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Research report

The processing of chimeric and dichotic emotional stimuli by connected and disconnected cerebral hemispheres

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HIGHLIGHTS

- Chimeric and dichotic stimuli were presented to two split-brain patients (D.D.V. and A.P.).
- Stimuli conveyed happy/sad expressions and participants judged their emotion content.
- The total split-brain patient D.D.V. neglects visual stimuli in the left hemifield.
- A.P. shows a right-hemispheric dominance in unimodal analysis.
- The valence hypothesis is confirmed in bimodal conditions by A.P. and the control group.

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ABSTRACT

Hemispheric asymmetries have been widely explored in both the visual and the auditory domain, but little is known about hemispheric asymmetries in audio–visual integration. We compared the performance of a partially callosotomized patient, a total split-brain patient and a control group during the evaluation of the emotional valence of chimeric faces and dichotic syllables (an emotional syllable in one ear and white noise in the other ear) presented unimodally (only faces or only syllables) or bimodally (faces and syllables presented simultaneously). Stimuli could convey happy and sad expressions and participants were asked to evaluate the emotional content of each presentation, using a 5-point Likert scale (from very sad to very happy). In unimodal presentations, the partially callosotomized patient's judgments depended on the emotional valence of the stimuli processed by the right hemisphere, whereas those of the total split-brain patient showed the opposite lateralization; in these conditions, the control group did not show asymmetries. Moreover, in bimodal presentations, results provided support for the valence hypothesis (i.e., left asymmetry for positive emotions and vice versa) in both the control group and the partially callosotomized patient, whereas the total split-brain patient showed a tendency to evaluate the emotional content of the right hemiface even when asked to focus on the acoustic modality. We conclude that partial and total hemispheric disconnections reveal opposite patterns of hemispheric asymmetry in auditory, visual and audio–visual emotion processing. These results are discussed in the light of the right-hemisphere hypothesis and the valence hypothesis.

1. Introduction

Studies on the cerebral lateralization of emotional processing have shown variable patterns of results, and the aspect of hemispheric asymmetry in this field still remains controversial [1]. According to the right-hemisphere hypothesis [2–4], a right-hemispheric dominance would underlie all aspects of emotional processing. On the other hand, according to the valence hypothesis [5–7] a right-hemispheric superiority would underlie the processing of negative emotions, whereas a left-hemispheric superiority would underlie the processing of positive emotions.

Hemispheric asymmetries in perception have been explored by means of several paradigms. In the auditory domain, the organization of cerebral auditory pathways makes it possible to evaluate the

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contribution of each hemisphere by presenting different stimuli in the two ears (dichotic listening). Exploiting this fact, a number of studies have shown that the presentation of an acoustic stimulus in one ear leads to a higher activation in the contralateral hemisphere (e.g., right ear/left hemisphere) rather than in the ipsilateral hemisphere [8,9]. In particular, the dichotic listening paradigm reveals a right ear advantage (REA), indicating a left-hemispheric superiority in linguistic processing [10,11], which has also been shown in ecological contexts [12]. The REA seems to be attributable to the involvement of the corpus callosum (CC) and the auditory cortex, besides attentional factors (see [13] for a review). Moreover, dichotic listening has been used to investigate the lateralization of emotional processing in the auditory verbal and nonverbal domains [14]. For example, Erhan and colleagues [15] asked participants to categorize emotional prosody of dichotically presented nonsense syllables as having positive or negative intonation, and they found a left ear advantage (LEA), even if they underlined an opposite electrophysiological correlate, namely a higher amplitude of the N100 component in the left rather than in the right hemisphere. These authors proposed that such a pattern of event-related potentials reflects phonetic analysis but that emotional evaluation is processed in the right hemisphere, thus supporting the right-hemisphere hypothesis. Of note, however, Erhan and colleagues pointed out that the LEA was stronger for negative than for positive emotions ([15], see also [72]). On the other hand, Herrero and Hillix [16] found a general lower recognition score for negative than positive emotional intonation sentences, and a significant interaction between the presentation ear and the emotional valence of stimuli, with a specific lowering of scores for the negative emotional sentences presented in the right ear. Schepman et al. [17] have recently confirmed this pattern of results, providing further support for the valence hypothesis.

Other controversial results were also obtained in EEG and neuroimaging studies in which different paradigms than dichotic listening were used. Recording event-related potentials and skin conductance, Meyers and Smith [18] did not find asymmetry in nonverbal affective stimuli processing. Nevertheless, in a functional magnetic resonance imaging study, Wildgruber and colleagues [19] found a stronger activation of the right hemisphere for acoustic stimuli with both positive and negative valence, thus supporting the right-hemisphere hypothesis.

Cerebral lateralization has also been largely studied in the domain of visual perception. Specifically, a paradigm used to investigate cerebral asymmetries in face processing is that of the chimeric faces [2], that are created by juxtaposing the left and right halves of two distinct faces. Studies that made use of chimeric faces showed that the right hemisphere is more specialized for face processing than the left hemisphere [20]. Also in this context, however, contrasting results have been obtained as regards emotion processing. Presenting chimeric emotional faces, Drebing and colleagues [21] provided support for the right-hemisphere hypothesis [21]. Killgore and Yurgelun-Todd [22], on the basis of an fMRI study, concluded that the valence and the right-hemisphere hypothesis are not mutually exclusive, but they should be considered as different possibilities to understand facial emotion processing. A similarly unclear pattern of results has been achieved by exploiting bilateral presentations of two emotional faces or unilateral presentations of one face, providing evidence in support for both the right-hemisphere hypothesis [23,24] and the valence hypothesis [25–27].

With regard to audio–visual integration, an important question is whether the fusion of multisensory inputs leads to a combination of the processing activities involved by each of the two sensory modalities considered in isolation, or whether the information presented in one sensory modality predominates over that presented in the other modality. Of note, a number of studies showed that multisensory integration is automatic and unintentional, although other studies suggested a different point of view (see [28] for a review). Collignon and colleagues [29] asked participants to classify vocal and visual stimuli according to their emotion content, finding that the categorization improved when vocal and visual expressions were congruent and that, in the incongruent conditions, participants based their evaluations mainly on the visual component (visual capture). On the other hand, Petrini et al. [30] found the opposite result, with the acoustic information prevailing during the evaluation of incongruent audio–visual emotional stimuli (auditory capture). Thus, it could be concluded that there is a reciprocal influence during auditory and visual processing of emotional information depending on congruence [31], but the prioritization of one sensory modality over the other does not seem to follow a clear rule when the two modalities convey conflicting contents.

