Emotion processing in congenital amusia: the deficits do not generalize to written emotion words

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Congenital amusia is a lifelong impairment in musical ability. Individuals with amusia are found to show reduced sensitivity to emotion recognition in speech prosody and silent facial expressions, implying a possible cross-modal emotion-processing deficit. However, it is not clear whether the observed deficits are primarily confined to socio-emotional contexts, where visual cues (facial expression) often co-occur with auditory cues (emotion prosody) to express intended emotions, or extend to linguistic emotion processing. In order to better understand the underlying deficiency mechanism of emotion processing in individuals with amusia, we examined whether reduced sensitivity to emotional processing extends to the recognition of emotion category and valence of written words in individuals with amusia. Twenty Cantonese speakers with amusia and 17 controls were tested in three experiments: (1) emotion prosody rating, in which participants rated how much each spoken sentence was expressed in each of the four emotions on 7-point rating scales; (2) written word emotion recognition, in which participants recognized the emotion of written emotion words; and (3) written word valence judgment, in which participants judged the valence of written words. Results showed that participants with amusia preformed significantly less accurately than controls in emotion prosody recognition; in contrast, the two groups showed no significant difference in accuracy rates in both written word tasks (emotion recognition and valence judgment). The results indicate that the impairment of individuals with amusia in emotion processing may not generalize to linguistic emotion processing in written words, implying that the emotion deficit is likely to be restricted to socio-emotional contexts in individuals with amusia.

Keywords: congenital amusia, emotion speech prosody, written emotion words, pitch, Cantonese

Introduction

Congenital amusia (amusia hereafter), or 'tone deafness', is a lifelong impairment in musical ability (Peretz et al., 2002). Individuals with amusia have limited ability to perceive and produce pitch (Peretz et al., 2002; Liu et al., 2010; Ayotte, Peretz & Hyde, 2002). Previous research estimated the prevalence rate of amusia to be approximately 1.5-4% (Nan, Sun, & Peretz, 2010; Peretz et al., 2008; Peretz & Vuvan, 2017; Pfeifer & Hamann, 2015; Wong et al., 2012). Several studies have shown that amusia extends to the language domain (Jiang et al., 2010; Jiang et al., 2012), as pitch is not only an important component of music but also plays a critical role in indexing phonetic/phonological differences in language (Ilie & Thompson, 2006; Zhang, Shao, & Huang, 2017). Several aspects of speech pitch processing have been found to be impaired in individuals with amusia, including prosody imitation (Kalmus & Fry, 1980), lexical tone perception (Liu et al., 2012; Nan et al., 2010; Shao, Zhang, Peng, Yang, & Wang, 2016; Zhang, Shao, & Chen, 2018; Zhang, Shao, & Huang, 2017), statement-question discrimination (Kalmus & Fry, 1980; Hutchins, Gosselin & Peretz, 2010; Liu, Patel, Fourcin, & Stewart, 2010), and phonological awareness (Jones et al., 2009; Sun, Lu, Ho, & Thompson, 2017).

In addition to phonetic/phonological differences, pitch cues also index the speaker's intended emotion, which is another important dimension of speech signals. Emotion is 'a mental and physiological state associated with feelings, thoughts, and behaviour', which plays an integral role in social interaction (Shott, 1979; Morris & Keltner, 2000). Emotion facilitates the formation and maintenance of social relationships (Keltner & Kring, 1998) and fulfils social functions such as ensuring social transmission of emotional interpretation of events, influencing others, and eliciting reactions from others (Frijda & Mesquita, 1994). Pitch, as an essential component of auditory processing in music and language (Lolli et al., 2015), is one of the cues that distinguish emotional portrayals. For example, speech

utterances produced in anger have higher pitch compared to those uttered in sadness (Fairbanks & Pronovost, 1939). As a result, pitch perception ability may affect how individual listeners communicate emotions through speech signals.

Despite the importance of emotion in speech communication and social interaction, the ability of emotion processing is not a universal human endowment. It has been reported that emotion processing in speech prosody is impaired in individuals with amusia (Lima et al., 2016; Lolli, Lewenstein, Basurto, Winnik, & Loui, 2015; Lu, Ho, Liu, Wu, & Thompson, 2015; Thompson, Marin, & Stewart, 2012), even though pitch variation in emotion expressions (somewhere between 1 and 5 semitones) is often larger than that in music (e.g. 1 semitone). Thompson et al. (2012) compared 12 controls and 12 individuals with amusia on a forced-choice emotion recognition task by providing semantically neutral utterances that conveyed emotions through prosodic cues only. The amusia group showed reduced accuracy for recognizing happy, tender, irritated and sad emotions. Participants with amusia also reported that they have difficulties understanding others' emotions or feelings from vocal cues in daily life. Lolli et al. (2015) showed that when the amount of information in speech signals is reduced by using a low-pass filter, emotional prosody impairments in individuals with amusia might be more severe. In a recent study, Pralus et al. (2019) reported that individuals with amusia showed a deficit for emotional prosody recognition in short voice samples carried by a single vowel, but not in long sentences. While there was a close to ceiling performance in the sentence materials, which may suggest a possible lack of sensitivity of long sentence materials for revealing the emotion recognition deficit in individuals with amusia, it is likely that individuals with amusia have an especially severe emotion processing deficit in brief speech materials with limited acoustic cues. Taken together, these findings supported the hypothesis that individuals with amusia have reduced sensitivity of emotional recognition compared to musically intact controls.

Interestingly, Lima et al. (2016) found that the impairment of individuals with amusia in emotion processing extends to the visual modality. The authors asked 13 individuals with amusia and 11 controls to rate emotions carried in emotional prosodies, nonverbal vocalizations and silent facial expressions, followed by two laughter perception tasks (authenticity and contagion). Individuals with amusia showed reduced recognition of emotion categories in emotional speech prosody, and such impairments extended to visual emotion recognition of silent facial expressions. Individuals with amusia also showed reduced sensitivity to emotional authenticity in the laughter perception task.

While the findings of Lima et al. (2016) suggested that there might be a cross-modal emotional processing deficit in individuals with amusia that prevails to emotional face recognition, the underlying deficiency mechanism of the observed deficits remains unclear. On the one hand, it is reasonable to speculate that the emotion deficits primarily have a socio-emotional origin (Lima et al., 2016), such that individuals with amusia are impaired in emotion processing in a face-to-face social setting, where visual cues (e.g. facial expression) often co-occur with auditory cues (e.g. emotion speech prosody) to express intended emotions. On the other hand, it is possible that the emotion-processing deficit is amodal in nature, which may be due to a deep impairment in the representation of emotion categories in the amusical brain. In order to tease apart these two hypotheses and to circumscribe the scope of emotion processing deficits in amusia, it is thus important to further examine emotion processing in the visual modality outside of socio-emotional context.

