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Dichotic-listening performance after complete callosotomy: No relief from left-ear extinction by selective attention

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ABSTRACT

The surgical section of the corpus callosum (callosotomy) has been frequently demonstrated to result in a left-ear extinction in dichotic listening. That is, callosotomy patients report the left-ear stimulus below chance level, resulting in substantially enhanced right-ear advantage (REA) compared with controls. A small number of previous studies also suggest that callosotomy patients can overcome left-ear extinction when the instruction encourages to attend selectively to the left-ear stimulus. In the present case study, we re-examine the role of selective attention in dichotic listening in two patients with complete callosotomy and 40 age- and sex-matched controls. We used the standardised Bergen dichotic-listening paradigm which uses stop-consonant-vowel syllables as stimulus material and includes both a free-report and selective-attention condition. As was predicted, both patients showed a clear left-ear extinction. However, contrasting the earlier reports, we did not find any evidence for a relief from this extinction by selectively attending to the left-ear stimulus. We conclude that previous demonstrations of an attention-improved left-ear recall in callosotomy patients may be attributed to the use of suboptimal dichotic paradigms or residual callosal connectivity, rather than representing a genuine effect of attention.

1. Introduction

Presenting two verbal auditory stimuli (e.g., words or syllables) dichotically – one to the left and one, at the same time, to the right ear – typically results in a perceptual preference of the right-over the left-ear stimulus (e.g., Bless et al., 2015; Bryden, 1988). This so-called right-ear advantage (REA) has been traditionally linked to the left hemispheric dominance for speech processing (e.g., Carey and Johnstone, 2014; Kimura, 1961; Van der Haegen, Westerhausen, Hugdahl and Brysbaert, 2013; Zatorre, 1989), whereby various models have been suggested to explain this association (for overview see Hiscock and Kinsbourne, 2011). Kimura (1967) – in the most influential dichotic-listening model – explained the phenomenon by postulating that the dichotic competition of the two stimuli leads to an "occlusion" of the ipsilateral ascending auditory pathways, so that initially each stimulus will be only represented in the contralateral hemisphere. Consequently, only the right-ear stimulus gets direct access to the speech processing left hemisphere, while left-ear information is only available to right hemisphere, which cannot process the phonological components of the stimulus to the same degree, leading to the REA. Later extensions of Kimura's model assumed that the left-ear stimulus can only reach the left hemisphere speech processing via the corpus callosum (Sparks and Geschwind, 1968; Westerhausen and Hugdahl, 2008), suggesting the magnitude of the REA can be attributed to inefficiency of this callosal relay. One alternative to Kimura's "structural model", is the "attentional model" proposed by Kinsbourne (Kinsbourne, 1970, 2003) which attributed the REA to an imbalance in the activation of the cerebral hemispheres. The model assumes that receiving verbal input activates the left hemisphere more than the right, which leads to an attentional orientation to the contralateral (right) space, producing the REA. This view is, for example, illustrated by a right-ear/side preference for audio-verbal imagery (Prete et al., 2016) or for hearing voices in white noise (Prete, D'Anselmo, Brancucci and Tommasi, 2018). Importantly, it is thought that the attentional bias can be overcome by the spread of activation across the corpus callosum, equilibrating the imbalance so that also information from the left ear can be reported (Kinsbourne, 2003).

Both the structural and attentional model of dichotic listening ascribe a central role to the corpus callosum in explaining the report of

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information from the left ear which originated from studies on patients with partial and complete callosotomy (e.g., Gazzaniga et al., 1975; Milner et al., 1968; Sparks and Geschwind, 1968; Springer and Gazzaniga, 1975; Zaidel, 1976). These so-called "split-brain" patients had undergone a surgical section of the corpus callosum (sometime together with other cerebral commissures) as method of treatment of intractable epilepsy (Fabri et al., 2017). When tested with dichotic listening, callosotomy patients typically show an "extinction" of the left ear (e.g., Clarke et al., 1993; Sparks and Geschwind, 1968; Springer and Gazzaniga, 1975; Tweedy et al., 1980), although not necessary for all implementations of the dichotic-listening paradigm (Musiek et al., 1989; Springer et al., 1978). That is, at least when using consonant-vowel (CV) syllables or rhyming words as stimulus material, post-surgery patients are unable to report the stimulus presented to the left ear above chance level (e.g., Clarke et al., 1993; Springer and Gazzaniga, 1975; Springer et al., 1978; Tweedy et al., 1980; Zaidel, 1976). The right-ear report, at the same time, appears unaffected or slightly increased compared to a control group with intact corpus callosum. This pattern is also found when comparing the performance before and after the surgery in the same patients (e.g., Musiek et al., 1984; Musiek and Wilson, 1979; Musiek et al., 1979; Risse et al., 1978; Sidtis et al., 1981). Furthermore, and in line with the topographical organisation of the corpus callosum (e.g., Fabri and Polonara, 2023; Schmahmann and Pandya, 2006), partial sections of the corpus callosum is sufficient to evoke the left-ear extinction, as long as the posterior third of the corpus callosum is affected (McKeever et al., 1981; Musiek et al., 1984; Musiek et al., 1985). Thus, studies on callosotomy patients support the notion that specifically the ability to recall the left-ear stimulus in dichotic listening relies on the posterior corpus callosum.