Many studies focused on the cerebral correlates of audio–visual integration and showed that different cerebral areas are implicated in this process: for example, Kreifelts and colleagues [32] found that the behavioral improvement during the simultaneous presentation of emotionally congruent bimodal stimuli correlated with an increased activation in the bilateral posterior superior temporal gyrus ([32]; see also [33], for a review) and in the right thalamus; other studies highlighted a left-hemispheric activation during bimodal processing, in particular in the middle temporal gyrus [34,35] and in the posterior superior temporal sulcus [36]. Jeong and colleagues [37] found that emotionally congruent audio–visual presentations enhanced the activity in auditory areas, whereas emotionally incongruent presentations enhanced the activity in face recognition areas, such as the fusiform gyrus. Ethofer and colleagues [38] have recently shown the importance of the orbitofrontal cortex in the mechanism of habituation to facial expressions and prosody, which highlights the role of this region as an important component of a system for emotional processing of faces and voices and as a neural interface among sensory areas. Finally, electrophysiological data demonstrated an early audio–visual crosstalk following stimulus presentation [39,34].

Another source of information about audio–visual neural correlates comes from studies on neurological patients. Hayakawa and colleagues [40] showed that a patient with amygdala and hippocampus lesions could not recognize fear from facial expressions, but was able to recognize them from prosodic and verbal stimuli, whereas a patient with a more extended lesion beyond the amygdala could not recognize fear expressions from prosodic and verbal stimuli, even if he was able to recognize them from facial stimuli [40].

Although audio–visual integration has been largely investigated, hemispheric lateralization in this field remains largely unexplored, even more so in the case of multisensory analysis in emotion perception. One of the possible sources of evidence consists in studying split-brain patients [41,42], individuals who have undergone the surgical resection of the corpus callosum (CC) as an extreme attempt to prevent the spread of epileptic seizures between the two hemispheres [43]. Importantly, comparisons among the performance of patients who have undergone different degrees of hemispheric disconnection (total or partial and, in the latter case, in different regions of the CC) provide us with a rare chance to study hemispheric competences [44]. Studies with callosotomized patients confirmed the right-hemispheric superiority in face processing [45], as well as the left-hemispheric superiority (REA) in dichotic listening ([46]; see [47], for a review). However the hemispheric superiority in emotion analysis remains controversial even as regards split-brain patients' results: Stone et al. [48] showed that both disconnected hemispheres could match equally well facial expressions to emotion words, but the left hemisphere performed poorly on a discrimination task. Làdavas

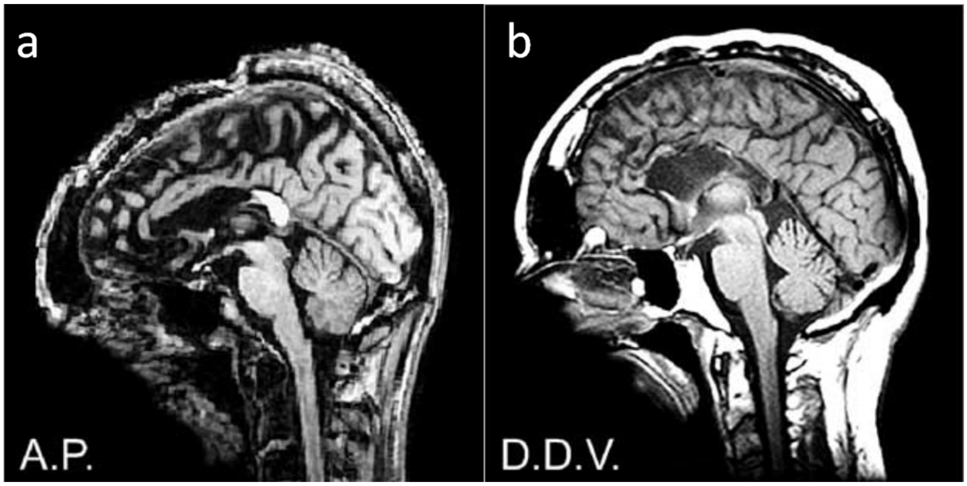

Fig. 1. Midsagittal MRI of patients. Left panel: A.P.'s brain, showing the anterior section of the corpus callosum, which saves the splenium. Right panel: D.D.V.'s brain, showing the complete absence of callosal fibers.

et al. [49], based on the results of a split-brain patient who was capable to discriminate emotional from neutral stimuli presented in both LVF and RVF, concluded that emotional processing could take place in either disconnected hemisphere, but only the right hemisphere produced an autonomic response to emotional stimuli [49]. A recent study in which a total split-brain patient and an anterior callosotomized patient were tested, provided support for the right hemisphere hypothesis in the case of bilateral presentation of faces with a hidden emotional content [24]. As reviewed by Gainotti [50], the right-hemispheric superiority in subliminally presented emotional content could be explained by a subcortical asymmetry in emotion detection.

The aim of the present study was to investigate hemispheric asymmetries in audio–visual integration and the way in which lateralized visual and acoustic emotional stimuli are processed by the two hemispheres. According to previous evidence on emotional analysis in the visual and acoustic modalities, one might expect that either the right-hemisphere hypothesis or the valence hypothesis is applicable also to the audio–visual domain.

First of all, we expected a moderate hemispheric asymmetry in emotion evaluation by healthy participants. Second, we expected a more extreme hemispheric lateralization pattern in a total split-brain patient regardless of the nature of stimuli, due to the complete absence of reciprocal callosal connections between the hemispheres. Finally, we expected that in a patient with an anterior callosal section, lateralization would appear weaker compared to that of the total split-brain patient, due to intact connections between posterior cortical areas, the posterior part of the CC being spared, but stronger compared to that of healthy subjects, because of the complete segregation of the anterior areas. However, we could not predict the direction of any lateralization, because of the mixed results available in the literature in both visual and acoustic domains, and the absence of clear evidence of cerebral asymmetry in multimodal integration of emotional stimuli.

2. Materials and methods

2.1. Participants

A patient with an anterior section of the CC, a patient with a total section of the CC, and 16 healthy participants took part in the experiment.

A.P. is a 47-year-old man, who underwent the surgical resection of a large anterior portion of the CC to reduce the spread of epileptic seizures. The surgery was carried out in 1993 and it left intact only the splenium (see Fig. 1a). A.P.'s postoperative IQ was 87, as measured by means of the Wechsler adult intelligence scale (WAIS), and his laterality quotient was +10, according to the Edinburgh Handedness Inventory [51].

