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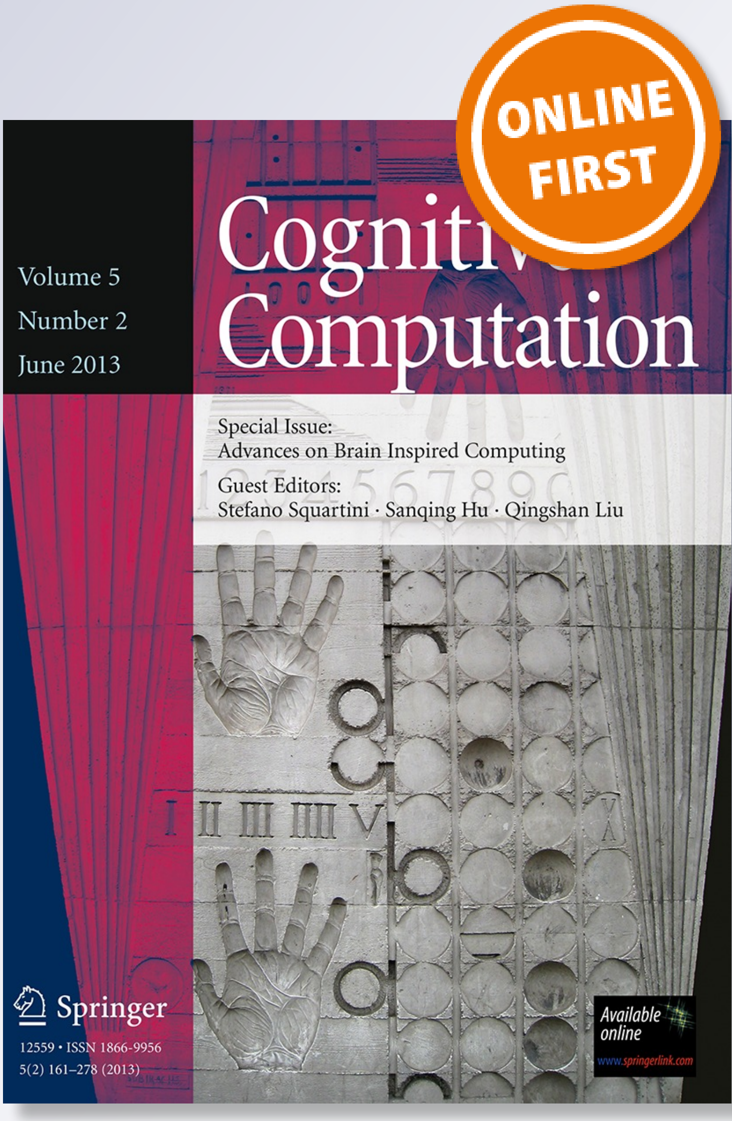

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Abstract The purpose of this study is to clarify the neural correlates of human emotional judgment. This study aimed to induce a controlled perturbation in the emotional system of the brain by multimodal stimuli, and to investigate whether such emotional stimuli could induce reproducible and consistent changes in electroencephalography (EEG) signals. We exposed 12 subjects to auditory, visual, or combined audio–visual stimuli. Audio stimuli consisted of voice recordings of the Japanese word "*arigato*" (thank you) pronounced with three different intonations (angry—A, happy—H or neutral—N). Visual stimuli consisted of faces of women expressing the same emotional valences (A, H or N). Audio–visual stimuli were composed using either congruent combinations of faces and voices (e.g., H $\times$ H) or noncongruent combinations (e.g., A $\times$ H). The data were collected using an EEG system, and analysis was performed by computing the topographic distributions of EEG signals in the theta, alpha, and beta frequency ranges. We compared the conditions stimuli (A, H or N), and congruent versus noncongruent. Topographic maps of EEG power differed between those conditions. The obtained results demonstrate that EEG could be used as a tool to investigate emotional valence and discriminate various emotions.

Keywords Emotion · Multimodal · EEG

A. Cichocki and F.B. Vialatte made equal contributions and should be considered as co-last authors of the present manuscript.

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Introduction

Judgment is the operation of the mind by which knowledge of values and relations of things is obtained. Judgment is important for decision-making, and involves both cognitive and infracognitive processes (see [11] for a review). Affective cognition is a recent topic of interest in neuroscience (see [9] for a review). In social cognition, judging the emotion of another human being is important to interpret communications; For instance, patients with emotional judgment disorders, such as patients suffering from major depression [15], can have serious social impairments. Understanding the complex mechanisms of the neural correlates of affective cognition is a topic of interest, considered as a "hard problem" in neuroscience [40]. Our purpose is to investigate the EEG correlates of human emotional judgments. To study the most subjective cognitive functions, we need to interact directly with them. From a neuroengineering perspective, this means that we need a technology that allows us to monitor and interact with cognitive functions in real time. Therefore, we need

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markers of affective cognition, if we want to be able to study affective cognition mechanisms.