However, the first dichotic-listening study on complete commissurotomy patients by Sparks and Geschwind (1968) also suggested a possible role of attention in overcoming the left-ear extinction. The authors gave Patient W.J. the "*strong instruction to attend to the left ear*" (p.8) which seemed to alleviate the extinction. Following the instruction, W.J. was able to report 35% rather than 0% of the left ear stimuli. Comparably, Springer and Gazzaniga (1975) reported an increase in correct left-ear identifications in the selective attention condition compared with the free-report condition in one of the three patients tested. However, this patient (J.K.) had only the anterior commissure and anterior one third of the corpus callosum sectioned so that remaining connections of the splenium might have carried the attention effect. Corballis and Ogden (1988) reported that two cases with complete callosotomy (A.A. and L.B.) which were tested with both a selective and in a divided attention condition, showed an increase of the correct left-ear recall (Patient L.B.: 16% increase: Patient A.A.: 108% increase) due to selective attention (compared with a condition asking to report all stimuli). Thus, as it appears that some callosotomy patients can access the left-ear stimulus representation by selective attention which otherwise was blocked from verbal report due the lack of callosal connections. While the callosal-relay model of dichotic listening does not offer a straight-forward explanation for this effect, one might speculate that anticipatory selective attention "opens" the ipsilateral auditory pathways from the left ear to the left hemisphere. Following the attentional model, the activation imbalance might be shifted using non-callosal pathways anticipating the required left-ear report. However, the selective attention effect was not found consistently and studies examining it in patients with other callosal pathologies contradict this observation (Pollmann et al., 2002; Reinvang et al., 1994; Sugishita et al., 1995). For example, Pollmann et al. (2002) found that callosal lesions (of various aetiology) irrespective of their location prevent patients from benefitting from selective attention.

In the present study, we revisited the left-ear extinction and the effect of directed attention in dichotic listening in two patients (P2 and P3) with complete callosotomy from the Ancona sample (Fabri and Polonara, 2023). As paradigm we utilised the standardised Bergen dichotic-listening paradigm (Hugdahl and Andersson, 1986; Hugdahl et al., 2009), which uses stop-consonant-vowel (CV) syllables (e.g.,/ba/, /pa/) as stimulus material and includes a free-report (called non-forced condition, NF), as well as two selective (or forced) attention conditions demanding to only attend to and report from one ear at the time. This choice was made as CV paradigms reliably produce a left-ear extinction after callosotomy (e.g., Clarke et al., 1993; Springer and Gazzaniga, 1975; Tweedy et al., 1980), and the use of one stimulus pair per trial, results in low working-memory load (for discussion see Westerhausen, 2019). It was predicted that both patients with total resection of the corpus callosum show a left-ear extinction, reflected by a left-ear recall below chance level and below the performance of an age- and sex-matched control sample. Furthermore, to indicate that selective attention indeed may be used to overcome the left-ear extinction, an increase in the correct recall by selective attention compared to a free-recall condition was predicted, specifically for the left-ear stimulus.

2. Material and methods

2.1. Subjects

Two right-handed men with MRI-verified complete callosotomy (P2 and P3) were tested in July 2009. P2 was at time of testing a 45-year-old man who had his second operation, which completed the callosotomy for the relief of a generalized multifocal epilepsy, at the age of 30 years. Magnetic-resonance-imaging (MRI) scan of P2 confirm the completeness of the callosal resections (see Fabri et al., 2005; Hausmann et al., 2021). P2 is strongly right handed, with a laterality index of +100, according to the Edinburgh Handedness Inventory (Oldfield, 1971). P2 has a full-scale IQ of 81 in the Wechsler Adult Intelligence Scale III.

P3 is a 33-year-old man who underwent partial callosotomy in 1994, and full callosal resection was completed in 1995. Moreover, P3 had a lesion in the first circonvolution of the right hemisphere and a small lesion in the right medial parietal cortex. Epileptogenic lesions in the left hemisphere were not detectable. His post-operative IQ has been reported as 83 (Fabri et al., 2005). He is right-handed, with a laterality quotient of +40 according to the EHI, although he was said to write with his left hand as a child, and was forced to switch, and remembers writing with his right hand by age of 10 years. He reported that he has always thrown and eaten with the right hand. When asked to print uppercase letters, he was able to do so with either hand, but was faster and more fluent with right hand.