D.D.V. is a 48-year-old man, who, in order to prevent the spread of epileptic foci, underwent the complete resection of the corpus callosum through different stages, the last of which occurred in 1994. The surgical resection left intact the anterior commissure (see Fig. 1b). D.D.V.'s postoperative IQ was 81, as assessed by the WAIS, and his laterality quotient was +100, according to the Edinburgh Handedness Inventory [51].

Both patients had no visual impairments or psychiatric symptoms (further details of the patients' status are provided by [52]). They were tested at the Epilepsy Center of the Polytechnic University of Marche (Torrette, Ancona), during a pause between routine neurological examinations.

The control group was composed of 16 male individuals (age: M = 24.44; SD = 1.35). According to self-report, all were right-handed, had normal or corrected-to-normal vision, and none of them had neurological or psychiatric histories. These participants were tested as volunteers at the Psychobiology Laboratory of the University of Chieti.

Informed consent was obtained from all participants prior to the beginning of the task and the experimental procedures were approved by the local ethical committee.

2.2. Stimuli

We used chimeric faces as visual stimuli and dichotic presentations as acoustic stimuli.

Facial stimuli were created from photographs contained in the Karolinska directed emotional faces [53], a database of female and male faces with both neutral and emotional expressions. Photographs of a female face in a happy pose (HA) and in a sad pose (SA) were selected and converted into gray-scale images, measuring $5.2^{\circ} \times 6.6^{\circ}$ of visual angle (198×252 pixel) at a distance of about 72 cm. From these images, hemiface components were created: the two photographs were centrally divided into two halves, in order to obtain one left sad hemiface, one right sad hemiface, one left happy hemiface, and one right happy hemiface. Chimeric faces were thus created by combining the 4 hemifaces to each other. The final set

Fig. 2. An example of chimeric face (HA/SA).

of visual stimuli was composed of 4 chimeric faces: HA left hemiface/HA right hemiface, HA left hemiface/SA right hemiface, SA left hemiface/HA right hemiface, SA left hemiface/SA right hemiface. In order to reduce the sense of strangeness possibly due to chimeric stimuli, the two half faces were separated by a thin white stripe (width: .02° of visual angle; see Fig. 2).

Acoustic stimuli were created by recording consonant–vowel syllables pronounced by a female actress with different emotional accent. The syllable/ba/was recorded with two different emotional intonations: happy (HA) and sad (SA). Stimuli were then handled with GoldWave Software v5.25 (GoldWave Inc., St. John's, NL, Canada). They were digitized (16 bit, sampling rate 44,100 Hz) and presented in a dichotic paradigm, in which the emotional syllable was presented in one ear and white noise (WN) was simultaneously presented in the other ear. Acoustic stimuli lasted 350 ms, including 50 ms of linear fade-in at the beginning of each stimulus and 50 ms of linear fade-out at the end of each stimulus. Dichotic stimuli were delivered by means of headphones (Philips SHP5400): an emotional syllable and white noise were presented in the opposite ears, with a common onset and a common duration of 350 ms. The final set of acoustic presentations was composed of 4 dichotic stimuli: HA syllable in the left ear/WN in the right ear, WN in the left ear/HA syllable in the right ear, SA syllable in the left ear/WN in the right ear, and WN in the left ear/SA syllable in the right ear. We chose to avoid the simultaneous presentation of different emotional syllables in the two ears in order to keep the complexity of conflicting information between visual and auditory input as manageable as possible for subsequent statistical analyses.

We presented happy and sad emotional expressions, on the basis of previous studies indicating that these two emotions are evaluated as highly opposite in valence (positive and negative, respectively), and are thus easy to differentiate from each other [54]. We chose to use the 350 ms presentation time to allow patients to effectively process all stimuli even in the case of bimodal (possibly conflicting) conditions, in which the cognitive load could be high. We also preferred to use a relatively long presentation time to make sure that the bimodal integration occurred, given that some electrophysiological data demonstrated that audio–visual integration may take place only at about 180 ms after stimuli onset [39]. On the other hand, there is evidence of lateralized effects obtained with long presentation time in both the acoustic (e.g., [55]) and the visual domain (e.g., [56,57]).

2.3. Procedure

Participants were administered four different sessions in which they were asked to evaluate the emotional valence of stimuli, using a 5-point Likert scale: from 1 = very sad, to 5 = very happy (1 = very sad; 2 = sad; 3 = neutral; 4 = happy; 5 = very happy), using the computer keyboard.

In the first session, only acoustic stimuli were presented. The 4 dichotic stimuli were presented in random order 5 times each, constituting a set of 20 acoustic stimuli. A white screen lasting 500 ms was followed by the presentation of a central fixation cross for 850 ms. After a first interval of 500 ms in which only the cross was shown, the dichotic stimulus was presented for a duration of 350 ms, so that the end of the acoustic input corresponded to the end of the cross presentation. Then, the screen went blank until the response was given, and the next trial started (see Fig. 3a).

In the second session, only visual stimuli were presented. The 4 chimeric faces were presented in random order 5 times each, constituting a set of 20 visual stimuli. A white screen lasting 500 ms was followed by the presentation of a black fixation cross in the center of the screen for 500 ms. The stimulus was then presented in the center of the screen with a duration of 350 ms. Then, the screen went blank until the response was given by the participant, and the next trial started (see Fig. 3b).

In the last two sessions, acoustic and visual stimuli were presented together. Each of these sessions were constituted by 80 stimuli, including all 16 possible combinations of the 4 chimeric faces and the 4 dichotic presentations, each combination being repeated 5 times in a random order. These two sessions were similar to each other: a white screen was presented for 500 ms, followed by the presentation of a black fixation cross in the center of the screen for 500 ms. The disappearance of the cross coincided with the simultaneous onset of both the chimeric face in the center of the screen and the dichotic stimulus in the earphones, both lasting 350 ms. Then, the screen went blank until the response was given, and the next trial started (see Fig. 3c). In the first of these two sessions, participants were asked to evaluate the emotional valence of the visual stimuli, ignoring the acoustic input, whereas, in the last session, participants were asked to evaluate the emotional valence of the acoustic stimuli, ignoring the visual input.

In order to specify which modality had to be attended to, at the beginning of each session instructions were presented on the computer screen. In the instructions it was also specified that the gaze had to be maintained at the center of the screen for all the testing time. At the end of a session, participants were allowed to take a short break before starting the next one.