To this end, we examined linguistic emotion processing in the visual modality, namely the recognition of emotion categories (happiness, anger, sadness and fear) and valence (positive, negative and neutral) of written words, in a group of Cantonese speakers with amusia and matched musically intact control subjects. In addition, participants with amusia and controls were tested on a baseline task of emotion speech prosody recognition, in

order to examine whether Cantonese speakers with amusia are impaired in the processing of emotion speech prosody. We focused on Cantonese in the current study, not only because emotion processing has not been examined before in Cantonese speakers with amusia, but also because some evidence indicates that speakers of Cantonese – a highly dense tonal language – have better musical abilities compared to non-tonal language speakers (Pfordresher & Brown, 2009; Bidelman, Hutka & Moreno, 2013), and that the prevalence rate of amusia appears to be lower among Cantonese speakers (Wong et al., 2012). As a result, it is yet unknown whether emotion prosody recognition is impaired or preserved in Cantonese speakers with amusia, who are under the influence of its dense tonal system. More importantly, although impairments of emotion prosody recognition were found in previous studies, and the deficits appeared to extend beyond the auditory domain (i.e. in emotional face recognition), it is still unknown whether it poses a significant problem for amusic individuals where linguistic cues are available. Therefore, in the current study, we examined emotion category and valence recognition of written words in a group of Cantonese speakers with amusia and matched controls.

To summarize, the current study aims to address the following two questions: (1) whether reduced sensitivity to emotion prosody recognition can be found in native Cantonese speakers with amusia; and (2) whether reduced sensitivity to emotional processing in Cantonese speakers with amusia extends to the recognition of emotion category and valence of written words in Chinese. For the first question, we predict that Cantonese speakers with amusia are impaired in emotion prosody recognition compared to controls, given the consistent findings of impairments in speech pitch (lexical tone) processing in Cantonese speakers with amusia (Liu, Maggu, Lau, & Wong, 2015; Shao et al., 2016; Zhang et al., 2018, 2017), and reduced sensitivity to emotion prosody recognition in English and Mandarin speakers with amusia (Lima et al., 2016; Lolli et al., 2015; Lu et al., 2015; Thompson et al.,

2012). As for the second question, a finding of reduced sensitivity to emotion processing in written words in the linguistic context would provide support for a deep, amodal emotion deficit in amusia irrespective of social contexts. On the other hand, if the deficit of emotion processing does not generalize to abstract emotion processing in the linguistic context, it implies that the emotion deficiency of amusia may primarily be confined to socio-emotional contexts.

Materials and methods

Participants

Twenty participants with amusia and 17 controls participated in the current study. They were recruited from a total of 338 participants who first took the Online Identification Test of Congenital Amusia (Peretz et al. 2008) at home. Among them, 61 individuals who scored lower than 71 and 170 individuals who scored over 85 were then invited to take the Montreal Battery for Evaluation of Amusia (MBEA) (Peretz, Champod, & Hyde, 2003) under the supervision of an experimenter in the lab. Eventually 20 and 17 participants were confirmed as individuals with amusia and controls respectively. All the participants with amusia scored at or lower than 71, while controls scored higher than 85 in the global score of MBEA (Nan et al., 2010). All the participants were native Cantonese speakers, right-handed and without a reported history of hearing, psychiatric or neurological disorders. None of them majored in linguistics or psychology, or received professional musical training. Individuals with amusia and controls were matched for age, sex and education level. The demographic characteristics of the participants are reported in Table 1. The experimental procedures were approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University. Informed written consent was obtained from all participants in compliance with the experimental protocols.

Stimuli and procedure

Three experiments were included in this study. In Experiment 1, we examined whether Cantonese speakers with amusia showed impairment in the recognition of emotional speech prosody, and an emotion prosody rating task was used. In Experiment 2 and 3, we tested whether emotion impairment in amusia would also affect abstract emotion processing of written words in Chinese. Previous research suggested that there were two basic dimensions of emotion processing: arousal, which was the level of activation, and valence, which referred to the level of pleasantness (Barrett, 1998). As previous studies on Chinese emotion words focused on emotion categories and valence (Lin & Yao, 2016), these two aspects of emotion processing were therefore examined in Experiment 2 and 3, respectively.

Experiment 1: emotion prosody rating task

The task of this experiment largely followed the previous research by Lima et al. (2016). A set of 80 semantically and emotionally neutral sentences with simple syntactic structures and length between 5 to 12 words were designed (see Supplemental Materials Table S1). Each sentence was randomly assigned to one of the four emotions (happiness, anger, sadness and fear), with 20 sentences in each category. Two students (1 male and 1 female, aged 18-24) from the School of Drama of The Hong Kong Academy for Performing Arts, who were native Cantonese speakers, were recruited. The two speakers were provided with the list of emotions and sentences to produce, and were instructed to express the emotions as naturally as possible. Each of them was asked to produce 40 sentences with the intention of communicating four emotions including happiness, anger, sadness and fear via 'tone of voice' cues. Each sentence was produced once, and if the expressed emotion was not natural enough, the experimenter would ask the speaker to repeat the sentence. The recordings were made in a sound-attenuated booth at a sampling rate of 11,025 Hz with 16 bits per sample.

Four independent judges who did not participate in the experiment and without a linguistic background were asked to judge the emotion of each sentence in a forced-choice task, and 15 most recognizable exemplars of each emotion were selected, generating a total of 60 sentences. The average recognition accuracy of the selected sentences in each emotion was 95% for happiness, 88.33% for anger, 85% for sadness and 78.33% for fear. The acoustic properties of the sentence materials, including the mean F0, min F0, max F0, duration and mean intensity are presented in Table 2.

The sentence stimuli were presented using E-prime 2.0. During a trial, a spoken sentence was presented binaurally via head-mounted headphones to the subjects. The duration of spoken sentences ranged between 2-5 seconds. After the presentation of a sentence, the participants were asked to complete a multidimensional rating procedure, indicating the extent to which each sentence was expressed in the four emotions (happiness, anger, sadness, and fear) on a 7-point rating scale (1 as lowest and 7 as highest). There was no time limit on the rating response. We used the multidimensional rating procedure instead of asking the participants to identify the intended emotion of each sentence, as this procedure is more sensitive than a forced-choice task. It could also capture cases where participants rated two or more categories as the highest for a given stimulus, which would show that they were not able to identify one single category as being the most salient. A total of 60 sentences without repetition (15 sentences × 4 emotions) were presented randomly to the participants. In order to familiarize them with the experiment, the participants first took a practice test, which contained sentences produced by the same two speakers in each emotion category but not selected for the experiment (see Supplemental Materials Table S1).

Experiment 2: emotion judgment task of written words

For this experiment, a set of ten disyllabic emotion words were randomly selected from those

proposed by Xu and Tao (2003) for each emotion category (happiness, anger, sadness and fear) (see Supplemental Materials Table S2). All words were adjectives. The stimuli were presented using E-prime 2.0. During a trial, a written word was presented in traditional Chinese characters in the center of a computer screen, and the participants were instructed to match the presented words to one of the four emotions categories (happiness, anger, sadness and fear) within 5 seconds. The 40 words (10 words × 4 emotions) without repetition were presented randomly to the participants. In order to familiarize them with the experiment, the participants first took a practice test, which contained disyllabic emotion words from Xu and Tao (2003) that were not used in the experiment.

