) do you use in a typical week?” and the percentages of use of English out of 100% are shown in Table 3. The participants tended to use English more than Japanese.

The mean number of words produced per trial in the phonological conditions was 5.84 (SD = 1.34) for Japanese and 5.98 (SD = 1.32) for English. The mean number of words produced per trial in the semantic condition was 7.61 (SD = 1.24) for Japanese and 6.95 (SD = 1.29) for English. There was no significant difference between the mean number of words produced per trial for L1 and L2 in the phonological condition ( $t(48) = -0.36, p = 0.719$ ) or the semantic condition ( $t(47.9) = 1.84, p = 0.071$ ).

**FTCD data quality and reliability.** Normality of LI values was assessed using Shapiro-Wilk tests. For the phonological tasks, data was normally distributed for L1 ( $W = 0.96, p = 0.507$ ) and L2 ( $W = 0.95, p = 0.278$ ). Data was also normally distributed for the semantic tasks for L1 ( $W = 0.97, p = 0.63$ ) and L2 ( $W = 0.98, p = 0.949$ ).

Split-half reliability was assessed by correlating the LI values from odd and even trials, using Spearman’s correlations for

consistency with Study 1. For phonological word generation, the split-half correlation was 0.6 for L1 and 0.83 for L2. For semantic word generation, the correlation was 0.61 for L1 and 0.69 for L2. This indicated moderate to good reliability for all tasks.

**LI values.** Normalized blood flow velocities for the left and right middle cerebral arteries are presented for each language and task in Figure 4. Table 4 shows summary statistics for L1 and L2 in both phonological and semantic word generation tasks. Bayes factors were computed to check the equivalence of the mean LI for the two tasks in the two languages using the R package ‘BayesFactor’ with default settings (Morey & Rouder, 2018). This gave a value of 0.211 for the Phonological task, which may be interpreted as moderate evidence for the null hypothesis, and a value of 0.368 for the Semantic task, which corresponds to anecdotal evidence for the null hypothesis (Lee & Wagenmakers, 2014).

Laterality indices for L1 and L2 were strongly correlated in both the phonological task (Spearman’s  $R = 0.769$ ) and the semantic task (Spearman’s  $R = 0.775$ ), closely replicating the results of Study 1. This is shown in the scatterplots in Figures 5a and 5b.

**Effects of age of acquisition and proficiency.** Points in Figure 5 are coded to show age of acquisition. We explored whether age of acquisition for English was related to strength of laterality in L2. There was no significant correlation between AoA and LI for the phonological task ( $r = -0.12, p = 0.583$ ; Figure 5A) or for the semantic task ( $r = -0.02, p = 0.907$ ; Figure 5B).

Data on the Quick Placement Test, the measure of proficiency in L2, were available for 24 participants. These were not correlated with the LI for either the phonological task:  $r = 0.11, p = 0.614$ , or the semantic task:  $r = 0.02, p = 0.932$ .

## Discussion

Study 2 found that most participants were left-lateralised for language on both tasks in both languages and there was close correspondence between the LIs for L1 and L2. Furthermore, the pattern of results was very similar for the phonological and semantic fluency tasks. For this sample we had direct measures of proficiency, but again we found no relationship between lateralisation and either age of acquisition or proficiency.