The two patients gave their responses using the right hand. As regards the control group, half of the participants used the right hand and the other half used the left hand. The whole task was controlled by E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA) and lasted about 30 min.

3. Results

Statistical analyses were carried out using the software Statistica 8.0.550 (StatSoft. Inc., Tulsa, USA). As regards control group scores, the different conditions in each of the 4 sessions were compared by means of different analysis of variance (ANOVAs), using the emotion judgment as the dependent variable. Preliminary ANOVAs were conducted for each session, using the response hand as a

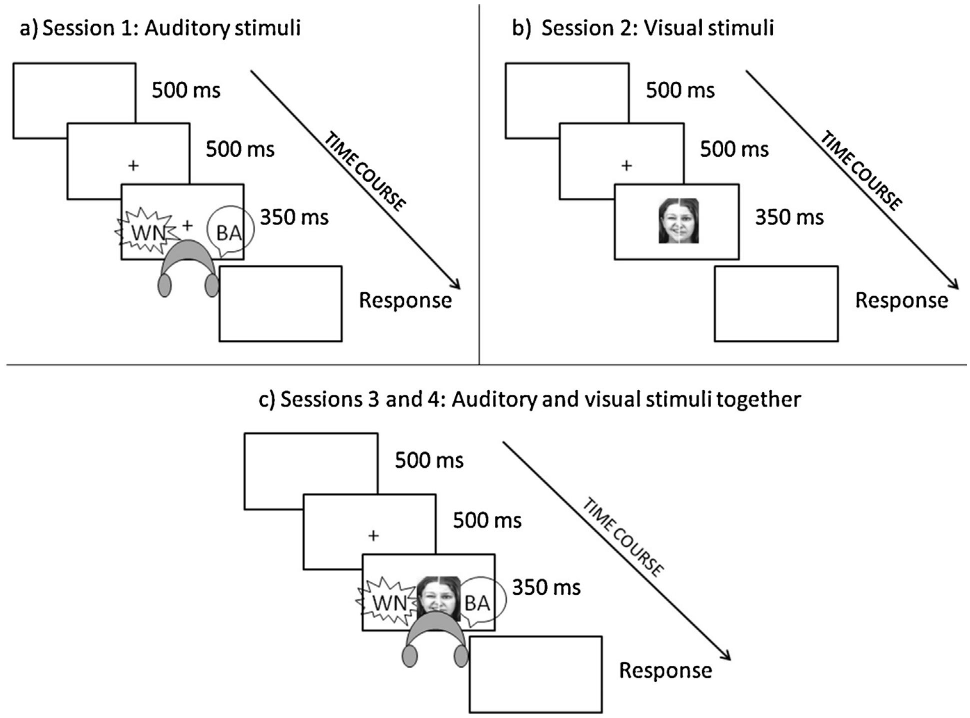

Fig. 3. Schematic representation of a trial in session 1: dichotic stimuli (top panel, on the left); in session 2: chimeric stimuli (top panel, on the right); and in sessions 3 and 4: bimodal presentations, with both dichotic and chimeric stimuli (bottom panel).

between-subjects factor, but neither the main effect of this factor nor interactions were significant. Thus, we carried out three repeated measures ANOVAs (one for each unimodal session and one for the two bimodal sessions). Post-hoc comparisons were carried out by means of Bonferroni test and corrected p-values are reported.

In the auditory session, the ANOVA was carried out using emotional tone (happy and sad) and presentation ear (left and right) as within-subject factors. Only the main effect of emotional tone was significant ($F_{(1, 15)} = 53.06$, $p < .001$, $\eta^2 = .78$), showing that happy syllables were evaluated as happier than sad syllables (happy: M = 3.94 ± .14; sad: M = 2.26 ± .10).

In the visual session, the ANOVA was carried out using face as within-subject factor (happy/happy, sad/sad, happy/sad and sad/happy). This main effect was significant ($F_{(3, 45)} = 157.49$, $p < .001$, $\eta^2 = .913$): post-hoc comparisons showed that the happy/happy face was evaluated happier than all of the other stimuli and that the sad/sad face was evaluated sadder than all of the other stimuli ($p < .001$ for all comparisons; HA/HA: M = 4.74 ± .07; SA/SA: M = 1.69 ± .12; HA/SA: M = 2.90 ± .12; SA/HA: M = 2.72 ± .14).

As regards the two bimodal sessions, the ANOVA was carried out using Target modality (visual and acoustic), face (happy/happy, sad/sad, happy/sad and sad/happy), emotional tone (happy and sad) and presentation ear (left and right) as within-subject factors. The main effect of target modality approached statistical significance ($F_{(1, 15)} = 4.27$, $p = .056$), visual stimuli being evaluated slightly more positively (M = 3.16 ± .07) than auditory stimuli (M = 3.03 ± .08). The main effect of face was significant ($F_{(3, 45)} = 36.05$, $p < .001$ $\eta^2 = .71$): post-hoc comparisons showed that the happy/happy face was evaluated happier than all of the other stimuli and that the sad/sad face was evaluated sadder than all of the other stimuli ($p < .001$ for all comparisons; HA/HA: M = 3.96 ± .1; SA/SA: M = 2.38 ± .1; HA/SA: M = 3.02 ± .09; SA/HA: M = 3.02 ± .08). The main effect of emotional tone ($F_{(1, 15)} = 49.23$, $p < .001$, $\eta^2 = .77$) showed that happy syllables were evaluated as happier than sad syllables (HA: M = 3.72 ± .07; SA: M = 2.47 ± .06). The main effect of presentation ear was not significant ($F_{(1, 15)} = .55$, $p = .47$; left: M = 3.09 ± .07; right: M = 3.11 ± .07).

As regards the significant interaction between target modality and face ($F_{(3, 45)} = 20.23$, $p < .001$, $\eta^2 = .57$), post-hoc comparisons showed that when visual judgments were required, the happy/happy face received a higher evaluation and the sad/sad face received a lower evaluation compared to all of the other conditions ($p < .001$ for all comparisons), whereas when auditory judgments were required, the happy/happy face was associated to higher evaluations than the sad/sad face ($p < .001$) and the sad/happy face ($p = .044$).