Experiment 3: valence judgment task of written words

For this experiment, a total of 133 disyllabic words including nouns, verbs and adjectives (Positive: 45, Neutral: 43, Negative: 45) were selected from A Dictionary of Chinese Praise and Blame Words: With Chinese-English Parallel Text (Starr, 2001) (see Supplemental Materials Table S3). Although the valence of each word was labelled in the dictionary, the valence label in the dictionary may not always match the perception of linguistically untrained participants. For example, Lin and Yao (2016) reported that while the word 'understand' was labelled as a word with positive valence in Xu and Tao (2003), it was classified as neutral or emotionless by the participants. To ensure that the emotional valence of words was aligned with the perception of linguistically untrained participants, 20 independent judges who did not participate in the experiment and without linguistic background were asked to indicate the valence of these 133 words. Based on their judgment, 20 words with the highest accuracy were selected for each category (positive, neutral, and negative) (see Supplemental Materials Table S3). The average recognition accuracy of the selected stimuli in each valence category was 96.75 % for positive words, 98.75% for

negative words and 92.75% for neutral words.

The stimuli were presented using E-prime 2.0. During a trial, a written word was presented in traditional Chinese characters in the center of a computer screen, and the participants were instructed to judge the valence of each presented word (positive, neutral, and negative) within 5 seconds. The 60 words (20 words x 3 valence) were presented once randomly to the participants. In order to familiarize them with the experiment, the participants first took a practice test, which contained disyllabic words extracted from the dictionary but not used in the experiment.

Data analysis

For Experiment 1, two sets of analyses were conducted following the previous study (Lima et al., 2016): (1) the accuracy rate which reflected the ratio of trials where participants assigned the highest rating to the intended emotion and lower rating to the remaining three emotions, and (2) the ambivalent rate which reflected the ratio of trials where participants assigned equally high ratings to two or more emotions. The reason for analyzing the ambivalent rate is that it could show whether participants are able to identify a single emotion category as most noticeable. The previous study (Lima et al., 2016) has reported that individuals with amusia gave more ambivalent responses than controls, suggesting that individuals with amusia showed reduced selectivity of emotion recognition. For the accuracy rate, the response to a trial was coded as '1' if the intended emotion category received the highest rating, and as '0' if not. For the ambivalent rate, the response to a trial was coded as '1' if two or more emotion categories received equally high ratings, and as '0' if not. Trials with ambivalent responses were coded as "incorrect" in the accuracy rate analysis. For Experiment 2 and 3, the response to each trial was coded as '1' or '0' (correct or incorrect) for each participant.

For Experiment 1, generalized mixed-effects models were fitted on accuracy and

ambivalence measures with *group* (amusia and controls), *emotion* (happiness, anger, sadness and fear) and their interaction as fixed effects, and with by-subject random intercept as random effects. We then constructed a series of more parsimonious models and compared these models with the full model. The significance of each fixed effect was determined by the log-likelihood ratio test. Likewise, generalized mixed-effects models were fitted on the accuracy rate with *group* (amusia and controls), *emotion* (happiness, anger, sadness and fear) and their interaction as fixed effects for Experiment 2, and with *group* (amusics and controls), *valence* (happiness, anger, sadness and fear) and their interaction as fixed effects for Experiment 3 with similar procedures.

Results

Experiment 1: emotion prosody rating task

Figure 1 and 2 display the accuracy and ambivalent rate of the two groups. Figure 3 shows the rating distribution on each emotional scale for each type of emotion stimuli. Only correct trials where the intended emotion received the highest rating were included in the plot of Figure 3. Accuracy results revealed that participants with amusia performed significantly worse than controls ($\chi^2 = 26.25$, $p < 0.001$). A significant main effect of *emotion* was also observed ($\chi^2 = 151.69$, $p < 0.001$), with happiness being recognized more accurately than the other three emotions (ps < 0.001), sadness and fear recognized more accurately than anger (ps < 0.001), and sadness recognized more accurately than fear ($p < 0.001$), according to post-hoc tests with Holm-Bonferroni correction. The *group* and *emotion* factors did not interact significantly ($\chi^2 = 1.84$, $p = 0.6$).

As for the ambivalent rate, participants with amusia showed a trend of higher ambivalent rate compared to controls ($\chi^2 = 11.64$, $p = 0.06$), suggesting that participants with amusia tended to be less capable of identifying one single emotion category as the most

salient, while also failing to identify the correct emotion of the given stimuli. The effect of *emotion* was significant ($\chi^2 = 20.87$, $p < 0.001$). Post-hoc tests using Holm-Bonferroni correction showed that happiness received the lowest ambivalent rates compared to the other three emotions (ps < 0.05). *Group* and *emotion* interacted significantly ($\chi^2 = 7.78$, $p = 0.05$). Post-hoc tests with Holm-Bonferroni correction showed that there was a group difference in fear ($p < 0.05$), where participants with amusia exhibited higher ambivalent rate than controls. The group difference was not significant in other emotion categories (ps > 0.05).

Experiment 2: emotion judgment task of written words

Figure 4 shows the accuracy rate of the two groups in Experiment 2. No significant *group* effect was found ($\chi^2 = 0.81$, $p = 0.37$), indicating that participants with amusia and controls performed similarly in recognizing emotion categories from written words. The effect of *emotion* was significant ($\chi^2 = 17.70$, $p < 0.01$), with happiness being more accurately recognized than anger ($p < 0.05$) and sadness ($p < 0.05$). No interaction between *group* and *emotion* was found ($\chi^2 = 6.07$, $p = 0.11$).

Experiment 3: valence judgment task of written words

Figure 5 shows the accuracy rate of the two groups in Experiment 3. No significant *group* effect was found ($\chi^2 = 0.05$, $p = 0.83$), indicating that participants with amusia and controls performed comparably in recognizing the valence of written words. The effect of *valence* was significant ($\chi^2 = 10.93$, $p < 0.01$), where neutral stimuli were recognized significantly less accurately than positive ($p < 0.05$) and negative ($p < 0.01$) stimuli. No interaction between *group* and *valence* was found ($\chi^2 = 2.41$, $p = 0.30$).

Discussion

The present study examined how emotion processing in emotional speech prosody and

written words were affected by amusia in native Cantonese speakers. There are two main findings. First, Cantonese speakers with amusia showed reduced sensitivity to emotional prosody recognition. Second, they exhibited preserved emotion category and valence recognition of written words in linguistic context.

As tonal language speakers, Cantonese speakers with amusia have constant exposure to small pitch changes in spoken communication, which may result in them being highly sensitive to subtle pitch differences relative to amusic speakers of non-tonal languages (Bidelman, Hutka, & Moreno, 2013; Wong et al., 2012). For example, Bidelman et al. (2013) found that in a task where participants were asked to detect pitch incongruities between two six notes melodies, Cantonese non-musicians performed better than English non-musicians. Besides, the prevalence rate of amusia appears to be lower among Cantonese speakers compared to non-tonal language speakers (Wong et al., 2012). Therefore, it is unclear whether Cantonese speakers with amusia would show impaired or preserved emotional prosody recognition in spoken sentences. The results of the current study revealed significantly reduced accuracy of emotional prosody recognition in Cantonese speakers with amusia compared to controls. This result corroborates with previous findings (Lima et al., 2016; Lu et al., 2015; Thompson et al., 2012) to indicate that individuals with amusia with diverse language backgrounds have impaired recognition of emotional speech prosody. It is also consistent with the hypothesis that conscious pitch processing (e.g. in recognition tasks) is selectively impaired in individuals with amusia (Moreau et al., 2013; Pralus et al., 2019; Zhang and Shao, 2018). However, this result differs from Pralus et al. (2019), which suggested that individuals with amusia performed similarly to controls in emotion prosody processing of spoken sentences. It should be noted that the sentences in the current study were short with 5 to 12 syllables. It is possible that the impairment of individuals with amusia in emotional prosody recognition becomes more salient in short speech samples where

acoustic cues indicative of the intended emotion are more restricted. Alternatively, it is also possible that the acoustic cues indexing emotional prosodies may differ between languages, and they may be differentially accessible to amusical speakers of a certain language. For example, the number of pauses could be one cue distinguishing emotional prosodies in French according to Bartkova et al. (2016), who found that anger stimuli had more short pauses (shorter than 250 ms), whereas joy stimuli had more short to mid pauses (between 250 ms and 400 ms). Possible cross-linguistic differences in emotion prosody processing await future investigations.