The control group comprised 40 neurologically normal men, which represent all right-handed men with an age of 5 years below and above the age of the patients (i.e., from 28 to 55 years) available from the Bergen dichotic listening database (Hugdahl, 2003). Thirty-three (82.5%) of the 40 controls had a REA, two no ear preference, and 5 (8%) a left-ear advantage in dichotic listening (see next section), thus, showing the typical proportions (see e.g., Westerhausen and Kompus, 2018). The mean age of the control group was 34.2 years (standard deviation, SD = 6.6 years). The database includes data accumulated from several different laboratories and includes data from native speakers of various languages. Nevertheless, all participants were tested with the same standardised paradigm and procedure (Hugdahl et al., 2009) which were also employed when testing P2 and P3.

2.2. Procedure and materials

The dichotic paradigm was the Bergen dichotic listening test (Hugdahl and Andersson, 1986; Hugdahl et al., 2009) using natural recordings of the six CV syllables which results from combining the six stop-consonants with the vowel /a/ (i.e.,/ba/,/da/,/ga/,/pa/,/ta/, and/ka/). The CV stimuli were recorded by a native Italian speaker, to match the native language of P2 and P3. The syllables are read with constant intonation and intensity. The stimuli were paired in all 36 possible combinations, with the left- and right-ear channel aligned to the onset of the "burst" of the consonant sound. The full set includes 30 dichotic-stimulus pairs, presenting different syllables to right and left ear (e.g.,/ba/-/ka/,/ka/-/ba/), as well as six homonymic pairs, presenting the same syllable to right and left ear (e.g.,/ba/-/ba/,/ka/-/ka/).

The stimuli were administered in three blocks, each containing all 36 pairings in a pseudo-randomized order. Each block was conducted with a different instruction. The NF instruction asks participants to repeat the syllable heard clearest, even if both stimuli were perceived. In the forced-right (FR) and forced-left (FL) condition participants are required to selectively attend to the right and the left ear, respectively, and report only the syllable presented there. The other channel was supposed to be ignored. During the FL and FR conditions, a sign with a left- and right-pointing arrows was placed in front of the patient to remind them which ear to attend. The patients performed each condition twice, so that each of the three conditions was tested with 60 dichotic trials. The control sample was tested ones per condition. The patients performed the NF condition first, followed by the FL and the FR attention conditions. Of note, the patients' performance was comparable in both runs of the paradigm and accordingly averaged across runs.

Before conducting the dichotic testing, both patients underwent monoaural testing. That is, the same CV syllables as used for the dichotic test were presented to one ear at the time, with no competing information presented to the opposite ear. This was done (a) to familiarise the patients with the stimulus material, and (b) to test for general sensory (hearing) or perceptual bias to one side. The tests consisted of a total of 48 monoaural trials, with each 24 trials selectively stimulating the left and the right-ear, respectively. Each of the six syllables was administered four times per ear. Monoaural testing was not available for the control sample.

The presentation of CV stimuli in both monoaural and dichotic testing was computer controlled using supra-aural headphones (K271, AKG Acoustics, Vienna, Austria). The stimuli were presented with a stimulus-onset asynchrony of 4000 msec, leaving a 3500 msec inter-stimulus interval during which the participant's response was collected. However, the stream of stimulus presentations was interrupted when necessary to allow the patients to keep up. The answer was given verbally and recorded by the experimenter together with an Italian native speaker.

The scoring of responses was based on the correctly recalled left- and right-ear stimuli. That is, in the NF condition, the percentage of correctly recalled left- (LE%) and right-ear stimuli (RE%) in the dichotic trials and were scored separately. For the forced condition, only the RE% under forced right instruction and LE% under forced left instruction were used for further analysis. Additionally, the laterality indices (LI) for the NF and monoaural conditions were calculated as *[(RE% -LE%)/(RE% + LE%)] x 100*. A forced-attention condition LI was determined by entering the RE% of the FR condition and LE% of the FL condition in the formula. Finally, using the NF condition as baseline, attentional gain scores were determined by subtracting the number of correct left-/right-ear recall obtained in the NF condition form left-/right ear recall in the FL/FR condition (FL gain and FR gain). Positive values indicated a relative gain in left-/right-ear recall by selective relative to the free report condition.

2.3. Statistical analysis

The patient data (i.e., percentage correct, laterality indices, gain scores) was tested against the control sample using *t*-statistics following Crawford-Howell method (Crawford and Garthwaite, 2012; Crawford and Howell, 1998). Following the directional predictions (i.e., patients should show a left-ear extinction, stronger laterality, reduced effect of selective attention), the comparisons were set-up as one-sided tests. The deviation from the control sample's mean was also expressed as z-values as effect-size measures, reflecting the standardised mean difference analogue to Cohen's *d*. To analyse the data of the control sample, we calculated a two-factorial 2 × 2 repeated measures ANOVA with the factors Ear (left vs. right) and Condition (NF, forced) in the control sample. Effect sizes are expressed as partial eta squared (η_p^2) and Cohen's *d* for repeated measures (d_z), respectively. All analyses were conducted in R (version 4.1.0) and scripts as well as raw data are available as OSF project (https://osf.io/9cba3/).