The interaction between target modality and presentation ear was significant ($F_{(1, 15)} = 6.34$, $p = .024$, $\eta^2 = .30$) and post-hoc comparisons showed that visual judgments were higher than auditory judgments when syllables were presented both to the left ear (visual modality: M = 3.17 ± .10; acoustic modality: M = 3.00 ± .11; $p = .04$), and to the right ear (visual modality: M = 3.15 ± .11; acoustic modality: M = 3.06 ± .11; $p = .002$). Moreover, in the acoustic modality, syllables presented to the right ear received higher evaluations than those presented to the left ear ($p = .036$), whereas evaluations did not differ according to auditory presentation side when the target modality was visual.

The three-way interaction among face, emotional tone and presentation ear ($F_{(3, 45)} = 3.41$, $p = .025$, $\eta^2 = .18$) was significant. To better clarify this interaction, two different ANOVAs were computed, by splitting the data according to presentation ear and using face and emotional tone as within-subject factors. As regards the right-ear presentation condition, a significant interaction between face and emotional tone ($F_{(3, 45)} = 4.60$, $p = .007$, $\eta^2 = .23$) showed that when the sad syllable was presented, the sad/happy face was judged as happier than the happy/sad face ($p = .047$). The interaction was not significant for the left-ear presentation condition.

In order to evaluate the effects of bimodal presentations, mean scores obtained in both the visual and the auditory unimodal sessions were compared to mean scores obtained in the bimodal

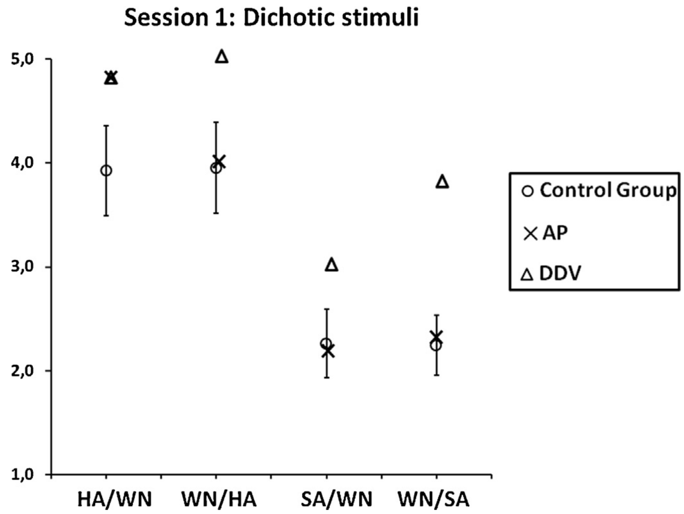

Fig. 4. 95% Confidence intervals of the control group (lines) and patients means (A.P.: cross; D.D.V.: triangle) in the first session: 4 dichotic stimuli.

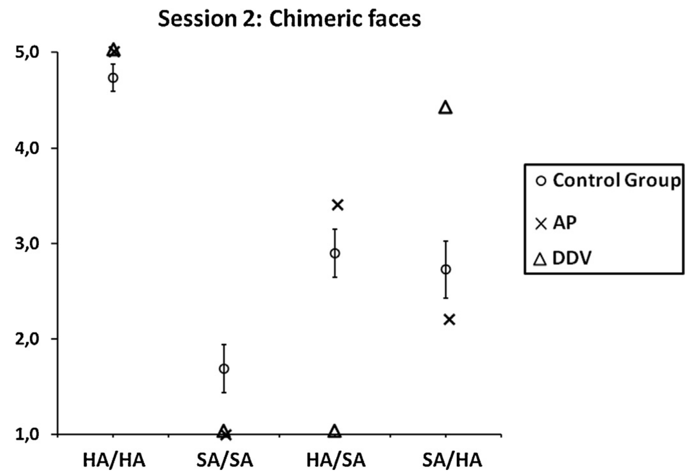

Fig. 5. 95% Confidence intervals of the control group (lines) and patients means (A.P.: cross; D.D.V.: triangle) in the second session: 4 chimeric faces.

sessions, using a series of Bonferroni corrected *t*-tests. In particular, scores recorded in the bimodal session in which participants were asked to judge the emotional valence of the visual stimuli (session 3) were compared with scores recorded in the visual session (session 2). The presentation of a happy tone to the right ear (WN/HA) led to higher evaluations of the sad/happy chimeric face ($t_{(15)} = -3.724$, $p = .032$). In the same way, scores recorded in the bimodal session in which participants were asked to judge the emotional valence of acoustic stimuli (session 4) were compared with the scores recorded in the auditory session (session 1). The presentation of the sad/sad face led to a lower evaluation of all acoustic stimuli (HA/WN: $t_{(15)} = 5.021$, $p = .002$; WN/HA: $t_{(15)} = 3.764$, $p = .030$; SA/WN: $t_{(15)} = 3.68$, $p = .036$; WN/SA: $t_{(15)} = 5.51$, $p < .001$), whereas the presentation of the happy/happy face led to higher evaluations of the sad syllable presented to both the left (SA/WN: $t_{(15)} = -4.69$, $p = .005$) and the right ear (WN/SA: $t_{(15)} = -5.397$, $p = .001$).

In order to compare the performance of the patients and the control group in each session, patients' means were compared with the 95% confidence intervals of the control group scores.

In session 1 (dichotic syllables), A.P.'s mean was above the cut-off of the 95% confidence intervals in the HA/WN condition, whereas D.D.V.'s means were above of the 95% confidence intervals in all conditions (see Fig. 4).

In session 2 (chimeric faces), A.P.'s means were above the cut-off of the 95% confidence intervals in HA/HA and HA/SA conditions, and they were below in SA/SA and SA/HA conditions. In this session, D.D.V.'s means were above the cut-off of the 95% confidence intervals in HA/HA and SA/HA conditions, and they were below in SA/SA and HA/SA conditions (see Fig. 5).

In session 3 (bimodal presentation with visual evaluation), A.P.'s means were above the cut-off of the 95% confidence intervals in all conditions in which HA/HA and SA/SA faces were presented, regardless of dichotic stimulation, and when HA/SA and SA/HA faces were presented together with SA/WN and WN/SA dichotic stimuli. In this session, D.D.V.'s means were above the cut-off of the 95% confidence intervals when the HA/HA face was presented together with WN/HA, SA/WN and WN/SA stimuli and when the SA/HA face was presented together with HA/WN, SA/WN and WN/SA stimuli; they were below the cut-off of the 95% confidence intervals when the HA/HA face was presented together with the HA/WN dichotic stimulus and in all the conditions in which SA/SA and HA/SA faces were presented, regardless of dichotic stimulation (see Fig. 6).