Human communication is based on both face and voice perception, therefore facial expression and tone of voice are important to understand emotions. Such multimodal brain processes are difficult to investigate. The brain is a complex machine, and unfortunately no optimal method exists to understand fully its mechanisms—especially when one intends to use noninvasive measurements. To understand the mechanisms of emotion, one has to ask first where these mechanisms could be located inside the brain. Anatomically, a huge literature emphasizes the role of subcortical areas in emotion processing (see, e.g., [23]). However, these areas do not work independently one from another, and consequently emotion processing necessarily involves large-scale networks of neural assemblies, in cortico–subcortical transient interactions, where the time evolution of the network is a key factor [36].

Stimuli can be used to interact with the subjective experience of emotions. On the one hand, video clips were used as stimuli in several studies. However, to date there is no consensus regarding the optimal video stimuli, and each study used its own criteria (Table 1). On the other hand, there is considerable evidence that multisensory stimuli presented in spatial or temporal proximity are bound by the brain into a unique perceptual gestalt [37]. What would happen if subjects were exposed to contradictory visual and auditory stimuli? Such contradiction is termed a "McGurk effect" [26]—the visual and auditory stimuli do not carry the same message. Subjects confronted with such multimodal emotional stimuli, and asked to provide feedback on their internal perceptions while their neural activities are recorded, are confronted with the difficulty of binding contradictory emotional features. Such stimuli cannot be easily designed in videos: the voice expression of emotion is related with the duration of the stimuli (e.g., a word pronounced with an angry tone is generally shorter than the same word pronounced with a happy intonation).

Appraisal theory is based on the idea that emotions are extracted from our evaluations (appraisals) of events that cause specific reactions in different people. Essentially, our appraisal of a situation causes an emotional, or affective, response that is going to be based on that appraisal. An example of this is going on a first date. If the date is perceived as positive, one might feel happiness, joy, giddiness, excitement, and/or anticipation, because one has appraised this event as one that could have positive long-term effects, i.e., starting a new relationship, engagement, or even marriage. On the other hand, if the date is perceived negatively, then our emotions, as a result, might include dejection, sadness, emptiness, or fear [34]. Grandjean and Scherer [14] recently published a thorough EEG study about eight different conditions of appraisal (stimuli used = International Affective Picture System—IAPS; [21]), showing different EEG topographies. They showed in this study that the valence of the emotions elicited depends on how we evaluate the context, in terms of appraisal. Many current theories of emotion now place the appraisal component of emotion at the forefront in defining and studying emotional experience. However, our study is not concerned with general observations of emotional mechanisms, and should be considered in the context of the experimental task (emotional judgment). One could model emotional experience as a confluence of two dimensions: valence and arousal [3]. Most contemporary psychologists who study emotion accept a working definition acknowledging that emotion is not just appraisal but a complex multifaceted experience with the following components:

Table 1 Comparison of emotion studies using video clips as stimuli

Study	Clip duration	No. of trials	Emotions tested	Apparatus
Aftanas et al. [1]	90 s	6	Neutral, positive, negative	18-Channel EEG
Hoshi et al. [17]	~1 min	22	Startle, anticipation (expectation/prediction), unpleasant	fNIRS
Doronbekov etal. [8]	180 s + 4 photos	6	"Extremely fearful and aversive" versus neutral	PET
Chakrabarti etal. [4] (empathy)	3 s (actor faces)	20	Happy, sad, angry, disgusted versus neutral	3-T fMRI
Conrad et al. [5]	60 s	4	Happy, sad, anger, fear	4-Channel EEG
Giuliani et al. [13]	10–20 s	35	Amusement	Blood pressure, ECG, skin conductance, respiration, movement (piezoelectric captors), finger and ear pulse
Tsoi et al. [35]	2–5 min	4	Humor	Psychological tests (ToM, PANAS, WCST, LSP, IQ)

PET positron emission tomography, *fMRI* functional magnetic resonance imaging, *fNIRS* functional near-infrared spectroscopy, *ToM* theory of mind, *PANAS* positive and negative affect schedule, *WCST* wisconsin card sorting test, *LSP* life skill profile, *IQ* intelligence quotient

- Cognitive appraisal [33]. Only events that are judged or appraised to have significance for our goals, concerns, values, needs, preferences, or well-being elicit emotion. This is the cognitive aspect of emotional valence.
- Subjective feelings. The appraisal is accompanied by feelings that are good or bad, pleasant or unpleasant, calm or aroused. This is a more perceptual aspect of emotional valence.
- Physiological arousal (e.g., [32]). Emotions are accompanied by autonomic nervous system activity.
- Expressive behaviors [10, 25]. Emotion is communicated through facial and bodily expressions, postural and voice changes.
- Action tendencies. Emotions carry behavioral intentions, and the readiness to act in certain ways.