3. Results

3.1. Monoaural test and homonyms in patients

P2 identified 15 and 13 (out of possible 24) of the left and right stimuli, respectively, in the monoaural condition providing an LI = −7.1% in the monoaural condition. He identified 8 out of 12 of the homonyms, whereby all syllables were identified correctly at least once in the dichotic and monoaural test. P3 identified 16 of the left- and 19 of the right-ear stimuli, resulting in a LI of 8.6%. He correctly identified 10 out of 12 of syllables in homonym trials of the NF condition. The main reason for this deviation from 100% was that the syllable /ba/ was consistently classified as /pa/ by the patient. The results of the monoaural test indicated that both patients were able to follow verbal instruction and revealed no hearing bias to one side.

3.2. Dichotic listening in patients

P2′ and P3's laterality in the NF condition is characterized by a strong right-advantage with an LI of 90.5% and 88.9%, respectively. Both patients were more than two and a half standard deviations above the mean LI of the control group (mean, *M*: 20.3%, *SD*: 24.0%; see Table 1). As shown in Fig. 1, the elevated LI was driven by a reduced recall of left-ear stimuli, which in both cases was below the chance level of 16.7%. With a z-value of −2.75 ($t_{39} = -2.72$, $p = .005$) for P2 and -2.60 ($t_{39} = -2.57$, $p = .007$) for P3, the left-ear recall also was significantly reduced relative to the control group. The right-ear recall was elevated in both patients compared with the control sample mean, but only for P3 ($t_{39} = 3.06$, $p = .002$) significantly (for P2: $t_{39} = 1.46$, $p = .076$).

Considering the forced attention laterality index, P2 (with an LI = 57.9%) and P3 (LI = 92.0%) were more than two standard deviations above the mean LI of the control sample (*M*:13.9%, *SD*: 19.3%). This deviation was mainly due to the left-ear recall under FL instruction (see Table 1, or Fig. 1, right panel) as both patients performed well-below chance level and deviated significantly from the control sample (P2: $t_{39} = -2.36$, $p = .01$; P3: $t_{39} = -2.56$, $p = .007$). For the right-ear recall, the performance was significantly reduced in P2 ($t_{39} = -2.36$, $p = .01$) compared with the controls but was enhanced in P3, although not significantly ($t_{39} = 1.61$, $p = .06$).

Analysing the gain by attention parameters under FL vs NF instruction, P2 showed a slightly increased left-ear recall in FL compared with NF (positive FL gain score), while P3's performance slightly decreased. The deviation from the control sample was, however, not significant. The FR gain score was negative in both patients, whereby this drop in performance was significant only for P2 (see Table 1).

3.3. Dichotic listening in the control sample

The ANOVA in the control sample replicated the well-established significant main effect of Ear (F (1,39) = 527.9, $p < .001$, $\eta_p^2 = 0.42$; see Fig. 2) indicating an overall right-ear advantage across the two conditions. The main effect of Condition (F (1,39) = 34.6, $p < .001$, $\eta_p^2 = 0.47$) revealed an overall increase in performance under selective attention compared with NF. The interaction of Ear and Condition was not significant (F (1, 39) = 2.1, $p = .15$, $\eta_p^2 = 0.005$; see Fig. 2), suggesting that the gain by selective attention was comparable for the left- and the right-ear recall. That is, the increase in FR vs NF in right-ear recall ($p < .001$, $d_z = 0.61$) and a significant increase in FL vs NF for left-ear recall ($p < .001$, $d_z = 0.85$) were both significant in post-hoc paired t-tests. The REA was significant in both the NF ($p < .001$, $d_z = 0.82$) and the forced condition ($p < .001$, $d_z = 0.69$; mean LI can be found in Table 1).

Table 1
Dichotic listening results of the two patients and the control sample (N = 40).

		Controls		P2				P3			
		mean	sd	score	z[a]	*t* (39)[b]	*p*	score	z	*t* (39)	*p*
NF	LE%	33.2	10.8	3.3	−2.75	−2.72	<0.01	5.0	−2.60	−2.57	<0.01
	RE%	49.9	11.3	66.7	1.48	1.46	0.08	85.0	3.10	3.06	<0.01
	LI	20.3	24.0	90.5	2.93	2.90	<0.01	88.9	2.86	2.83	<0.01
FC	LE%	44.8	16.0	6.7	−2.39	−2.36	0.01	3.3	−2.6	−2.56	<0.01
	RE%	57.8	13.7	25.0	−2.39	−2.36	0.01	80.0	1.63	1.61	0.06
	LI	13.9	19.3	57.9	2.30	2.25	0.02	92.0	4.05	4.00	<0.01
Gain	LE gain	3.5	4.1	1.0	−0.61	−0.60	0.28	−0.5[c]	−0.97	−0.96	0.17
	RE gain	2.4	3.8	−12.5	−3.86	−3.81	<0.01	−1.5	−1.00	−0.99	0.16

Notes. a) z-value, i.e. the patient's deviation from the control sample mean divided by the standard deviation (sd); b) *t* values (degrees of freedom) for the test against the control sample mean using the Crawford-Howell method (see text for details); c) average increase across both runs of the paradigm; *Abbreviations*: NF = non-forced (free report) condition, FC = Forced condition; LE%/RE% = left and right ear correct recall in percent; LI = laterality index, i.e. the difference between right and left recall divided by the sum of both; LE/RE gain: absolute change in score from NF to the respective selective attention (forced) condition.