Lima et al. (2016) suggested that emotion recognition abnormalities of individuals with amusia extended beyond the auditory domain to emotional face recognition, which posed the question of whether this emotion deficiency is amodal in nature or rooted in socio-emotional processing. The current study found no significant differences between individuals with amusia and controls in both emotion recognition and valence judgement of written words, indicating that the performance of amusic individuals on abstract emotion processing in written linguistic materials was not affected by their impairment in musical ability. In other words, such impairment in amusia does not appear to extend to linguistic emotion processing in written words, which suggests that the emotion deficit is likely to be restricted to the socio-emotional domain. One possible explanation for this result is that amusic participants could rely on their language ability to perform the task, for example, by making use of semantic knowledge to compensate for their emotional processing deficit. On the other hand, it is worth noting that Leveque et al. (2018) failed to replicate the finding of emotional face recognition deficits reported in Lima et al. (2016) with static faces, which casts some doubt on the hypothesis of an emotion processing deficit in the visual modality in individuals with amusia. Future studies should further investigate visual emotion processing in amusia.

Previous studies observed that participants with amusia showed difficulties in speech intonation perception when processing sentences with linguistic information removed (Ayotte et al., 2002; Patel et al., 2005; Hutchins et al., 2010). However, although amusic individuals performed slightly worse than controls in discriminating statement and question intonation, the group difference was not significant. One possible explanation is that when given the linguistic information, the stimuli could be processed through the speech mode and resulted in some preserved sensitivity to speech prosody; in contrast, when linguistic information was removed, stimuli were processed in the musical mode, resulting in reduced sensitivity (Ayotte et al., 2002; Lu et al., 2015). In the current study, when participants were presented with the visual stimuli (written words), they might process the stimuli via the language mode, as linguistic information was readily accessible from the written materials. It is possible that individuals with amusia may be able to establish and access abstract categories of emotion and concepts of emotional valence based on semantics of text materials, exploiting intact semantic mechanisms separate from emotional processing in speech prosody or facial expression.

It is worth noting that in Lima et al. (2016), individuals with amusia gave significantly more ambivalent responses than controls in the emotion prosody rating task, while in our study individuals with amusia only showed a trend of higher ambivalent rate compared to controls, and the group difference only reached significance in the fear condition. This discrepancy may be attributed to the different manipulations of emotion categories. In the current study, four emotion categories (happiness, anger, sadness and fear) were tested, whereas Lima et al. (2016) employed more emotion categories (amusement, anger, disgust, fear, pleasure, relief and sadness), which might cause more confusion and consequently significantly higher ambivalent rate in the amusic group. A higher ambivalent rate might indicate that individuals with amusia were deficient in the selectivity of emotion recognition,

especially for emotion categories that were difficult to recognize. In the current study, amusic participants often confused fear with sadness (52.1%) compared to happiness (20.7%) (also see Figure 3). The confusion in amusic participants can be at least partially attributed to their poor pitch processing ability, due to the similarity in F0 characteristics between fear and sadness stimuli (see Table 2).

We found a significant main effect of emotion in the emotional prosody rating task, where happiness received higher accuracy rate and lower ambivalent rate compared to the other three emotions, which requires an explanation. This result may be explained by the acoustic features of happiness (Thompson et al., 2012), which exhibited higher F0 that may enable participants to more easily distinguish it from the other emotions (see Table 2). The main effect of emotion was also significant in the emotion recognition task in written words, where happiness also received a higher accuracy rate. It is likely that processing positive faces or words has an advantage compared to negative faces or words, for the reason that the cognitive processing for negative events is more protracted and elaborate (Leppänen & Hietanen, 2004). Several studies have shown that when presented with positive faces (Leppänen & Hietanen, 2004) or words (Stenberg et al., 1998), participants gave faster responses compared to negative ones. Therefore, it might be easier for both groups to recognize words in happy emotions compared to other negative emotions (fear, anger, sadness). Lastly, in the valence judgment task of written emotional words, neutral stimuli had lower accuracy rate compared to positive and negative stimuli. This result may be due to the greater difficulty of judging the neutral valence for the selected stimuli. The rating results of the 20 independent judges also indicated that the neutral stimuli were judged least accurately among all valences.

To conclude, the present study confirmed that native Cantonese speakers with amusia showed reduced sensitivity to emotional speech prosody. This study also extended the

previous studies on emotional processing in amusia by revealing that the emotion processing deficits in individuals with amusia do not generalize to abstract emotion processing in written emotion words, which may be due to their reliance on semantic cues. The current findings circumscribed the scope of emotion processing deficits, by pinpointing a potential locus of socio-emotional processing deficit in amusia. That being said, the participants' performance in the written emotion word task (Experiment 2) was quite high, which may have limited its sensitivity to reveal a potential deficit of individuals with amusia in abstract emotion processing. Future studies can employ more challenging tasks to further verify this finding.

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Declaration of interest

The Authors report no conflicts of interest.

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Table 1. Demographic characteristics of the participants. F = female, M = male, L = left, R = right. For handedness assessment, all the participants completed a handedness background test (Oldfield, 1971).

	Amusics		**Controls**	
	Mean	SD	Mean	SD
Age (years)	22.15 (18-28)	2.46	21.82 (18-28)	3.07
Gender	12M 8F		9M 8F	
Handedness	20R 0L		17R 0L	
Education	Undergraduate		Undergraduate	
MBEA				
Scale	54.00	15.51	89.87	6.94
Contour	58.54	18.45	89.65	4.53
Interval	55.64	15.86	90.06	4.15
Rhythm	55.55	18.00	90.97	6.60
Metric	50.69	11.48	73.71	15.76
Memory	69.36	22.46	97.27	2.89
Global	57.29	13.89	88.59	2.91

Table 2. Acoustic cues of the sentence stimuli in the emotion prosody rating task (Experiment 1).

	Emotion	Mean F0 (Hz)	Min F0 (Hz)	Max F0 (Hz)	Duration (ms)	Intensity (dB)
Female speaker	Happiness	271.31	184.84	393.06	1727	62.97
	Anger	249.07	122.88	370.67	1600	64.57
	Sadness	216.85	135.84	345.50	2240	52.47
	Fear	239.66	167.18	311.60	1492	60.54
Male speaker	Happiness	159.84	113.51	217.38	1338	65.58
	Anger	151.81	107.85	206.01	1468	65.77
	Sadness	111.72	91.52	173.10	1403	62.41
	Fear	133.42	95.83	175.89	1227	65.71

Figure 1. Accuracy rate of amusic and control participants for each emotion condition in the emotion prosody recognition task (Experiment 1). The box indicates the 25th - 75th percentile range and the solid horizontal line indicates the median. The separated line shows the chance level performance (25%).