We investigated emotional judgments, i.e., cognitive appraisal of emotional stimuli. Our results indicate that EEG could be used as a tool to investigate emotional valence judgments. These results should not be compared to emotional perception (the subjects did not feel the emotion, but instead performed a judgment about the observed emotion).

The purpose of our study was to induce a controlled perturbation in the emotional system of the brain by multimodal stimuli, and to control if such stimuli could induce reproducible changes in EEG signal. We used a combination of photos and voices with congruent or noncongruent emotional valence. Through the investigation of this "abnormal" perceptual condition, we intend to reveal the mechanisms of normal emotional judgment (how one can distinguish the valence of emotions in a given stimulus). The use of three different valence stimuli (neutral, angry, happy) is compared.

Method

We recruited 12 subjects for this study. Within those 12 subjects, 10 subjects were female and 2 were male. There was no statistical effect of sex on the results reported; however, 2 male subjects only are not sufficient to rule out any possible effect. All subjects were young (age = 21.9 ± 0.31 years) healthy adults, without prior history of any neurological or psychiatric disorders. They all signed an informed consent form, and the experiment complied with the Riken BSI's ethic review board guidelines. All subjects were screened to be right-handed using the Edinburgh handedness test. The Positive and Negative Affect Schedule (PANAS, [42]) was collected for each subject before and after the experiment, and no subject displayed unusual PANAS scores (which might have been indicative of mood disorders).

We exposed these subjects to auditory, visual, or combined audio–visual stimuli. Stimuli were presented for 2 s; afterwards the subjects were asked to answer within a 3 s window, and then had 5 s of rest (one trial = 10 s). Audio stimuli consisted of voice recordings of the word "*arigato*" (thank you) pronounced with three different intonations (angry—A, happy—H or neutral—N). Visual stimuli consisted of photos of faces of women expressing the same emotional valences (A, H or N). The voice and face recordings were taken from professional actresses, and afterwards assessed blindly by 10 subjects to rank the emotional content of the stimuli. Audio–visual stimuli (Fig. 1) were composed using either congruent combinations of faces and voices (e.g., H × H) or noncongruent combinations (e.g., A × H):

- In the first session, the subjects were exposed to visual stimuli only. Fifty-four stimuli were presented in a pre-decided random order (18 for each emotional valence), and so that two consecutive emotions were always different.
- In the second session, the subjects were exposed to audio stimuli only. Fifty-four stimuli were presented in a pre-decided random order (18 for each emotional valence), and so that two consecutive emotions were always different.

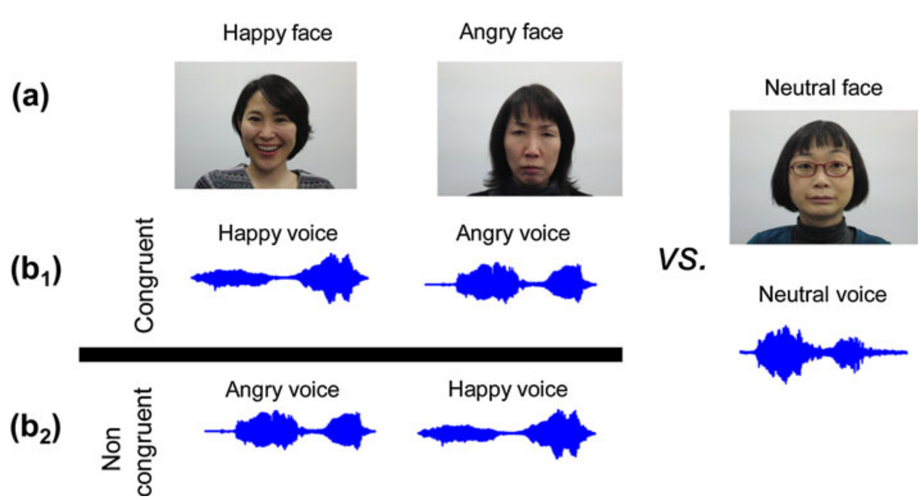

Fig. 1 McGurk effect. Visual stimuli (**a**) are combined with audio stimuli (**b**). Subjects will expect congruent stimuli (**b$_1$**), where visual and auditory clues are concordant (e.g., happy face and happy voice). Noncongruent stimuli (**b$_2$**), where visual and auditory clues are discordant (e.g., happy face and angry voice), will induce distortions in either the visual or auditory perception (this distortion is termed a "McGurk effect")

- In the third session, the subjects were exposed to the combined audio–visual stimuli. One hundred sixty-two stimuli were presented in a pre-decided random order (18 for each of the 9 emotional valence combinations), and so that two consecutive emotions were always different, and so that the same number of trials occurred for all possible pairs of stimuli. This session was presented in three consecutive blocks of 54 stimuli.