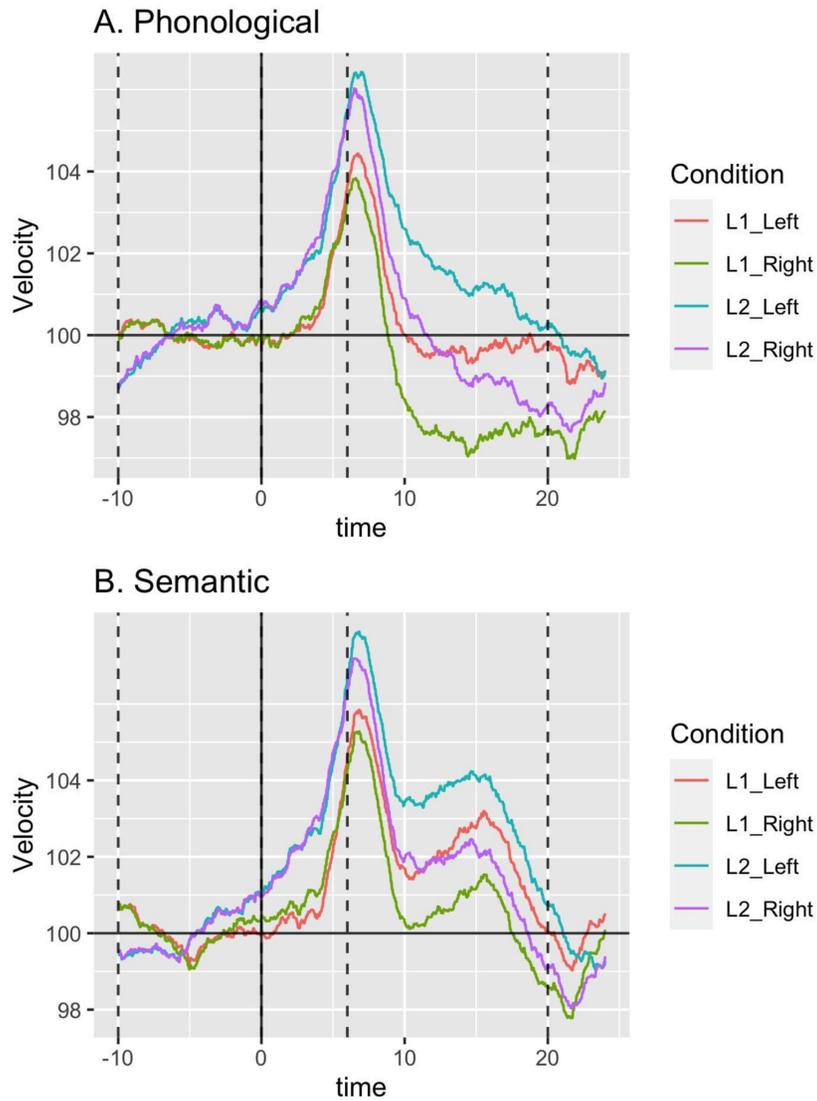
## General discussion

The results of Studies 1 and 2 show strong similarity despite the differing format of the tasks (covert and overt), native languages (French/ German and Japanese), and English proficiencies (mostly highly proficient but varying between basic and advanced proficiency).

The correlations between the LIs for L1 and L2 were uniformly high (ranging from .70 to .78) with 79% of participants left lateralised for L1 and 76% of participants left lateralised in L2. The data reported here add to a growing pool of results

**Table 3. Demographics for the Study 2 participants, N=25 (19 female).**

Characteristic	Mean (sd)
Age, years	29.32 (6.73)
Age of English acquisition, years	10 (4.21)
Time using English, years	11.08 (6.43)
English overall score/60	47.38 (7.1)
English speaking/100	65.65 (20.96)
English listening/100	69.78 (16.48)
English reading/100	65.43 (16.51)
English writing/100	69.78 (18.8)



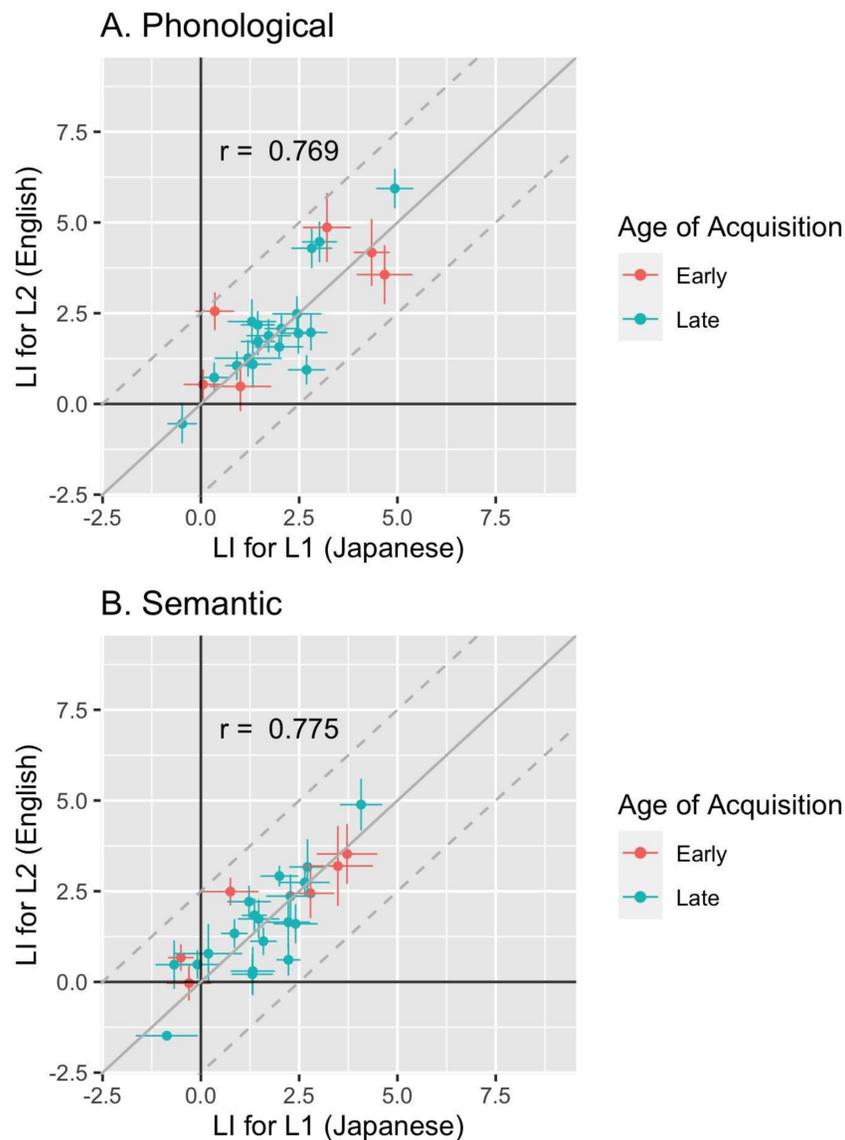
**Figure 4.** Left and right hemisphere activation is displayed as a function of epoch time in seconds for word generation for L1 (Japanese) and L2 (English) in Study 2. Plot 4a shows the phonological word generation task, and 4b shows the semantic word generation task. Dotted lines indicate the start and end of the baseline period (from -10 to 0 seconds) and the period of interest (from 6 to 20 seconds). L1, first language; L2, second language.