Figure 2. Ambivalent rate of amusic and control participants for each emotion condition in the emotion prosody recognition task (Experiment 1). The box indicates the 25th - 75th percentile range and the solid horizontal line indicates the median.

Figure 3. Rating on each emotional scale for each emotion condition in the emotion prosody recognition task (Experiment 1). The box indicates the 25th - 75th percentile range and the solid horizontal line indicates the median.

Figure 4. Accuracy rate of amusic and control participants in the emotion judgment task of written emotion words (Experiment 2). The box indicates the 25th - 75th percentile range and the solid horizontal line indicates the median. The separated line shows the chance level performance (25%).

Figure 5. Accuracy rate of amusic and control participants in the valence judgment task of written emotion words (Experiment 3). The box indicates the 25th - 75th percentile range and the solid horizontal line indicates the median. The separated line shows the chance level performance (33.3%).

Table S1. Stimulus list in Experiment 1 (Emotion prosody rating task).

Emotion category	Speaker	Sentence	Meaning in English	Stimuli selected
Happiness	Female	黑色嘅牆會吸熱	Black wall absorbs heat	Test
Happiness	Female	佢邊彈結他邊唱歌	He is singing and playing guitar	Test
Happiness	Female	最近轉左天氣	The weather has changed recently	Test
Happiness	Female	日本起中國隔離	Japan is next to China	Test
Happiness	Female	本書起張枱上面	The book is on the table	Test
Happiness	Female	啤牌有四種花色	Poker have four suit	Test
Happiness	Female	佢將啲相掛左起牆上面	He put the photo on the wall	Test
Happiness	Female	呢個係用尼煮飯嘅煲	This is a pot for cooking rice	Test
Happiness	Female	我最近寫左一篇文	I worte an article recently	Test
Happiness	Male	我哋去買嘢嘅時間有一個鐘	We have an hour for shopping	Test
Happiness	Male	呢幅畫係梵高畫	This is drawn by Van Gogh	Test
Happiness	Male	按摩可以減輕肌肉酸痛	Massage can relieve muscle soreness	Test
Happiness	Male	佢去左做運動	He exercised	Test
Happiness	Male	全球有 249 個國家	There are 249 countries in the world	Test
Happiness	Male	彩虹有七隻顏色	Rainbow has seven colours	Test
Happiness	Female	我起報紙登左個廣告	I placed an advertisment on the newspaper	Practice
Happiness	Male	佢係我爸爸既一位朋友	He is a friend of my father	Practice
Happiness	Male	一年有四個季節	There are four season in a year	Not selected
Happiness	Male	部電話差緊電	The phone is charging	Not selected
Happiness	Male	我去過一次會展	I have been to the Exhibition Centre once	Not selected
Anger	Female	公園入面有一個雕像	There is a statue in the park	Test
Anger	Female	佢今日晏就食咗兩碗飯	He ate two bowl of rice yesterday	Test
Anger	Female	我地起會議室開會	We have a meeting in the convention centre	Test
Anger	Female	我啱啱先到呢度	I have just arrived	Test
Anger	Female	屋企對面有一間學校	There is a school opposite my house	Test
Anger	Female	政府決定發展核能	The government decided to develop nuclear energy	Test
Anger	Female	朵花起衣櫃入面	The flower is in the closet	Test
Anger	Male	佢哋係媽咪既學生	They are my mother's students	Test
Anger	Male	呢件事發生起英國	It happened in the UK	Test
Anger	Male	競選進入最後階段	Election enters the final stage	Test
Anger	Male	呢本係長篇小說	This is a novel	Test
Anger	Male	佢已經上左機	He has already got on the plane	Test

Anger	Male	佢將件蛋糕俾左我	He gave me the cake	Test
Anger	Male	等陣有籃球比賽	There will be a basketball competition later	Test
Anger	Male	呢篇文章講緊航天科技	This article talks about aerospace technology	Test
Anger	Male	啱啱過左三點鐘	It has just passed three o'clock	Practice
Anger	Female	太陽係由東邊升起	The sun rises from the east	Not selected
Anger	Female	沙田有銀行	There is a bank in Shatin	Not selected
Anger	Female	鯨魚係哺乳類動物	Whales are mammals	Not selected
Anger	Male	足球係一種運動	Football is a sport	Not selected
Sadness	Female	今晚我去見朱生	I am going to see Mr.Chu tonight.	Test
Sadness	Female	空氣係由唔同氣體混合而成	The air is made up of a mixture of gases	Test
Sadness	Female	月亮反射太陽既光	The moon reflects the sun and the light	Test
Sadness	Female	啲人等緊巴士	People are waiting for the bus	Test
Sadness	Female	啲資料寫左上黑板	The data have been written on the blackboard	Test
Sadness	Female	佢嘅手錶帶係皮造	The watch band is made in leather	Test
Sadness	Female	佢用較剪將條線剪斷	He cut the line with a scissors	Test
Sadness	Male	佢起寫字樓番工	He worked in the office	Test
Sadness	Male	運動前要熱身	Warm up before exercise	Test
Sadness	Male	媽咪今日去搭地鐵	Mum is going to take the subway today	Test
Sadness	Male	下就陽光最猛烈	The sun is the strongest in the afternoon	Test
Sadness	Male	佢披左一條披肩	He wore a shawl	Test
Sadness	Male	佢同我朋友幾似樣	He looks similar with my friend	Test
Sadness	Male	世界有五大洋	There are five oceans in the world.	Test
Sadness	Male	佢有收集鉛筆嘅習慣	He has the habit of collecting pencils	Test
Sadness	Female	佢係我地既代課老師	He is a substitute teacher	Practice
Sadness	Female	天文台話今日係二十度	The Observatory said that it is 20 degrees today.	Practice
Sadness	Female	太陽系有八大行星	The solar system has eight planets	Not selected
Sadness	Male	生理學研究生物功能	Physiological study biological functions	Not selected
Sadness	Male	佢聽日有一場演講	He will have a speech tomorrow	Not selected
Fear	Female	佢間屋起馬路隔離	His house is next to the road	Test
Fear	Female	紅蘿蔔最初係紫色	Carrots are originally purple	Test
Fear	Female	佢係一個基督徒	He is a Christian	Test
Fear	Female	佢而家著緊綠色外套	He is wearing a green coat	Test
Fear	Female	我起網上面買左兩盒蘋果	I bought two boxes of apples from the Internet.	Test

Fear	Female	佢起公園附近散步	He is walking near the park	Test
Fear	Female	我而家讀緊中五	I am studying Grade 5	Test
Fear	Male	我啱啱食完飯	I have just finished eating	Test
Fear	Male	佢企起門隔離	He stood next to the door	Test
Fear	Male	我訂左聽日既飛	I have booked tomorrow's ticket	Test
Fear	Male	封信放左起信箱	The letter is in the mailbox	Test
Fear	Male	呢個係計畫既一部分	This is a part of the plan	Test
Fear	Male	我而架二十五歲	I am twenty-five years old.	Test
Fear	Male	佢識煮野食	He knows how to cook	Test
Fear	Male	呢塊球拍係打網球用	The is a tennis racket	Test
Fear	Male	佢起梳化訓著左	He fell asleep in the sofa	Practice
Fear	Female	歌德風格源自法國	Goethe style originated from France	Not selected
Fear	Female	佢幫我地影左三張相	He helps me to take three pictures	Not selected
Fear	Female	嗰位係我細佬	he is my brother	Not selected
Fear	Male	我飲左兩杯水	I drank two cup of water	Not selected

Table S2. Stimulus list in Experiment 2 (Written word emotion matching task).