For all trials, the task was to judge if the percept was neutral, angry, or happy—the subjects provided their judgment by pressing a button. This forced the subjects

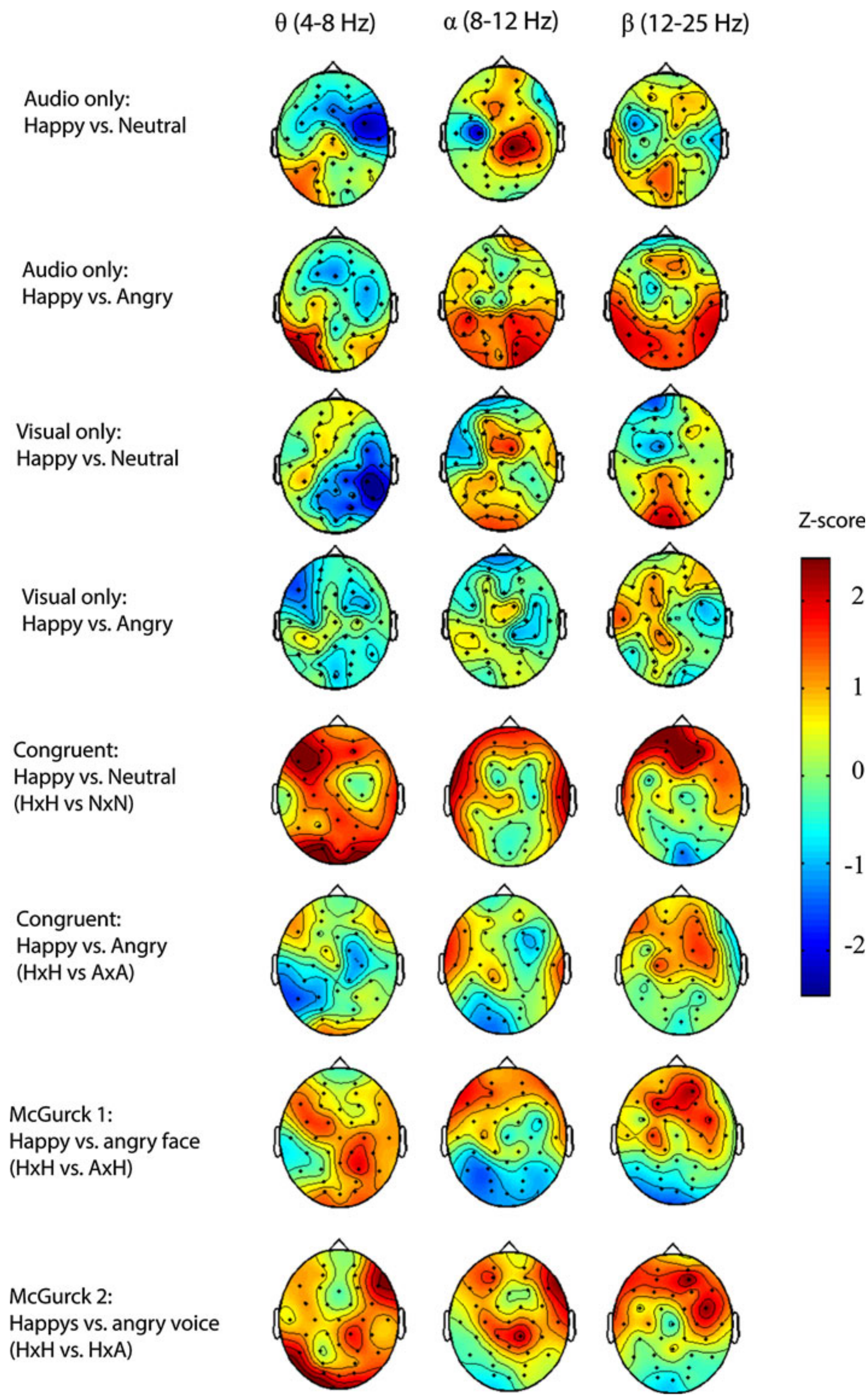

Fig. 2 Neurodynamics of happiness. Illustrations of the differences between emotional valences in the θ (4–8 Hz), α (8–12 Hz), and β (12–25 Hz) ranges. Each figure represents the Mann–Whitney z-score between both conditions (for all trials and all subjects): for instance, for H × H versus N × N, *red colors* represent increases in the happy condition as compared with the neutral condition, and *blue colors* represent decreases. A z-score with an absolute value $|z| \geq 2$ corresponds to a p value of 0.05 ($|z| \geq 3$ corresponds to $p = 0.01$) (Color figure online)

to perform emotional judgments also in case of noncongruent stimuli.