**Table 4.** Summary statistics for Study 2 laterality indices.

Task	Language	Mean trials	mean LI	se LI	% left	% bilateral	% right
Phonological	L1	19.12	1.96	0.28	72	28	0
Phonological	L2	19.52	2.01	0.38	76	20	4
Semantic	L1	19.00	1.53	0.28	72	28	0
Semantic	L2	19.12	1.65	0.28	64	32	4

supporting the idea that laterality of expressive language processing is the same for L1 and L2 in proficient bilinguals.

It is worth highlighting that our studies only used expressive language tasks, which typically produce strong lateralisation.



**Figure 5.** Scatterplot showing individual mean LIs in L1 and L2 for (a) Phonological and (b) Semantic Word Generation, with horizontal and vertical error bars denoting standard errors. The continuous grey line corresponds to the point of equality of the two measures, and the dotted lines show the limits where difference between LIs is  $\pm 2.5$ .

Where discrepancies in laterality have previously been reported, this has been for receptive language tasks - both in behavioural contexts (dichotic listening), and in neuroimaging (comprehension or lexical decision tasks) (Gurunandan *et al.*, 2020; Hull & Vaid, 2007; Wartenburger *et al.*, 2003). It is possible that the processes that drive this effect seen in the literature are not recruited during expressive language production. There would be considerable interest in studying laterality of perception and comprehension of spoken language using FTCD, for which we have developed some paradigms that have good reliability (Woodhead *et al.*, 2020).

Split-half reliabilities for all tasks were also uniform and high (ranging from .58-.83) for both languages. This suggests that

previously reported dissociations between laterality for L1 and L2 could simply reflect low reliability of the chosen measure. We believe our results are not an artefact of bimodality in the distributions; few cases had atypical lateralisation, and we used nonparametric correlations to guard against undue influence on correlations by outliers.

Age of acquisition has been proposed as a key factor in determining divergence of lateralisation patterns. For example Hull & Vaid (2007) found that bilinguals who were exposed to a second language before the age of 5 years had more bilateral representation than those who acquired a second language later. In our studies, age of acquisition (defined as age at first acquiring L2) ranged from 0–15 in Study 1 and 0–13 in Study 2. We

found no difference in lateralisation strength for L1 and L2 in those who acquired English early compared to those who acquired English later in either study for both phonological and semantic word generation tasks. This suggests that when a second language is proficiently acquired, lateralisation patterns of expressive language remain stable, regardless of age at which acquisition began.

Our research can also add to the literature regarding lateralisation and proficiency. Study 2 included participants with proficiency levels varying from basic to advanced as measured by the standardised Quick Placement Test. [Gurunandan et al. \(2020\)](#) reported that increasing proficiency of L2 accompanied more divergent lateralization patterns between L1 and L2. This result was not replicated in our study, with participants of all proficiencies showing similar LI strengths across all tasks. As we found no indication that degree of language laterality is of functional significance this opens up the possibility that variations in strength of LI, as measured by FTCD, may reflect anatomical differences. Individual variation in anatomy of the cerebral blood vessels has been documented ([Payne, 2017](#)), but has not, to our knowledge, been related to measures of lateralised blood flow.

#### Limitations

**Sample population:** Our samples were relatively small, with relatively few individuals with early age of acquisition or low proficiency. Given the dearth of data on cerebral lateralisation in bilinguals, we feel that nevertheless, the data are worth reporting so they can contribute to future meta-analyses. To that end we have made the data openly available in a repository.

**Language assessment:** In study 1, we used a self-report questionnaire to describe our sample and assess language history and proficiency, but behavioural measurements of proficiency may have revealed a wider response range for correlational analysis. Although Marian and colleagues established high reliability and validity for the self-report questionnaire used here, and validated it against behavioural measures, their questionnaire was devised to describe a population rather than provide an analysis measure of individual differences ([Marian et al., 2007](#)).