Emotion	**Word in Chinese**	**Meaning in English**	**Stimuli selected**
Happiness	稱心	Satisfy	Test
Happiness	痛快	Delighted	Test
Happiness	欣慰	Grateful	Test
Happiness	歡暢	Happy	Test
Happiness	舒暢	Comfortable	Test
Happiness	舒心	Comfortable	Test
Happiness	如意	Wishful	Test
Happiness	順心	Satisfy	Test
Happiness	幸福	Blessed	Test
Happiness	驚喜	Surprise	Test
Anger	憤怒	Angry	Test
Anger	忿恨	Hateful	Test
Anger	激憤	Indignant	Test
Anger	生氣	Angry	Test
Anger	憤懣	Resentful	Test
Anger	憤慨	Indignat	Test
Anger	忿怒	Angry	Test
Anger	窩火	Angry	Test
Anger	暴怒	Fury	Test
Anger	不平	Injustice	Test
Sadness	哀怨	Sad	Test
Sadness	悲慟	Sorrowful	Test
Sadness	沉重	Heavy	Test
Sadness	感傷	Sentimental	Test
Sadness	辛酸	Bitter	Test

Sadness	酸辛	Bitter	Test
Sadness	心酸	Bitter	Test
Sadness	悲愴	Sad	Test
Sadness	無奈	Helpless	Test
Sadness	蒼涼	Desolate	Test
Fear	嚇人	Scary	Test
Fear	畏怯	Timid	Test
Fear	緊張	Nervous	Test
Fear	惶恐	Fearful	Test
Fear	慌張	Panic	Test
Fear	驚駭	Frightening	Test
Fear	恐慌	Panic	Test
Fear	慌亂	Panic	Test
Fear	心虛	Guilty	Test
Fear	惶惑	Bewildered	Test
Happiness	爽心	Pleased	Practice
Happiness	願意	Willing	Practice
Happiness	樂意	Willing	Practice
Happiness	得志	Successful	Practice
Sadness	慘痛	Painful	Practice
Fear	害怕	Afraid	Practice

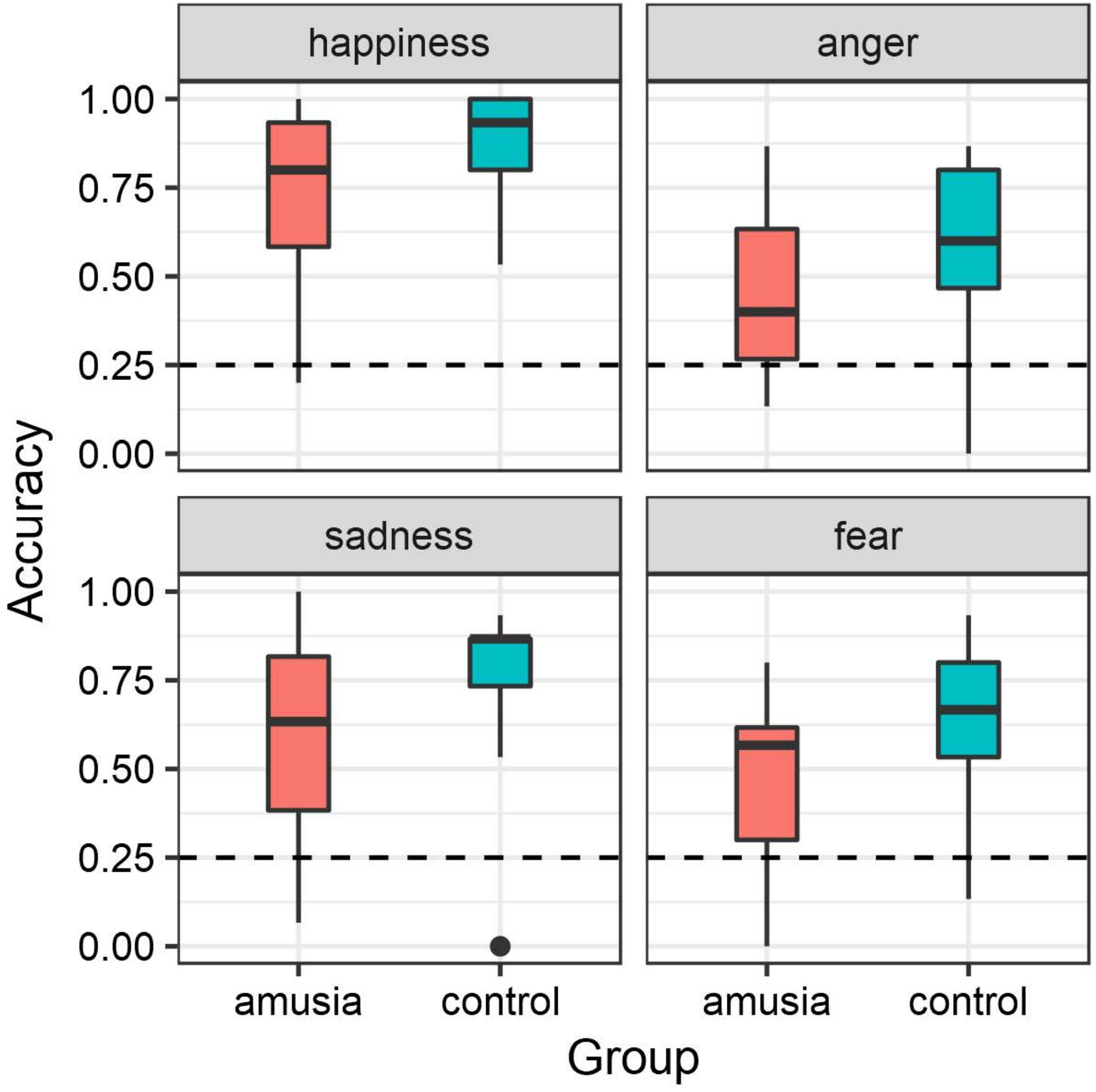
Table S3. Stimulus list in Experiment 3 (Written word valence judgment task).