Neurophysiological data were collected with a 64-channel Biosemi EEG system with active electrodes in a shielded room. The sampling rate was fixed at 1,024 Hz with a notch filter at 50 Hz and an analog bandpass filter between 0.5 and 100 Hz. The topographic distributions of EEG signals (relative power) in the θ (4–8 Hz), α (8–12 Hz), and β (12–25 Hz) ranges were afterwards computed using the Welch periodogram method [41] on the period during stimulus presentation. Those power spectra were afterwards normalized (divided by the total energy of the spectrum) to provide relative power estimates. We compared the conditions stimuli (A, H or N), and congruent versus noncongruent using Mann–Whitney tests. Topographic maps of EEG power differed between those conditions on all subjects.

Results

The presented results are group effects, obtained on all subjects for a given stimulus condition. When comparing conditions with emotional stimuli versus stimuli with neutral valence (see below Figs. 2, 3), one can draw a number of observations. First of all, for monomodal stimuli. There is a common pattern between emotional visual stimuli: in the theta range a decrease in the right temporal area and a general imbalance of power between hemispheres (left hemisphere higher); and an increase in the alpha and beta ranges in the occipital channels. In the auditory condition, there is an imbalance between right and left hemisphere over the central area in the alpha range (right hemisphere higher). For multimodal stimuli, another common pattern between emotional conditions (both in H × H versus N × N and in A × A versus N × N) is observed, with a general increase of the EEG power in peripheral areas, for all frequency ranges.

When comparing monomodal happy and angry emotional valences, significant changes ($p < 0.05$) can be observed in the occipital area in auditory condition: in happy condition the occipital area activity increases in all frequency ranges. As for visual stimuli, there is a slight increase in the left fronto–temporal channels in the theta range, and a decrease in the right fronto–temporal channels in the beta range, for visual stimuli and angry valence. However, these effects disappear in the congruent visuo–auditory condition (A × A versus H × H). In this condition, there is an increase in the occipital area for A × A stimuli in the alpha range, together with an increase in the temporal areas for the H × H condition.

In the noncongruent condition, however, specific effects are observed:

- When comparing a congruent stimulus with a noncongruent stimulus with a visual difference (H × H versus A × H or A × A versus H × A), one can observe a distinct pattern: a longitudinal shift of power in the alpha range (increased in the frontal area, decreased in the occipital area). The same shift is obtained in the beta range, but only for the H × H versus A × H condition.
- When comparing a congruent stimulus with a noncongruent stimulus with an auditory difference (H × H versus H × A or A × A versus A × H), another distinct pattern is visible: a lateral shift of power in the alpha range (increased in the right central area, decreased in the left temporo–occipital area); and a longitudinal shift of power in the beta range (increased in the frontal area, decreased in the occipital area).

In the theta range, significant differences are observed when the noncongruent stimulus contains a happy face (H × H versus H × A or A × A versus H × A), with an increase in the left occipital area (for H × H versus H × A, there is in addition an increase in the right occipital and right frontal areas). Finally, in all the noncongruent conditions, an increase of activity is observed in the theta range, in a right centro–temporal location (C_4, CP_4).

We assessed the stability of this effect over trials, by studying separately the first and last trials. We compared in each condition (auditory, visual, multimodal stimuli; with angry, happy or neutral valence) the Fourier-transform values in each frequency range (θ, α, β) in the nine first and nine last trials. We found no significant difference of medians in any condition. A slight increase in the standard deviation in the auditory angry condition was observed ($p = 0.03$ using a Levene test without post hoc correction), but this test was not significant when taking into account post hoc corrections ($p \gg 0.05$).

The difference between monomodal and multimodal stimuli with the same valence shows some comparable trend between neutral, angry, and happy conditions (Fig. 4). The β range activity increases when comparing multimodal stimuli with audio stimuli, but in contrast decreases when comparing multimodal stimuli with visual stimuli. A similar effect is observed in the α range for the neutral condition, but the decrease spares the frontal areas, seems weaker in the angry condition, and cannot be observed in the happy condition. In the θ range, a consistent increase is observed in the occipital areas when comparing multimodal stimuli with audio stimuli. There is no clear difference between multimodal stimuli and visual stimuli in the θ range.