For study 2, we had a direct measure of language proficiency, but we did not find any coherent associations between level of proficiency and lateralisation.

**Method:** While test-retest reliability of FTCD measurements is high and the time-locked correlation analysis of CBFV is robust and non-invasive, the main limitation of the method is that findings can only be interpreted on a hemispheric level, and do not give information about brain regions within a hemisphere

that are involved for processing first and second languages. To uncover the specific networks involved in processing L1 and L2, we would need techniques that provide finer-grained information about within-hemisphere localisation, microcircuitry, and connectivity ([Abutalebi & Green, 2007](#)).

#### Conclusions

In two studies, we showed that proficient bilinguals have comparable levels of lateralisation for L1 and L2 when laterality is measured using FTCD during modified versions of the well-validated word generation tasks. Our results indicate that degree of language laterality is reasonably stable in individuals, rather than simply reflecting error of measurement.

Laterality and language are multidimensional constructs, and in future work FTCD could be used to test bilingual laterality with different tasks and larger, more heterogeneous samples, differing on what [DeLuca et al. \(2019\)](#) referred to as “the spectrum of experiences”. As an inexpensive, non-invasive, comfortable, easily applicable, mobile, and child-friendly method, with a high temporal resolution, FTCD can complement fMRI, allowing us to test large samples and track changes throughout development, with repeated administration and with different tasks.

#### Data availability

##### Underlying data

Open Science Framework: Bilingual FTCD, <https://doi.org/10.17605/OSF.IO/VD9DT> ([Bishop et al., 2021a](#)).

This project includes the original raw and processed data for study 1. Please see the [Data Dictionary](#) for a description of the files.

Open Science Framework: Lateralisation in bilinguals, <https://doi.org/10.17605/OSF.IO/MDCZ5> ([Bishop et al., 2021b](#)).

This project includes the raw data for study 2 and processed data for studies 1 and 2, with custom scripts used for analysis.

Data are available under the terms of the [Creative Commons Zero “No rights reserved” data waiver](#) (CC0 1.0 Public domain dedication).

#### Author contributions

Conception and design (CRG, KEW, DVMB, HP, MM, EG, MS); data collection (CRG, HP, MS); data processing and statistical analyses (CRG, DVMB, SCH, ZVJW, HP, MS); interpretation of data (CRG, KEW, DVMB, HP); drafting and revising the manuscript (CRG, KEW, DVMB, SCH, ZVJW, HP, EG, MS).

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Current Peer Review Status: ? ✓ ✗

## Version 1

Reviewer Report 20 March 2017

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Although functional asymmetries between the hemispheres have been known since the mid-19<sup>th</sup> century, we still lack a thorough understanding of the underlying mechanisms. In particular, we do not have precise models that reveal which factors drive hemispheric specialization, how lateralization processes of different cognitive functions interact with each other, and how the brain integrates processes that are lateralized to opposite hemispheres. In the present study, Grabitz and colleagues aimed to investigate whether the hemispheric lateralization of first and second languages is different. Hemispheric dominance was assessed by functional transcranial Doppler sonography (fTCD) in 26 high proficiency bilinguals with either German or French as their first language (L1) and English as their second language (L2). fTCD was used to assess task-dependent blood flow velocity changes in the left and right middle cerebral arteries during a cued word generation task. The authors report that the majority of participants (22/26) were significantly left lateralized for both L1 and L2. They found no significant difference between the lateralization of L1 and L2, as assessed by a lateralization index (LI). They conclude that in highly proficient bilinguals, there is strong concordance for cerebral lateralization of first and second languages. Although the study was competently performed, there are some concerns about the conceptual planning of the study and the application of fTCD.

Conceptual foundations of the study: There are many aspects of functional neuroanatomy that might differ between L1 and L2, for instance the recruitment of brain regions, the strength of brain activity in specific regions or the connectivity between language regions. Hemispheric lateralization is only one aspect. It might have been useful to explain why the authors assessed in particular hemispheric dominance, it might have been useful to state why they anticipated that language lateralization is stronger for a bilingual person's first language than for the second language, and it might have been useful to explain what they authors would have had concluded when they had found significant differences between the lateralization of L1 and L2 –

expect that there are significant differences. To interpret non-significant differences, as in the present study, it is also necessary to explicitly state how strong the LI would be expected to differ between L1 and L2. What is a minimal difference that would have been considered as relevant? It is also not clear whether the authors intended to assess differences between L1 and L2 on a group level or in individual subjects? What would be the putative role of interindividual differences? In summary, in its present version of the manuscript a theoretical concept is completely missing. Without this concept, it is not possible to properly interpret the findings. The manuscript gives the impression that the authors were just looking for differences in a rather exploratory way.