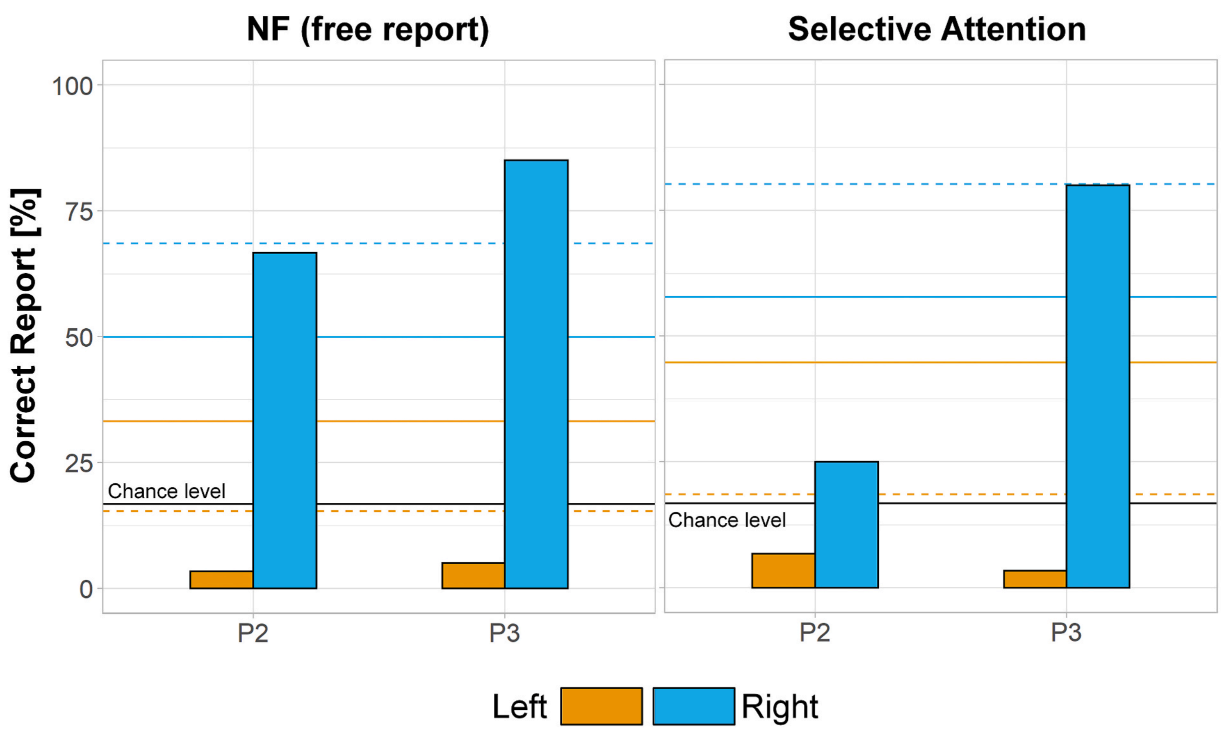

Fig. 1. The patients' percentage correct left- and right-ear recall in the free (left plot) and selective attention (right) condition. Solid blue lines mark the mean right-ear recall in the control sample, while the dotted blue line indicates the upper critical value from which the deviation to the mean is significant. Comparably, the orange lines indicate the mean (solid) left ear recall of the control sample and the lower critical value. The black line demarks the "chance level" of guessing what was heard (i.e., one out of six stimuli, or 16.7%).

4. Discussion

Analysing the dichotic-listening performance in two patients with complete callosotomy, we replicated the left-ear extinction reported in the literature (e.g., Clarke et al., 1993; Milner et al., 1968; Musiek et al., 1989; Sparks and Geschwind, 1968; Springer and Gazzaniga, 1975). However, contrasting earlier findings (Corballis and Ogden, 1988; Sparks and Geschwind, 1968; Springer and Gazzaniga, 1975), we did not find evidence for a release of this extinction by asking the participants to selectively attend to and report the left-ear stimulus.