Discussion

We first of all analyzed congruent emotional judgment. Emotional judgment is known to be associated with neural correlates in the left and right dorso–lateral prefrontal cortex [16, 19, 22, 27–29]. We indeed observed in the congruent condition strong activations in the prefrontal channels, especially in the alpha and beta ranges. We can complete this theory with our congruent multimodal observations: for H × H versus A × A condition, one can see an increase in the temporal area for H × H condition and an increase in the occipital area for the A × A

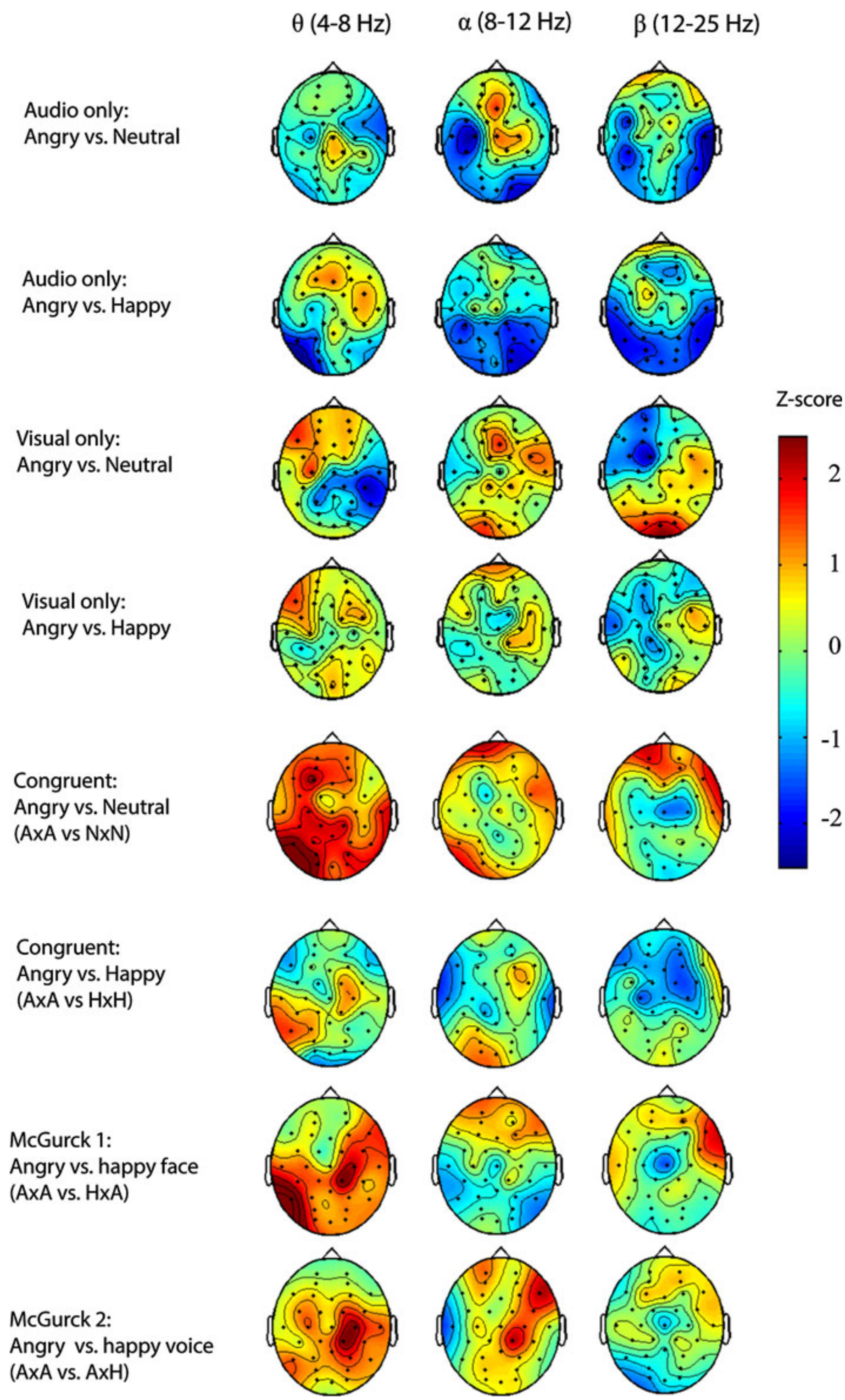

Fig. 3 Neurodynamics of angriness. Illustrations of the differences between emotional valences in the θ (4–8 Hz), α (8–12 Hz), and β (12–25 Hz) ranges. Each figure represents the Mann–Whitney *z*-score between both conditions (for all trials and all subjects): for instance, for A × A versus N × N, *red colors* represent increases in the angry condition as compared with the neutral condition, and *blue colors* represent decreases. A *z*-score with an absolute value $|z| \geq 2$ corresponds to a *p* value of 0.05 ($|z| \geq 3$ corresponds to $p = 0.01$) (Color figure online)