Application of fTCD: Before performing a study, it might be a useful exercise to ask whether the imaging technique used is a suitable tool to answer the question asked. I have serious doubts that fTCD can be applied for that purpose. The authors expect to find differences between the lateralization of L1 and L2. It is important to know whether the technique is sufficiently sensitive to find differences, if they exist. As mentioned before, the authors do not explicitly state what differences they expect. In our opinion, it is rather unlikely that the hemispheric dominance (left, right, bilateral) of L1 and L2 will be different. If a subject is for instance left dominant for L1, we do not expect that she will be right dominant for L2. The expected differences will most likely be on a smaller scale. A subject that is left dominant for L1 might be a bit less left dominant for L2. Is fTCD able to find these differences? Unfortunately, there are no methodological studies that assessed how sensitive fTCD is to find potentially small differences in the degree of lateralization. We certainly agree that fTCD is a useful tool to determine hemispheric dominance (that is, left- or right-hemispheric lateralization). It is, however, unknown if the technique can be used to also assess small differences in the degree of hemispheric lateralization. Large methodological studies in this regard, in particular from independent groups (i.e., not from the developers of AVERAGE), are missing. One might also ask why the developers report correlations between fTCD and other techniques (such as fMRI or the Wada test) as high as  $r \sim 0.9$  (and even much higher), when it is not possible to reproduce these findings even with the same modality. Furthermore, fTCD assesses blood flow velocity changes in the vascular territory of the left and right middle cerebral artery. This territory however shows a high interindividual variability. While one might argue that main network nodes of the language system, such as "Broca's area", lie within this territory in all subjects, other regions that are also active during the task might be included in the calculation of the LI in some subjects, but not in others. What are the consequences when one compares a LI between subjects? In summary, it is unclear whether fTCD is sensitive enough to measure small differences between the lateralization of L1 and L2.

To conclude, the study deals with an interesting topic and is competently performed. However, the theoretical foundation should be described in more detail, the expected difference between the LI of L1 and L2 should be reported, and it should be made clear that fTCD is able to measure the expected differences at all.

**Competing Interests:** No competing interests were disclosed.

**We confirm that we have read this submission and believe that we have an appropriate level of expertise to state that we do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

Author Response 24 Jun 2021

**Dorothy Bishop**, University of Oxford, Oxford, UK

*'explain why the authors assessed in particular hemispheric dominance' – many reasons for differences in L1 and L2: recruitment of brain regions, strength of brain activity, connectivity between language regions*

We now make it clear that we recognise that there are potentially many ways in which language processing may differ for the two languages in bilinguals, but we do not think that invalidates a decision to look specifically at brain lateralisation, which has previously been discussed as potentially differing between languages.

*State why it was anticipated that language lateralization is stronger for a bilingual persons L1 than for L2.. Explain what the authors would have concluded when they had found significant differences between the lateralisation of L1 and L2. Explicitly state how strong the LI would expected to differ between L1 and L2.*

We now go into more detail regarding predictions from prior literature. The prediction of discrepant laterality between languages was not strong: In the literature, there are reports of both the same strength of lateralisation for L1 and L2 and also reduced lateralisation for L2. A finding of significant difference in lateralisation between L1 and L2 would have lent further support to one side of this debate.

*What is a minimal difference that would have been considered as relevant? There are issues with interpreting non-significant findings.*

As well as reporting Bayes Factors for mean comparisons, we have now conducted further analysis using the Bland-Altman method, which is specifically designed to address this issue.

*It is also not clear whether the authors intended to assess differences between L1 and L2 on a group level or in individual subjects? What would be the putative role of interindividual differences?*

This is a within-subjects study, with each person tested in both their languages, so the differences are evaluated in individual subjects. The correlations that are reported depend on there being individual differences in the extent of lateralisation. The result, therefore, hinges on interindividual differences.

*Important to know if technique is sensitive to find differences if they exist – are there methodological studies to assess the sensitivity of fTCD to small differences in lateralisation? ' I have serious doubts that fTCD can be applied for that purpose. The authors expect to find differences between the lateralization of L1 and L2. It is important to know whether the technique is sufficiently sensitive to find differences, if they exist.'*

Since this study was conducted, we have reported a study of test-retest reliability of laterality indices assessed using fTCD, which we now cite. They are high enough to give confidence that the degree, as well as direction of laterality measured this way, is reasonably stable. See Woodhead, Z. V. J., Bradshaw, A. R., Wilson, A. C., Thompson, P. A., &

Bishop, D. V. M. (2019). Testing the unitary theory of language lateralization using functional transcranial Doppler sonography in adults. *Royal Society Open Science*, 6(3), 181801.

<https://doi.org/10.1098/rsos.181801>.