Given the hypothesized relevance of callosal relay (Hiscock and Kinsbourne, 2011; Kinsbourne, 2003; Musiek and Weihing, 2011; Westerhausen and Hugdahl, 2008), specifically for the recall of left-ear stimuli, the observed left-ear extinction after callosotomy in P2 and P3 was predicted and is in line with the literature. However, not all studies found an extinction after complete callosotomy and rather reported a depression in performance when compared with healthy controls or the expected chance level (e.g., Corballis and Ogden, 1988; McKeever et al., 1981; Musiek et al., 1981; Pechstedt, 1989; Wale and Geffen, 1986). One explanation for this inconsistency might be found in the exact dichotic listening paradigm used as variations in stimulus material and implementation have shown to significantly affect task performance in healthy individuals (Westerhausen, 2019). In particular, the use of non-rhyming stimuli (such as digits) appears to prevent the left-ear extinction (although not always; see Milner et al., 1968; Musiek and Wilson, 1979; Musiek et al., 1979; Sparks and Geschwind, 1968). Springer et al. (1978) compared the performance of five commissurotomy and callosotomy patients in a digit and a (rhyming) CV dichotic paradigm. The authors found that three of the patients showed left-ear recall below or around chance level in the CV paradigm while none did in the digit paradigm. Similarly, Musiek et al. (1989) testing one patient with a digit, a CV, and rhyming words (e.g., *pen* - *den*) dichotic paradigm, found a left-ear recall around or below chance level for CVs and words but not for digits. Thus, it appears that for non-rhyming

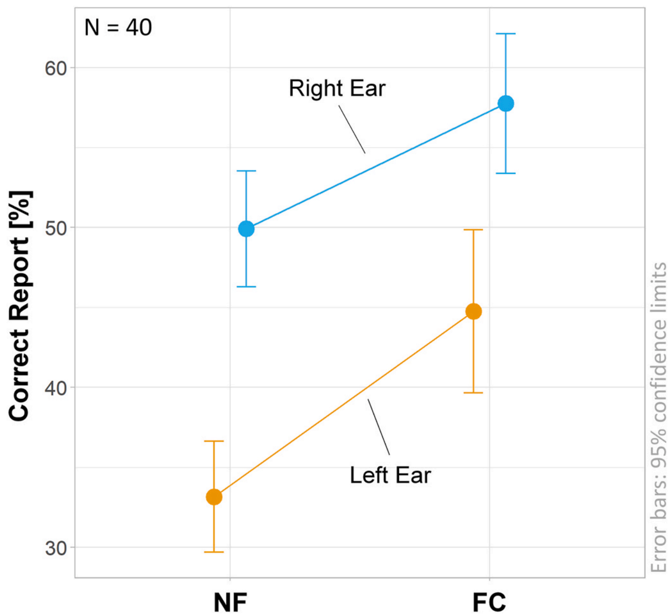

Fig. 2. The control samples' left- and right-ear recall in the free report (NF) and selective attention (FC) conditions. Error bars indicate the 95% confidence interval. The main effects of Ear (indicating an REA) and Condition (FC > NF) were significant (for test statistics see text). Note, the mean values depicted here, are identical to those indicated as lines in Fig. 1.

stimuli, the left-ear information is still accessible for the left hemisphere. Digits used as stimuli (e.g., *two* and *five*) – even when perfectly aligned between the input channels – will differ substantially in their spectral profile (e.g., onset of the first formant). It has been suggested that only high spectro-temporal overlap between the two channels – as achieved when using rhyming stimuli – produces a "true" dichotic stimulation (Wexler and Halwes, 1983) resulting in two stimuli being perceived as one (Repp, 1976; Westerhausen et al., 2013). The lack of this perceptual fusion for digits, might indicate that the ipsilateral ascending auditory pathways are not fully suppressed, so that left-ear stimuli are represented in the left hemisphere and can be reported also without intact corpus callosum.

A second finding of the present study was the enhanced right-ear recall in patients as compared to controls, which was particularly pronounced in P3. This effect has been frequently reported in the callosotomy literature (e.g., Clarke et al., 1993; Musiek et al., 1989; Springer et al., 1978; Tweedy et al., 1980; Zaidel, 1976) and in relation to other conditions affecting the integrity of the corpus callosum (see e.g., Benavidez et al., 1999; Mataró et al., 2006; Ocklenburg et al., 2015). Studies in healthy participants additional suggest that stronger callosal connectivity (e.g., a bigger midsagittal corpus callosum) not only increases the likelihood of reporting the left-ear stimulus but also decreases the right-ear report (Steinmann et al., 2018; Westerhausen et al., 2006). Following the attention model, these finding might be explained by assuming that activating the right hemisphere and orienting to the left ear stimulus, leads to gradual deactivation of the left hemisphere and, consequently, a reduction in the right ear recall (Kinsbourne, 1970, 2003). From the perspective of the callosal-relay model of dichotic listening, these findings are surprising, as the processing of the right-ear stimulus in the left hemisphere should be independent of the corpus callosum. It has been suggested, however, that the right-ear enhancement can be explained by a release from auditory competition between the two stimuli for speech processing (Musiek et al., 1989; Westerhausen et al., 2006). With the corpus callosum intact, the left-hemispheric representation of the two stimuli can be considered a weighted mixture of "callosal" left- and "acallosal" right-ear stimulus (Westerhausen and Kompus, 2018) whereby the processing of more salient stimuli (usually right) is affected by the second stimulus. Complete sectioning the corpus callosum, isolates the representation of the right-ear stimulus from the left, removing the competition and enhancing the right-ear recall.