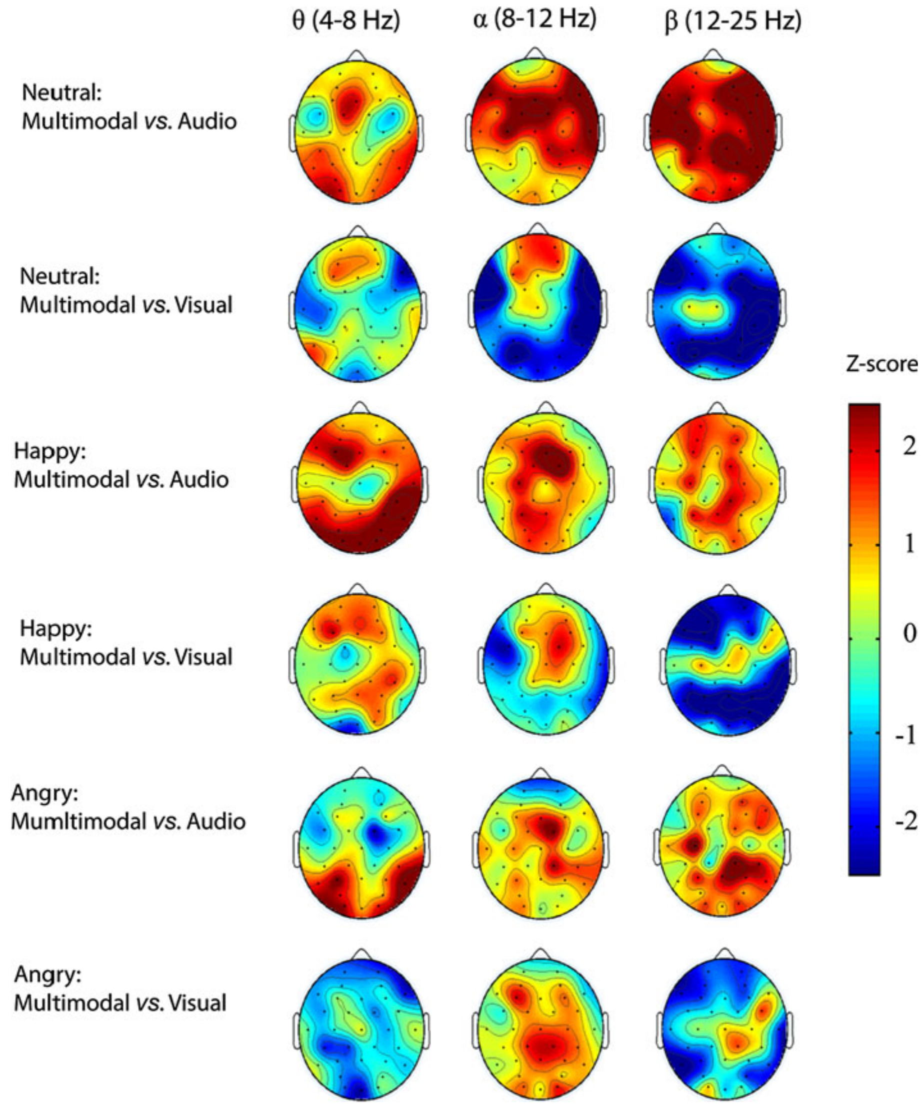

Fig. 4 Multimodal versus monomodal stimuli. Illustrations of the differences between stimuli modality in the θ (4–8 Hz), α (8–12 Hz), and β (12–25 Hz) ranges. Each figure represents the Mann–Whitney *z*-score between both conditions (for all trials and all subjects): for instance, for multimodal versus audio, *red colors* represent increases in the multimodal condition as compared with the monomodal audio condition, and *blue colors* represent decreases. A *z*-score with an absolute value $|z| \geq 2$ corresponds to a *p* value of 0.05 ($|z| \geq 3$ corresponds to $p = 0.01$) (Color figure online)

condition in the alpha range. This could indicate a preference for the visual stimuli in the angry emotional judgment and a preference for the auditory stimuli in the happy emotional judgment. Indeed, it has been reported that threat-related expressions (including angry faces) have specific influence on visual processing, that other emotions would not induce [31]. From our result, we observe an angry–visual and happy–auditory preferential association.