Valence	Part of Speech	Word in Chinese	Meaning in English	Stimuli Selected
Positive	Noun	榜樣	Model	Test
Positive	Noun	才華	Talent	Test
Positive	Noun	典範	Model	Test
Positive	Noun	風度	Demeanor	Test
Positive	Noun	瑰寶	Treasure	Test
Positive	Noun	傑作	Masterpiece	Test
Positive	Noun	精華	Essence	Test
Positive	Noun	猛將	Valiant Soldier	Test
Positive	Verb	愛戴	Love	Test
Positive	Verb	奮鬥	Strive	Test
Positive	Verb	奉獻	Dedication	Test
Positive	Verb	鼓勵	Encourage	Test
Positive	Verb	誇獎	Praise	Test
Positive	Adjective	安詳	Serene	Test
Positive	Adjective	昂揚	High-spirited	Test
Positive	Adjective	昌盛	Prosperity	Test
Positive	Adjective	充沛	Abundant	Test
Positive	Adjective	出眾	Outstanding	Test
Positive	Adjective	慈祥	Kindly	Test
Positive	Adjective	聰慧	Intelligent	Test
Positive	Noun	寶庫	Tresure house	Practice
Positive	Verb	捍衛	Defend	Practice
Positive	Noun	抱負	Ambition	Not selected
Positive	Noun	表率	Model	Not selected
Positive	Noun	成果	Result	Not selected
Positive	Noun	範例	Example	Not selected
Positive	Noun	功勞	Credit	Not selected
Positive	Noun	豪情	Pride	Not selected

Positive	Noun	氣節	Integrity	Not selected
Positive	Verb	馳名	Well-known	Not selected
Positive	Verb	弘揚	Promote	Not selected
Positive	Verb	激勵	Excitation	Not selected
Positive	Verb	凱旋	Triumph	Not selected
Positive	Verb	緬懷	Remember	Not selected
Positive	Verb	銘記	Remember	Not selected
Positive	Verb	培養	To Cultivate	Not selected
Positive	Verb	佩服	Admire	Not selected
Positive	Verb	謙讓	Modest	Not selected
Positive	Adjective	悲壯	Tragic	Not selected
Positive	Adjective	動人	Attractive	Not selected
Positive	Adjective	豐碩	Rich	Not selected
Positive	Adjective	剛強	Strong	Not selected
Positive	Adjective	高超	Excellent	Not selected
Positive	Adjective	果斷	Decisive	Not selected
Positive	Adjective	煥發	Shine	Not selected
Positive	Adjective	儉樸	Simple	Not selected
Neutral	Noun	結果	Result	Test
Neutral	Noun	朋友	Friend	Test
Neutral	Noun	結局	Ending	Test
Neutral	Noun	典型	Typical	Test
Neutral	Noun	內幕	Stable Push	Test
Neutral	Noun	旗號	Banner	Test
Neutral	Noun	巢穴	Nest	Test
Neutral	Verb	流傳	spread	Test
Neutral	Verb	傳播	spread	Test
Neutral	Verb	指派	Assign	Test
Neutral	Verb	訪問	Interview	Test
Neutral	Verb	直立	Upright	Test
Neutral	Verb	參加	Participate	Test
Neutral	Verb	打算	Intend	Test
Neutral	Verb	出現	Appear	Test
Neutral	Verb	聲言	Voice	Test
Neutral	Verb	重演	Iterate	Test
Neutral	Adjective	無限	Unlimited	Test
Neutral	Adjective	明顯	Obvious	Test
Neutral	Adjective	保守	Conservative	Test
Neutral	Noun	意志	Willpower	Practice

Neutral	Adjective	小心	Careful	Practice
Neutral	Noun	手法	Skill	Not selected
Neutral	Noun	信譽	Reputation	Not selected
Neutral	Noun	心思	Thought	Not selected
Neutral	Noun	精力	Energy	Not selected
Neutral	Noun	血汗	Sweat	Not selected
Neutral	Noun	威力	Power	Not selected
Neutral	Noun	交情	Friendship	Not selected
Neutral	Verb	施加	Apply	Not selected
Neutral	Verb	辯護	defend	Not selected
Neutral	Verb	佔據	occupy	Not selected
Neutral	Verb	策動	Engineer	Not selected
Neutral	Verb	約束	constraint	Not selected
Neutral	Verb	投入	Input	Not selected
Neutral	Adjective	強硬	Tough	Not selected
Neutral	Adjective	熱心	Enthusiastic	Not selected
Neutral	Adjective	和善	Kind	Not selected
Neutral	Adjective	威風	Imposing	Not selected
Neutral	Adjective	細密	Detailed	Not selected
Neutral	Adjective	新奇	New	Not selected
Neutral	Adjective	小巧	Small	Not selected
Neutral	Adjective	嚴肅	Serious	Not selected
Neutral	Adjective	永久	Permanent	Not selected
Neutral	Adjective	長遠	Long	Not selected
Neutral	Adjective	忠實	Loyal	Not selected
Neutral	Adjective	充足	Sufficient	Not selected
Negative	Noun	敗家子	Spendthrift	Test
Negative	Noun	幫凶	Accomplice	Test
Negative	Noun	暴徒	Thug	Test
Negative	Noun	勾當	Illegal Business Deal	Test
Negative	Noun	浩劫	Catastrophe	Test
Negative	Noun	傀儡	Puppet	Test
Negative	Verb	巴結	Fawn	Test
Negative	Verb	敗壞	Corrupt	Test
Negative	Verb	包庇	Cover	Test
Negative	Verb	串通	Collusion	Test
Negative	Verb	得逞	Success	Test
Negative	Verb	揮霍	Squander	Test