The reviewers clearly have a very negative impression of fTCD as a measure of laterality, but it's unclear what they prefer. The Wada technique is a blunt instrument that is useful in clinical contexts for making a basic distinction between left, right and bilateral, but it is neither feasible nor useful for measuring degrees of lateralisation. With fMRI one can quantify the LI, but the results will depend on the statistical approach (e.g. height or extent of statistic, %signal change etc), ROI studied and on thresholding. The kinds of individual difference in vasculature that the reviewers mentioned may well affect the observed LI - we now make that point in the Discussion. However, this will be as true for measures from fMRI as for fTCD, and in addition, with fMRI, the issue is complicated by the possibility of individual differences in localisation of language regions.

So, while we accept that fTCD is not perfect, neither are other methods, and part of our goal in ongoing research is to use them as complementary methods. Indeed we regard it as a worthwhile endeavour in future to consider how far the LI in fTCD relates to anatomical variation. But we don't see any of these as reasons to dispense with the results we have obtained, which we regard as part of a complex pattern of evidence on these issues.

*Why did the developers report correlations between fTCD and other techniques (such as fMRI or Wada test) as high as  $r \sim 0.9$ , when it is not possible to reproduce these findings even with the same modality?*

We cannot say why the Münster group who developed fTCD reported these correlations. Our work is independent of theirs and we have not used the Average software for some years, though the processing steps we adopt are largely the same. The correlations they originally reported were based on small sample sizes and would have large confidence intervals around them. In addition, language laterality, as conventionally measured, is usually not normally distributed and should be evaluated with a nonparametric correlation coefficient. We hope to obtain data on larger samples in future that will provide more solid evidence on the relationship between lateralisation as assessed by fTCD and fMRI.

**Competing Interests:** No competing interests were disclosed.

Reviewer Report 05 December 2016

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**Tom Hope**

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This is a succinctly written paper reporting the novel results from a non-invasive technique (functional transcranial doppler ultrasound) that examines changes in blood flow velocities in the left and right middle arteries in response to a cued word production task in a person's native language (L1, either French or German) and in their second language (L2, English). The participants were young proficient bilingual speakers immersed in an English context. The aim was to examine the degree of lateralisation in response to this task in L1 and in L2. The data are appropriately analysed with suitable correction for the number of comparisons made where required.

**Rationale**

It is important to deploy non-invasive methods that can be used to assess brain response for a particular tasks in children and in adults. The specific question addressed concerns the extent to which L1 and L2 reveal a comparable pattern of asymmetry as revealed by the measure of blood flow velocity.

It is worth noting that both hemisphere play a role in speech processing in monolingual speakers. Functional imaging data are consistent with the idea that regional activation during speech production is bilateral for motor, premotor, subcortical, and superior temporal regions whereas middle frontal activation is predominantly left lateralised (Price, 2010). As the authors correctly note, neuroimaging data strongly implicate common regions in the processing of L1 and L2. Indeed from a neurocomputational point of view, there is no reason to envisage that the processing of a second language would recruit radically distinct regions (Green, 2003). Instead, different languages may recruit different microcircuits within common regions (e.g., Paradis, 2004). We should then expect differences attributable to the distinct phonological and syntactic properties of words in different languages and commonalities in terms of their reference to common entities. Consistent with this possibility, Correia *et al.* (2014), using multi-voxel pattern analysis, reported discriminating neural response in multiple temporal, parietal and frontal cortical regions to individual spoken animal nouns (horse/duck) in English and Dutch combined with an invariant response pattern to the translation equivalents (paard/eend) indicative of access to common semantic/conceptual knowledge in regions such as the anterior temporal pole. In modelling recovery post-stroke, we found that models implicating the same brain regions were equally predictive for both monolingual and bilingual speakers displaying parallel recovery patterns (Hope *et al.*, 2015). Evidence for selective recovery post-stroke does not contradict this position, but rather points to a difficulty in control (Green, 2008). Detailed determination of this possibility in the context of speech production awaits future research. However, the Wada test (using injection of intracarotid amobarbital), referred to by the authors as the gold standard in determining lateralization, strongly implicates left hemisphere representation for both languages of a bilingual speaker (e.g., Rapport, Tan & Whitaker, 1983). A non-invasive method as reported here provides a useful adjunct despite its noted limitations in terms of identifying the microcircuits involved.

**Participant information**

Self-reported proficiency does generally correlate reasonably well with more objective measures as the authors note. Nevertheless, it is usually desirable to report such objective measures. For

instance, for vocabulary measures the various tests under the rubric of LexTale offers a good source (Brysbaert, 2013; Lemhöfer & Broersma, 2012). There are also Quick Placement tests to assess syntactic knowledge.

### **Procedure**

Given the experimenter spoke English all the time how was the transition to the word generation task managed, in particular the switch from describing a picture in L1 to the naming task?

### **Data analysis**

The word generation task involved an interval for the silent generation of words in response to a cued letter (15 secs) followed by a 5 second recall interval. Although this interval is short and so constrains information on relative difficulty, it is of interest to know the mean scores and their variance. If there is variance, does such variance have detectable effects on the signal?