These effects could involve either emotional judgment processes, or basic attentional processes. Indeed, human attention depends on high-level information, such as goals, contextual cues, important objects, and image interpretation [43]. When subjects perform an emotional judgment task, they are involved in a top-down process. However, bottom-up features (such as contrast and saliency) can influence visual attention (see, e.g., [20]). An attentional mechanism may indeed explain the differences observed when comparing multimodal and monomodal stimuli: the subjects are focusing their attention on visual, auditory, or both perceptual modes. One could conjecture that attention also plays a role in emotional judgments: when subjects perceive angry faces, a specific attentional process would be triggered, due to a well-known reaction of preparation to danger (the Colavita visual dominance effect; see, e.g., [39]), involving mixed bottom-up and top-down processes (e.g., [12]). Perception of angry emotion means a potential danger, which would place the subject in a preferential visual dominance mode. Nevertheless, attentional processes may not be the only factor. Threatening facial expression can induce avoidance behavior, visible in eye-tracking [31]. Associations have been reported in previous publications between the valence of stimuli, and their temporal or visual dominance: broadband power increases in the occipital area are associated with negative valence stimuli [30].

Monomodal stimuli did show a stronger effect for auditory rather than visual stimulation. When checking the responses of the subjects, we observed that the response errors were higher for auditory ($\sim$20 %) than for visual stimulation ($\sim$5 %). This difference may be explained as follows: the subjects had more difficulties judging the emotional content, which may have increased the intertrial variability of EEG responses. This could also be a consequence of the specificity of facial emotional processing [6]: faces are more primitive biological stimuli, and as such, they may require very little cognitive mediation, and stronger involvement of subcortical processing (especially the amygdala).

Regarding noncongruent stimuli, two general observations can be derived: the first is that comparing congruent and noncongruent stimuli increases the significance of valence comparison in EEG. In other words, it may be easier to detect neurodynamics of emotional cognition using such protocols. It has been observed that cross-modal emotional stimuli modulate brain responses in functional magnetic resonance imaging (fMRI) studies, proving that cross-modal integration of emotional stimuli is possible (see, e.g., [7]). Perception of congruent stimuli in one perceptual modality could automatically activate representations in the other modality [6], which would produce increased EEG responses when they bind successfully.

In addition, it seems that a significant neural correlate of multimodal cognitive integration of emotional stimuli exists in the centro-temporal location (C_4, CP_4), in the theta range. Another interesting observation is the power shift in the alpha range: longitudinal shift for angry face/happy voice ([A $\times$ A or H $\times$ H] versus A $\times$ H) and lateral shift for happy face/angry voice [(A $\times$ A or H $\times$ H) versus H $\times$ A)]. The effects correspond to an increase in the occipital area for noncongruent stimuli when there is an angry face, and an increase in the left temporo-occipital area for noncongruent stimuli when there is an angry voice. We interpret this effect as a preference of the subjects for the angry stimulus, which is attended preferentially when the stimuli are noncongruent, which leads to increased alpha activity in either the occipital channels (visual cortex) or the left temporo-occipital channels (auditory cortex) for visual or auditory negative valence stimuli, respectively. This result shows a specific dominance effect of threatening stimuli.

It is plausible that, after some repetitions of trials, a given face/voice does not arouse the same emotions that it aroused in the beginning of the experiment. However, we could not observe any habituation effect: the responses observed at the beginning of the experiment remained stable with subsequent stimuli. This might however be due to the small number of trials (18 only per condition); our study might be underpowered to observe this effect. A study with larger number of stimuli or with repetitions of similar stimuli (e.g., succession of angry faces) might provide some clues about habituation.

We conjecture that the use of noncongruent stimuli could lead to new understandings of emotional judgment and emotional processes in general. Studies about the integration of noncongruent emotional stimuli would, for instance, be of great importance in pathologies with emotional dysfunctions (e.g., in psychiatry: bipolar disorders, depression, anxiety; or in neurology: aging and dementia). Finally, the specific EEG changes observed in the congruent/noncongruent conditions may be biased by cultural traits of the Japanese subjects [18]. There are considerable cultural differences in judgment of emotions between Westerners and Japanese subjects [2, 38]; For instance, we observed significant differences when comparing multimodal stimuli with either monomodal visual or monomodal auditory stimuli. This may be due to cultural preferences of Japanese subjects towards visual stimuli [24]. Studies from Western Caucasian subjects using a similar protocol would be necessary to control for this effect.

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