In session 4 (bimodal presentation with auditory evaluation), A.P.'s means were above the cut-off of the 95% confidence intervals when the HA/WN dichotic stimulus was presented together with SA/SA and HA/SA faces, when the WN/SA dichotic stimulus was presented together with SA/SA and SA/HA faces, and in all conditions in which WN/HA and SA/WN stimuli were presented together with any chimeric face. In this session, D.D.V.'s means were above the cut-off of the 95% confidence intervals when the HA/WN stimulus was presented together with the HA/HA face, when the WN/HA stimulus was presented together with HA/HA and SA/HA faces, when the SA/WN dichotic stimulus was presented together with the SA/HA face, and when the WN/SA stimulus was presented together with HA/HA, HA/SA and SA/HA faces; they were below when the HA/WN stimulus was presented together with both SA/SA and HA/SA faces, when the WN/HA stimulus was presented together with the HA/SA face, and when the SA/WN stimulus was presented together with the SA/SA face (see Fig. 7).

4. Discussion

The performances of the two patients were very different from one another. In general, the total split-brain patient (D.D.V.) showed a rightward bias; moreover, his evaluations in bimodal presentations were mainly based on visual rather than acoustic stimuli, even when he was explicitly required to judge the auditory input. On the other hand, the results of the partially callosotomized patient (A.P.) largely resembled those of the control group and he did not show difficulties in paying attention to either visual or acoustic stimuli, when required. Differently from the control group, however, A.P. showed a trend for a leftward bias in the emotional evaluation of both acoustic and visual stimuli presented in isolation. This pattern of results confirms a right-hemispheric superiority in emotion detection, already known in the visual domain (see [24], for similar lateralization results in the same patient), and adds new evidence in the auditory domain.

As regards the results of D.D.V., in the auditory session they seem to be in line with the valence hypothesis, given that he attributed a higher score to happy syllables presented to the right than to the left ear, and at the same time he attributed a lower score to sad syllables presented to the left than to the right ear [5–7]. However, this pattern was not evident in the other conditions. In particular, with visual presentation, D.D.V. seemed totally incapable at detecting emotions expressed by the left hemiface: his judgments were based solely on the expression of the right hemiface. At first glance, this pattern of results seems to suggest a left hemispheric

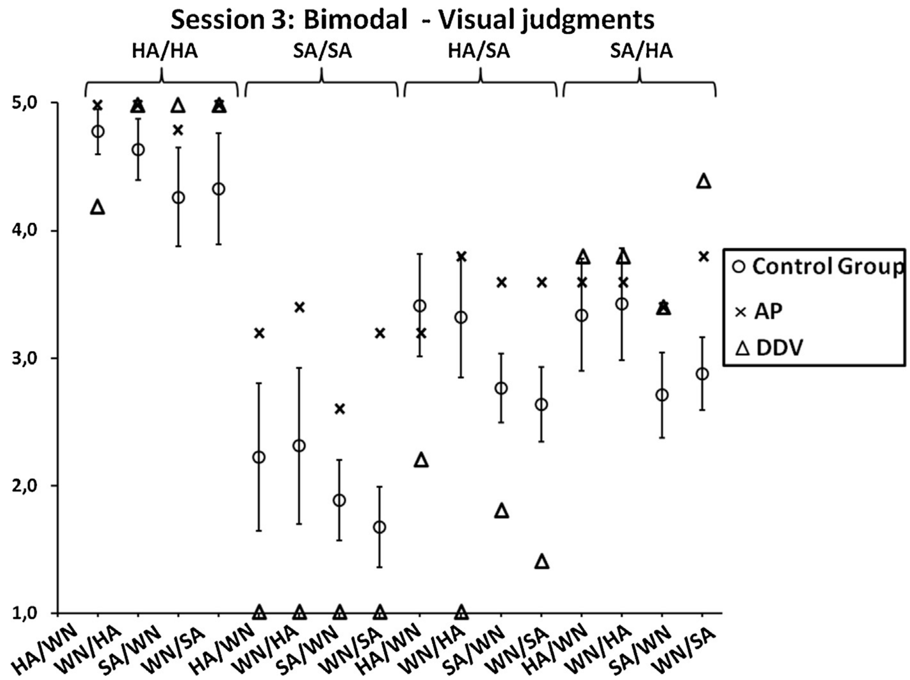

Fig. 6. 95% Confidence intervals of the control group (lines) and patients means (A.P.: cross; D.D.V.: triangle) in the third session, in which chimeric faces and dichotic stimuli were presented together and it was asked to evaluate the visual stimuli: 16 bimodal conditions.

dominance, that could be ascribed either to a hemispheric asymmetry in emotional face processing or to a left-hemispheric dominance due to the use of the right hand for responding. However, another explanation could be found in the literature on split-brain patients. In fact, several studies carried out with split-brain patients showed – only following total resection – a sort of attentional deficit of the right hemisphere [58,59,24]. In the present study, the use of the sole right hand in providing responses, makes it difficult to conclude if D.D.V. showed a spatial neglect or less, however, testing the same split-brain patient (D.D.V.), Hausmann and colleagues [58] found a rightward bias when D.D.V. carried out a line bisection task using either the left or the right hand; Corballis and colleagues [59,60] described the same kind of bias in D.D.V. leading the authors to conclude that D.D.V. shows a sort of spatial hemineglect. A crucial point is that the results of D.D.V. are in contrast with those of other patients with partial (either anterior or posterior) callosotomy, who do not show hemineglect. Corballis and colleagues [59] proposed that the spatial neglect of D.D.V., caused by the complete