### **Estimates of reliability**

The authors nicely use odd-even trials to estimate signal reliability for the asymmetry index. This estimate proved significant for the production task in the native language (L1) but not for the second language, English (L2). If there is no asymmetry difference then shouldn't there be a significant correlation when alternate trials are taken from different language runs?

**Competing Interests:** No competing interests were disclosed.

**We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.**

Author Response 24 Jun 2021

**Dorothy Bishop**, University of Oxford, Oxford, UK

#### *Comments under Rationale*

We thank the reviewers for providing an overview of the literature on microcircuitry, which we now mention in the Discussion

#### *Usually desirable to report objective measures of language proficiency*

Please see response to reviewer 1. We did not have such measures for Study 1, but we do for study 2.

#### *Given the experimenter spoke English all the time, how was the transition to the word generation task managed, in particular the switch from describing a picture in L1 to the naming task?*

Alas, this was not noted at the time of data collection for Study 1 and we do not have a record of how this was handled, though we do state that the examiner used English throughout. For Study 2, the experimenter switched instruction languages according to the tested languages.

**Data analysis.** *The word generation task involved an interval for the silent generation of words in response to a cued letter (15 secs) followed by a 5 second recall interval. Although this interval is short and so constrains information on relative difficulty, it is of interest to know the mean*

scores and their variance. If there is variance, does such variance have detectable effects on the signal?

We were not sure we had interpreted this correctly; in Study 1 words were generated covertly, therefore we did not have a record of responses. However, in previous studies with monolinguals, we have specifically considered whether varying task difficulty affects laterality. Where difficulty is varied by constraining the task (requiring words starting with 2 specific letters rather than one), this reduced performance but did not affect the LI. (Badcock, N. A., Nye, A., & Bishop, D. V. M. (2012). Using functional transcranial Doppler ultrasonography to assess language lateralisation: Influence of task and difficulty level. *Laterality*, 17(6), 694–710. <https://doi.org/10.1080/1357650X.2011.615128>). In Study 2 subjects generated words overtly and we report data on number of words produced. There was no relationship between number of words generated and LI.

**Estimates of reliability** The authors nicely use odd-even trials to estimate signal reliability for the asymmetry index. This estimate proved significant for the production task in the native language (L1) but not for the second language, English (L2). If there is no asymmetry difference then shouldn't there be a significant correlation when alternate trials are taken from different language runs?

We were also puzzled by the differing estimates of split half reliability - as it turns out when we reanalysed the data for this version, using our current analysis scripts, the estimate of split half reliability was more similar for the two languages: for L2, the original analysis gave  $r = .28$ . With our new method, one participant met criteria as an outlier and was excluded, and we also used Spearman rather than Pearson correlation, and based the LI on the mean rather than peak of the difference waveform; this gives  $r = .60$ . Please note: the analytic decisions leading to these changes were made a priori: we used the scripts and outlier exclusion criteria that we documented in Woodhead et al (2019), and list here how each modification of the method affected the correlation:

- Discarding one participant with noisy data (participant 14),  $R = 0.44$
- Using Spearman's correlations instead of Pearson's,  $R=0.49$
- Using mean LI method instead of peak,  $R=0.60$

We feel this provides further justification for basing analyses on mean rather than peak values: the latter can be more noisy, especially if the data do not show a single pronounced peak.

**Competing Interests:** No competing interests were disclosed.

Reviewer Report 05 December 2016

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? **Marc Brysbaert**

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It pains me to have to write this review. The research done is good and reliable (and hence the Wellcome Trust may decide to publish it), but the question addressed is futile and the methods used far from optimal. Therefore, I fear that if this article is indexed to PubMed Central, it will not do the authors much good.

For a start, the authors had anticipated that language lateralization might be stronger for a bilingual's first language than for the second language. In 1992, Paradis already called this the Loch Ness Monster of research on laterality and bilingualism. There is no sound evidence whatsoever that L2 processing would be less lateralized than L1 processing (as the authors indeed found). There is even very good evidence that as L2 proficiency increases, it increasingly uses the very same brain areas as L1 processing. Only at low levels of L2 proficiency can one sometimes see extra right and left hemisphere activity, arguably because the participants are using all types of strategies, including non-language ones.

Second, the authors are using the crudest neuroscientific technique available, fTCD. As they say, it is cheap, it can be applied easily (but leads to a considerable loss of participants), but it is also very crude, as it only compares to blood flow to the left vs. the right hemisphere. In the present study, the reliability is good (except for L2 processing), but even so it remains a technique that only can tell you something about more left than right processing, nothing more. So, in the end the authors are investigating a strawman hypothesis with an uninformative technique.

Third, there are power issues. A lot of subject-related variables are tested on a group of 26 participants. Luckily the authors did not find anything significant, because any significance they would have found, would have been very likely due to a statistical fluke, which cannot be replicated (see papers by Gelman).