In this context it is interesting to note that a recent study (Hausmann et al., 2021) investigated the allocation of attentional bias in both P2 and P3 with the greyscales task. The greyscales task (Mattingley et al., 1994) requires participants to judge the darker (or brighter) of two left-right mirror-reversed luminance gradients under conditions of free viewing, and offers an efficient means of quantifying pathological attentional biases in patients with unilateral lesions. In this study, Hausmann et al. (2021) found a pronounced, pathological neglect-like rightward bias in the greyscale task in both P2 and P3, suggesting strong dependence on a single hemisphere (the left) in spatial attention, which is opposite to what one expects from individuals with intact commissures. Similar to the dichotic-listening bias observed in the present study, the right bias, and strong dependence on the left hemisphere, was especially pronounced in P3, though still present in P2, and might indicate a general bias in patients with complete callosotomy towards stimuli located in right hemispace which is independent from stimulus modality. A pronounced attention shift has been reported previously in patients with partial and complete callosotomy (Hausmann et al., 2003), suggesting that resection of the posterior corpus callosum produces a consistent attention bias (usually to the right), depending on which hemisphere assumes control (usually the left), and seems not idiosyncratic to the patients studied. As suggested by Pollmann (2010), it might be the attentional reorienting signals originating from the right temporal-parietal junction, which are interrupted by the callosal lesion leading to an uninhibited rightward bias of the left hemisphere in dichotic listening.

The present study also aimed to evaluate whether (anticipatory) attention to the subdominant left ear enables complete callosotomy patients to overcome the inaccessibility of left-ear stimuli. In contrast to three earlier reports (Corballis and Ogden, 1988; Sparks and Geschwind, 1968; Springer and Gazzaniga, 1975), we did not find any indication that this is the case in P2 and P3. With attention direct selectively to the left ear, both patients reported left-ear stimuli below chance level, and no improvement in the left-ear recall as compared to the NF condition was found. Also, the left-ear recall was significantly reduced compared with the control group, resulting in a strong, almost perfect, right-ear advantage across the forced conditions. The control group, at the same time, was able to enhance the left ear recall as expected (Hugdahl et al., 2009).

This contradiction of present with previous findings might again be explained by differences in the dichotic paradigm or the patients. Firstly, two of the studies (Corballis and Ogden, 1988; Sparks and Geschwind, 1968) used non-rhyming words or digits as stimulus material so that it cannot be excluded that – as discussed above – due to the insufficient spectro-temporal overlap of the stimuli, left-ear information is part of the initial left-hemispheric stimulus representation, rendering it accessible for attentional selection in working memory. Secondly, Corballis and Ogden (1988) presented three stimulus pairs per trial, so that the patients had to retain and repeat three stimuli per trial in the selective attention condition as opposed to six in the free-recall condition. The higher load in the free-recall condition is likely to meet the limits of working-memory capacity (Penner et al., 2009) and participants tend to develop a report strategy favouring the dominant right ear in this situation (Freides, 1977) which also has been demonstrated in callosotomy patients (Pechstedt, 1986, 1989). Thus, the apparent improvement in recall in the selective attention as compared with the free-recall condition reported by Corballis and Ogden (1988) might be at least partly explained by a selective omission of left-ear stimuli in the free-recall condition as result of the increased memory load. The reduction in overall performance (left and right recall) in free-recall as compared to the selective attention condition, further supports this notion. In contrast, the dichotic paradigm used by Springer and Gazzaniga (1975) was very similar to the present; utilising pairwise presented CV syllables as stimulus material, requiring one answer per trial. However, patient JK, who reportedly was able to utilise attention to improve left-ear recall by Springer and Gazzaniga (1975), had undergone partial anterior and not complete section of the corpus callosum. Thus, one might speculate that the spared posterior segment, which has been shown to support the left-ear performance in dichotic listening in healthy individuals (Steinmann et al., 2018; Westerhausen et al., 2009) and in lesion studies (Pollmann et al., 2002), might be taken to explain the patient's attentional gain. In line with this observation, two other patients reported by Springer and Gazzaniga (1975), namely JH and JKn, who had undergone a complete section of the corpus callosum, did not benefit from the selective attention instruction. Likewise, the fourth patient (EG), who had only a partial posterior section of the corpus callosum (resulting from a tumour resection) did not show a substantial increase in the left ear score in the attend-left compared with the free-report condition. Nevertheless, the patients reported by Sparks and Geschwind (1968) and Corballis and Ogden (1988) had undergone commissurotomy, so that residual posterior callosal connections cannot explain their findings. Given the above, we are tempted to conclude that previous demonstrations of selective attention effects to improve left-ear recall after callosotomy might be attributed to the use of suboptimal paradigms or residual callosal connectivity, rather than being a genuine attention effect.