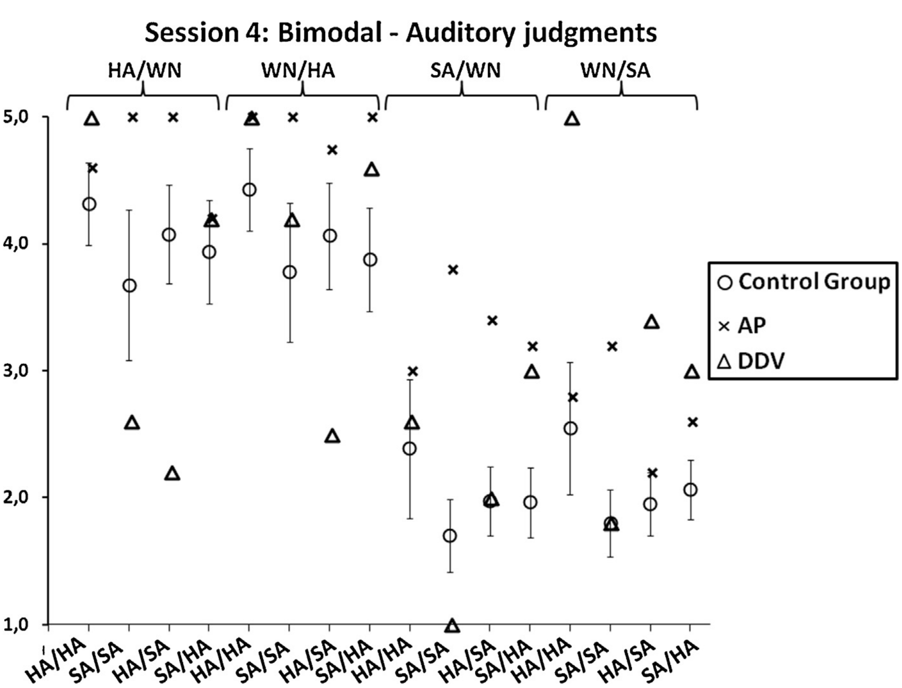

Fig. 7. 95% Confidence intervals of the control group (lines) and patients means (A.P.: cross; D.D.V.: triangle) in the fourth session, in which chimeric faces and dichotic stimuli were presented together and it was asked to evaluate the auditory stimuli: 16 bimodal conditions.

absence of callosal fibers, is due to a failure to shift attention from the right hemifield to the left hemifield, and they suggested the possibility to test the same patient without the use of the central fixation cross, in order to avoid the need to shift attention from the center to the side of the screen. In the present study this problem was in some way sidestepped, by means of showing chimeric faces in the center of the screen. Nevertheless, the present results seem to confirm the presence of hemineglect in patient D.D.V. Moreover, we added new data, testing the patient with acoustic stimuli: from the present results we can conclude that the spatial neglect of D.D.V. is not applicable to the auditory domain, differently from patients who suffer from hemineglect after a unilateral cerebral lesion [61], but it seems to be confined to the visual domain. In the auditory domain, a consonant-vowel dichotic paradigm carried out with 4 split-brain patients [62] showed that the REA was equivalent for the right and the left hand responding. Overall, the explanation of our results as due to the use of the right hand would not be valid in the auditory session, in which D.D.V. did not show the rightward bias, even if he used the right hand only.

During the bimodal presentation, acoustic stimuli were substantially ignored by D.D.V., who based his responses on the right hemiface: given that D.D.V. could successfully carry out the dichotic task, he disregarded acoustic stimuli only in the case in which they were presented together with visual stimuli. In other words, the dichotic presentation alone highlighted the validity of the valence hypothesis, with opposite-valence emotions being processed better by the two hemispheres, whereas the simultaneous audio–visual presentation showed a supremacy of the visual stimuli overshadowing the acoustic stimuli (visual capture). This was of course true when D.D.V. was required to evaluate visual stimuli, but, importantly, also when required to evaluate acoustic stimuli.

This set of results shows a multifaceted picture. Whereas Corballis and colleagues [59] concluded that the attentional deficit of D.D.V. is attributable to a deficit in shifting attention, an ability involving the ventral attentional system, and that it could disappear if D.D.V. can base his responses on the dorsal attentional system, our results seem to support another perspective: the main deficit of the patient does not seem to reside in attentional shifting, but in his attentional bias toward the right visual field. In fact, chimeric faces were presented centrally, thus not requiring gaze orienting or attentional shift, but nonetheless D.D.V. showed a rightward bias. Moreover, among the perceptual modalities we tested, the visual modality, but not the auditory modality, revealed a spatial hemineglect. In conclusion, the results of the total split-brain patient provided support for the valence hypothesis in the auditory domain, showed a hemineglect in the visual domain, and revealed a strong visual capture, thus confirming the hemineglect, in audio–visual processing.

The results of the anterior split-brain patient, A.P., were different from those of D.D.V. in all sessions. In dichotic presentations, A.P.'s evaluations seem to support the right hemisphere hypothesis: happy and sad syllables were evaluated as happier and sadder, respectively, when presented in the left ear (right hemisphere) than in the right ear (left hemisphere), supporting the right-hemispheric dominance in emotional processing of both positive and negative expressions. The results in the visual modality also provide support for the right hemisphere hypothesis: the happy/sad chimeric face was evaluated as happier by A.P. than by the control group, and the sad/happy chimeric face was evaluated as sadder by A.P. than by the control group. This pattern shows that in the partial split-brain patient, the right-hemispheric dominance for both positive and negative emotions might be even more evident than in the control group. In audio–visual presentations, A.P. did not show difficulties in evaluating either visual or acoustic stimuli. However, in the bimodal session in which visual evaluations were required, A.P.'s results did not support the right hemisphere hypothesis, but they seemed to be in line with the valence hypothesis: the evaluations of the chimeric faces were lower when the sad syllable was presented to the left ear (right hemisphere) and higher when the happy syllable was presented to the right ear (left hemisphere). In the bimodal condition in which auditory evaluations were required, the results of A.P. showed that when the emotional syllables, regardless of their valence, were presented to the left ear (right hemisphere), they led to a greater weight of the (hemi)facial expression shown to the left (thus, to the right hemisphere), with lower scores for the chimeric sad/happy than happy/sad face; when the emotional syllables were presented to the right ear (left hemisphere), they led to a greater weight of the (hemi)facial expression shown to the right (thus, to the left hemisphere), with lower scores for the chimeric happy/sad than sad/happy face. These results suggest that when auditory evaluations were required, the hemisphere contralateral to the ear presented with the syllable was more activated, which led to a greater salience of the contralateral hemiface. To conclude, the results of the anterior callosotomized patient provide support for the right hemisphere hypothesis only with unimodal stimulation. It is important to note that the difference between D.D.V. and A.P. is the presence of the splenium in A.P., who however lacks all the other portions of the CC. By means of diffusion-weighted tensor magnetic resonance imaging and probabilistic tractography, Beer et al. [63] have recently shown the presence of direct connections between visual and auditory cortices within each hemisphere and that white matter projections from both visual and auditory areas cross hemispheres in the posterior portion of the CC, with auditory and visual information passing through the superior and inferior splenium, respectively. This anatomical evidence lends support to the result that the performance of A.P. was very similar to that of the control group, because in both cases audio–visual information may be exchanged between hemispheres trough the fibers of the splenium. However, some difference exists between A.P. and the control group, suggesting that other callosal regions are implicated in this task.