Fourth, individual differences are thought to be of interest. Still, they are studied with subjective scales. Why not measure the proficiency with a vocabulary test (e.g., LexTALE, Shipley)? Why use Likert scales? In several studies (involving the French and Spanish Lextale tests), I've reported that although there is a good correlation between subjective estimates on the basis of a Likert scale and the Lextale scores, for individual participants there can be a big difference, because participants use different comparison groups (e.g., L2 learners compare their performance to other L2 learners, not to L1 speakers). If the authors want to keep on using subjective measures, they may want to try descriptions as the levels defined by the European framework.

As said, if the goal of the Wellcome Open Research initiative is to make all reliable empirical data available, I am not against publication. However, for the above reasons I do not think this publication will do the authors (nor the journal) much good. The only bit of information I found of value was Figure 4. Even then it would be good to see this supported by fMRI validation. I know the Knecht group did so, but still I'd like to see it done in other groups as well. I'm very curious, for instance, to what extent the bilateral patterns are valid. We rarely see them in fMRI research.

**Competing Interests:** No competing interests were disclosed.

**I confirm that I have read this submission and believe that I have an appropriate level of**

**expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 24 Jun 2021

**Dorothy Bishop**, University of Oxford, Oxford, UK

Brysbaert, while unenthusiastic about our original paper, accepted that "if the goal of the Wellcome Open Research initiative is to make all reliable empirical data available, I am not against publication." Nevertheless, he queried whether the study was worth doing, given that prior work with fMRI had not found discordant laterality for two languages in bilinguals. In addition, it was felt that reliance on self-reported proficiency was non-optimal, and that there were concerns about concluding a lack of difference between languages when sample size, and hence statistical power, was low. He also expressed misgivings about the method we had used, functional transcranial Doppler ultrasound.

*1. Prediction of different laterality in L1 and L2 is futile. We already know that is not the case.*

If we understood this point correctly, the reviewer is arguing that the fact that laterality is the same in L1 and L2 for proficient bilinguals is so well established that it is pointless to provide a further demonstration of the point. We disagree. The literature has not always been consistent and most studies are small, so an accurate picture may only become clear when there is sufficient information for a meta-analysis. Our aim was to use fTCD to contribute to this literature. We accept that the reviewer has a very low opinion of fTCD, but we do not think this is justified, and indeed would argue that the strong correlations between L1 and L2 laterality indices obtained with this method provide some evidence that individual variation in degree of lateralisation are meaningful.

*2. fTCD is not sensitive enough to detect relevant hemispheric differences*

We now provide more arguments in support of fTCD. We note also reviewer 2's comment: 'A non-invasive method as reported here provides a useful adjunct despite its noted limitations in terms of identifying the microcircuits involved.' Brysbaert states that fTCD only tells you about left- vs right hemisphere blood flow. That's exactly what we are interested in, so this criticism does not seem valid. We should stress we are not making massive claims for fTCD - it clearly has its limitations - but dismissing a study on laterality just because it uses this method seems premature. It is one tool in the range of possible methods: we need to do more work with all of them (behavioural, fTCD, fMRI) to study how they relate to one another and how reliable and sensitive they are, in order to make progress in laterality research. This is exactly what we are doing in our current research programme.

*3. 'there are power issues. A lot of subject-related variables are tested on a group of 26 participants.'*

We agree that there are power issues. Brysbaert claims the result is unlikely to replicate. We have now included Study 2 - this confirms that the result does replicate, and generalises to another language and task (semantic fluency).

In terms of the subsequent exploratory analysis of correlations with other measures, as noted by reviewer 2: 'The data are appropriately analysed **with suitable correction for the number of comparisons made where required.**' (our emphasis). However, we agree the sample is too small of sensible exploratory analyses, and have now modified our focus to the Age of Acquisition effect, which is a matter of some debate in the literature. Other variables are reported for completeness, but we agree that it is not sensible to report all correlations in the absence of a priori predictions.

*4. 'individual differences are thought to be of interest. Still, they are studied with subjective scales. Why not measure the proficiency with a vocabulary test (e.g., LexTALE, Shipley)? Why use Likert scales? In several studies (involving the French and Spanish Lextale tests), I've reported that although there is a good correlation between subjective estimates on the basis of a Likert scale and the Lextale scores, for individual participants there can be a big difference, because participants use different comparison groups (e.g., L2 learners compare their performance to other L2 learners, not to L1 speakers). If the authors want to keep on using subjective measures, they may want to try descriptions as the levels defined by the European framework'*

We agree. This point was also made by Reviewers 2, though they also pointed out that self-reported proficiency correlates reasonably well with more objective measures. A strength of study 2 is that it used more objective measures of language proficiency. We thank the reviewer for the excellent suggestions for measures to be used in future work.

**Competing Interests:** No competing interests were disclosed.

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