Of note, the data of the age-matched control group showed the expected results from the literature (Hugdahl, 2003; Hugdahl et al., 2009). That is, both attending to the left and to right ear, led to a significant improvement for the attended ear ("gain") compared to the free-recall condition. Assuming an information processing perspective analogue with the biased competition model (Shinn-Cunningham, 2008), these effects suggest a two-stage processing of dichotic stimuli (Hiscock et al., 1999; Westerhausen and Kompus, 2018; Wood et al., 2000): an initial "bottom-up" stage in which a representation of the two competing stimuli is formed in auditory working memory, and a second cognitive-control stage which modulates this representation for response selection following the task instruction. In neurotypical individuals, the representation of the right-ear stimulus is more salient than the representation of the left-ear stimulus in the first stage. This representational bias may result from a callosal-relay delay/degradation of the left-ear stimulus information reaching the left hemisphere or from the weaker activation of the right hemisphere within the attentional model (Hiscock and Kinsbourne, 2011). During the second stage, controlled selective attention resolves the competition by "top-down" biasing the working-memory representations in favour of either ear (Westerhausen and Kompus, 2018). Following this interpretation, the results found in patients with complete callosotomy suggest that the initial representation (that is accessible to language processing) only consists of the right-ear stimulus (when appropriate dichotic paradigms are used) and the selective attention instruction does not change this. Neither during the formation of the initial representation, nor during second-stage processes can selective attention be utilised to make left-ear information accessible for further processing as the required callosal connections are missing.

One limitation of the present study is that both patients exhibited a somewhat reduced overall performance level when identifying the syllables both when considering the monoaural task and the dichotic stimuli (homonyms) which is contrast to an almost perfect identification rate in healthy participants (see e.g., Hugdahl, 2003). As P3 particularly struggled with the /ba/-/pa/ distinction, one might speculate that the stimulus material or method of data recording favoured the /pa/ answer. However, as the presentation of all stimuli was systematically balanced between ears, we do not expect a systematic effect on laterality when determined across all dichotic trials. The results of the monoaural task support this notion by showing a relatively negligible interaural difference compared with the NF condition in both patients. A second limitation might be the order in which the conditions were presented, as the selective attention conditions always followed the NF condition. While this order recommended to minimize potential carry-over attention effects between conditions (see Hugdahl et al., 2009), the patients' sustained attention might reduce compared with the control sample, increasing performance differences between patients and controls in the later conditions. For example, patient P2 showed a drop in overall performance in the third (attend right) condition. However, no such effect was observed in P3 or in the here crucial selective attention to the left ear condition, so that this cannot explain the overall results. A third limitation is that we compared both patients with a neurotypical control group and not with a group of epileptic patients without callosal surgery. The callosotomy patients consequently differ from the control group also by other epilepsy-associated characteristics (e.g., potential difference in brain development, including compensatory mechanism) in addition to the surgery which could potentially influence the findings. Dichotic listening studies on patients with drug-resistant epilepsy and intact corpus callosum, however, find a reduced rather than enhanced REA compared with controls which was mainly driven by a reduction of the right-ear recall (e.g., Carlsson et al., 2011; Lee et al., 1994). This supports the conclusion that callosal section, and not the primary pathology, caused the enhanced laterality found in P2 and P3.

Taken together, by using a well-established dichotic-listening paradigm which is considered an accurate measure of laterality (i.e., rhyming stimuli, low working-memory load), we replicated the left-ear extinction in two cases of complete callosotomy. In this, we added two new observations on patients not before tested with dichotic listening to the small body of literature which is otherwise characterized by repeated testing of the same split-brain individuals. We did not confirm earlier reports on other callosotomy patients suggesting that selective attention to the left ear allows to overcome this extinction. Thus, we have no indication that the representation of the left-ear stimulus can be accessed by the left hemisphere in absence of the corpus callosum. This observation underlines the relevance of the corpus callosum in explaining the magnitude of the right-ear advantage also in the healthy brain, and suggests that dichotic-listening paradigms – when designed and administered appropriately – represent a construct-valid method for assessing inter-hemispheric callosal integration (Musiek and Weihing, 2011; Westerhausen and Hugdahl, 2008).

Credit author statement

René Westerhausen: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. Mara Fabri: Data curation, Writing- Reviewing and Editing. Markus Hausmann: Investigation, Conceptualization, Methodology, Data curation, Writing-Reviewing and Editing.

Data availability

Analysis script and data are available from an OSF platform (https://osf.io/9cba3/)

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