The control group did not show hemispheric asymmetries in unimodal presentations. As reported above, we expected a pattern of lateralization in favor of either the valence or the right hemisphere hypothesis. The absence of evidence in any direction in visual and auditory sessions could be attributed to the long presentation time used. As we specified above, we chose longer presentation times compared to the classical range of tachistoscopic presentation (around 150 ms) to ensure stimulus processing by the patients. However, a sign of hemispheric lateralization is evident in the interaction between target modality and presentation ear: in fact, when an auditory judgment was required, syllables presented to the right ear received higher evaluations than syllables presented to the left ear. This result could be interpreted in the direction of the valence hypothesis: when the right hemisphere is activated by the presentation of a syllable, auditory judgments decrease possibly because of the right-hemispheric sensitivity for negative emotions. Similarly, when auditory evaluations were required, the happy/happy face was judged as happier than the sad/happy face, but not than the happy/sad face. Again, this result could suggest that the right hemisphere is more sensitive than the left in detecting the sad hemiface. On the other hand, direct comparisons between unimodal and bimodal sessions point in the same direction: the sad/happy chimeric face was judged as happier when it was presented together with the happy syllable to the right ear (left hemisphere), whereas no differences were recorded when the same syllable was presented to the left ear (right hemisphere): in accordance with the valence hypothesis, the higher activation of the left hemisphere, more involved in positive emotion processing, could have led to judge the face as happier. The absence of other evidence in support of the valence hypothesis in healthy participants might have depended, in our vision, upon the long exposure of the stimuli. This point could be viewed, however, as a demonstration of the maintenance of the central fixation by participants: due to the relatively long presentation time of the stimuli, it could be expected that observers could move their gaze showing a pattern of lateralization due to the preferential saccadic movements direction. Instead, the absence of a clear 'lateralized preference' could be interpreted as an indirect evidence of the participants' adherence to instructions in maintaining the gaze in the center of the screen. Obviously, the lack of eye-tracking measurements makes this evidence speculative rather than objective, but the results seem to accommodate this possibility.

The difference between the healthy participants' and the patients' results could depend on interhemispheric projections: as regards unimodal sessions, in the connected brain the hemispheric interchange leads to a substantially symmetric analysis of bilateral stimuli, whereas the absence of callosal fibers could explain the patients' more asymmetric performances. In fact, in these conditions A.P. based his ratings on the leftward stimuli. Probably, in the case of unimodal stimulation, after the bilateral exchange of perceptual analysis, which can occur through the intact splenium of the patient, the output of each hemisphere could be projected toward the frontal areas (by intrahemispheric fibers), where the absence of anterior interhemispheric connections prevents the balance between hemispheres, leading to the right-hemispheric superiority in emotional processing. This possibility is in accordance with the 'modified valence hypothesis' (MVH, [64,65]): the classical hemispheric superiority in a specific valence emotional analysis (valence hypothesis) would depend on the prefrontal specialization in positive and negative emotional content by each hemisphere, while the posterior region would show the right-hemispheric superiority in all emotional processing. Despite the MVH did not receive great consideration, recent studies support its validity. For example, Stefanics et al. [66] have recently found support for the MVH, recording ERPs during the processing of unattended facial emotions, with early components supporting the right hemisphere hypothesis, and late lateralized components supporting the valence hypothesis. Considering that A.P.'s frontal lobes were disconnected, the MVH could explain his performance. However, in the unimodal acoustic condition, the performance of D.D.V. provided support for the valence hypothesis. From this pattern of results, we can suppose that in the case of total interhemispheric disconnection, each hemisphere shows its superiority in a specific emotional domain. Also this pattern of result could be viewed in accordance with the MVH: the complete callosal section in D.D.V. does not allow an exchange between the hemispheres, thus the relative dominance of each hemisphere could emerge. From this perspective, the frontal areas of D.D.V. receive a 'specialized' output from the posterior areas in which a valence-specific processing was carried out. Thereafter, as regards the two main hypotheses on lateralized emotion processing, we can speculate that they are both true, with the right hemisphere hypothesis supported in the case of partial hemispheric connections (A.P.) and the valence hypothesis supported in the case of hemispheric independence (D.D.V.). Moreover, in bimodal sessions, the increased weight of cognitive load – due to the simultaneous stimulations of both hemispheres – reduces the right-hemispheric superiority, supporting in any case the valence hypothesis, except for the performance of the split-brain patient, which we attribute to an attentional bias rather to an asymmetric emotional processing. Finally, there is to consider that the mean age of the control group is lower than that of the patients. However, it is well known that a strong difference exist in callosal morphometry concerning both sex and age [67]. The effect of sex was controlled in this study, testing all male participants. As regards the effect of age, callosal morphometric changes are shown especially before reaching adulthood [68], when the callosal fibers are not completely myelinated, but a number of studies lacked in finding significant difference in callosal morphometry in the adulthood [69,70]. Moreover, the main age related thinning of the CC was observed in width of anterior half of CC [71], which was absent in both patients (thus, a comparison with the control group would be meaningless). In conclusion, it would seem reductive to attribute the difference found in the present study to the difference in age between participants and control group.

To sum up, the present study suggests an articulate balance between the two cerebral hemispheres in auditory, visual and audio–visual processing. The results of A.P. in the two unimodal sessions seem to support the right hemisphere hypothesis; however, a more complete examination of the results shows that this is the sole evidence in line with the right hemisphere hypothesis, whereas the other findings substantially support the valence hypothesis, especially when the cognitive load becomes heavy. In fact, opposite hemispheric specializations for positive and negative emotion processing are found in (i) bimodal presentations in the control group (connected hemispheres), (ii) bimodal presentations in A.P. (anteriorly disconnected hemispheres), and (iii) acoustic presentation in D.D.V. (totally disconnected hemisphere). As regards bimodal presentations, we found a strong visual capture in the case of totally disconnected hemispheres. Importantly, when visual stimuli were presented (alone or together with acoustic stimuli), only the total split-brain patient showed a predominant role of the left hemisphere, probably due to an attentional bias, rather than an asymmetric emotional processing, which was not present in auditory processing. The debate on the validity of the right hemisphere/valence hypothesis remains controversial, but the present study adds evidence in support of both theories depending on the task, and suggests that the valence hypothesis is more able to account for results as the cognitive load becomes heavier.

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