Negative	Adjective	骯髒	Dirty	Test
Negative	Adjective	傲慢	Arrogant	Test
Negative	Adjective	笨拙	Clumsy	Test
Negative	Adjective	草率	Rash	Test
Negative	Adjective	脆弱	Weak	Test
Negative	Adjective	放肆	Presumptuous	Test
Negative	Adjective	固執	Stubborn	Test
Negative	Adjective	荒唐	Absurd	Test
Negative	Verb	吹捧	Flatter	Practice
Negative	Verb	顛覆	Overturn	Practice
Negative	Noun	黨羽	Henchmen	Not selected
Negative	Noun	慣技	Trick	Not selected
Negative	Noun	後果	Consequences	Not selected
Negative	Noun	貨色	Trash	Not selected
Negative	Noun	伎倆	Trick	Not selected
Negative	Noun	論調	Talk	Not selected
Negative	Verb	暗藏	Hidden	Not selected
Negative	Verb	遷就	Yield	Not selected
Negative	Verb	操縱	Control	Not selected
Negative	Verb	兜售	Hawk	Not selected
Negative	Verb	泛濫	Delute	Not selected
Negative	Verb	誇耀	Show off	Not selected
Negative	Adjective	繁瑣	Cumbersome	Not selected
Negative	Adjective	糊塗	Confused	Not selected
Negative	Adjective	昏庸	Fatuous	Not selected
Negative	Adjective	可恥	Shameful	Not selected
Negative	Adjective	刻薄	Mean	Not selected
Negative	Adjective	空虛	Emptiness	Not selected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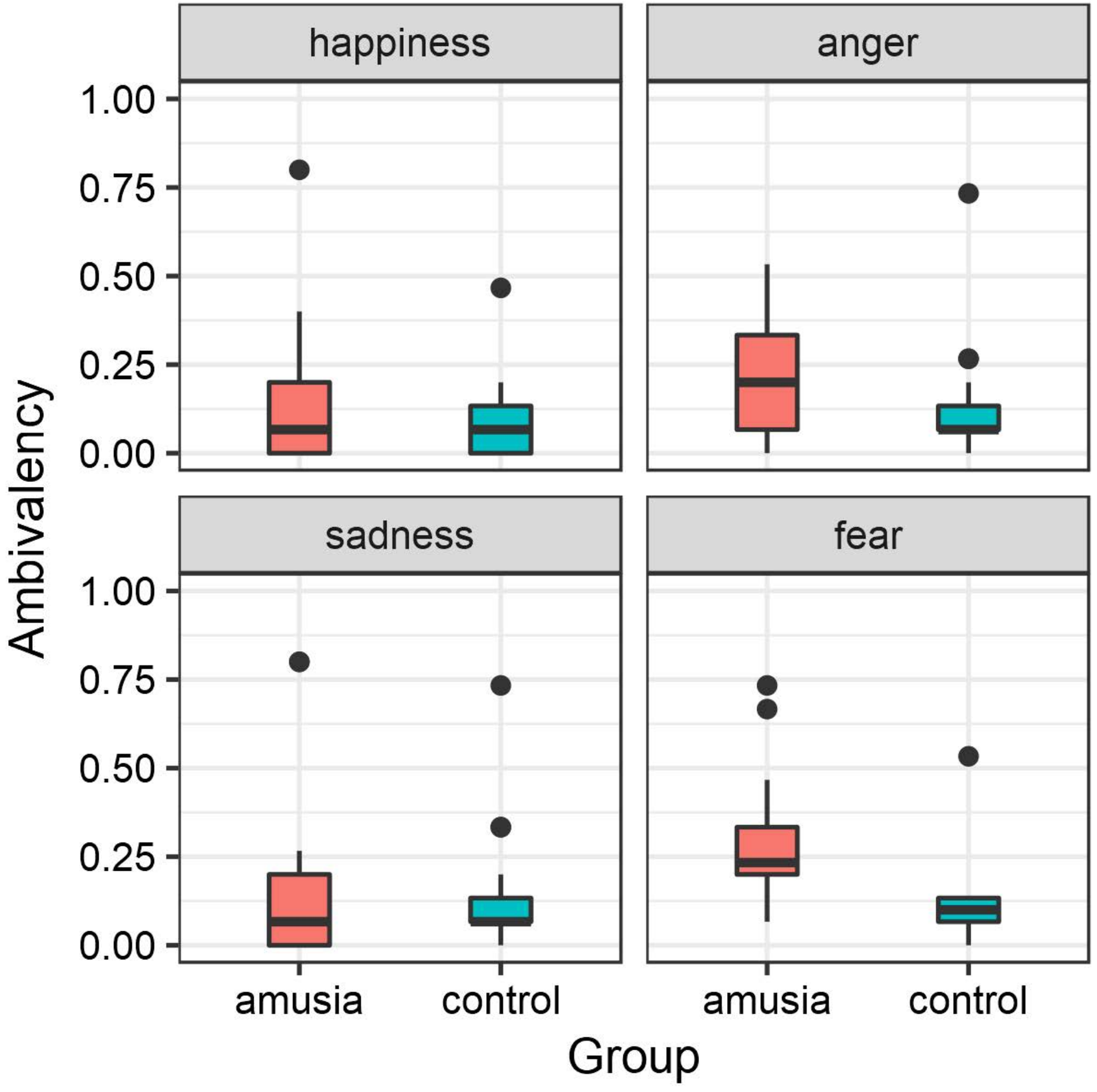
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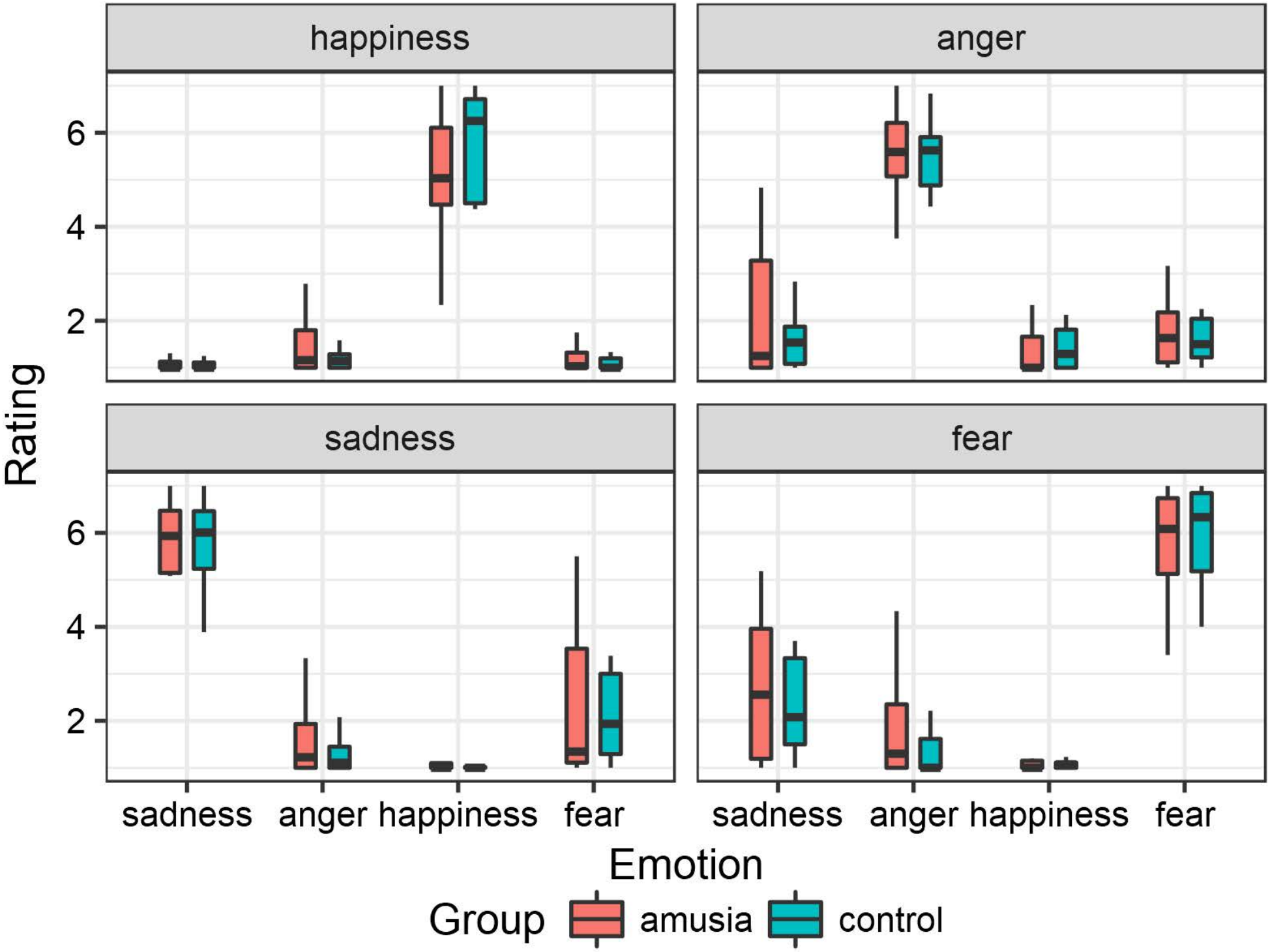
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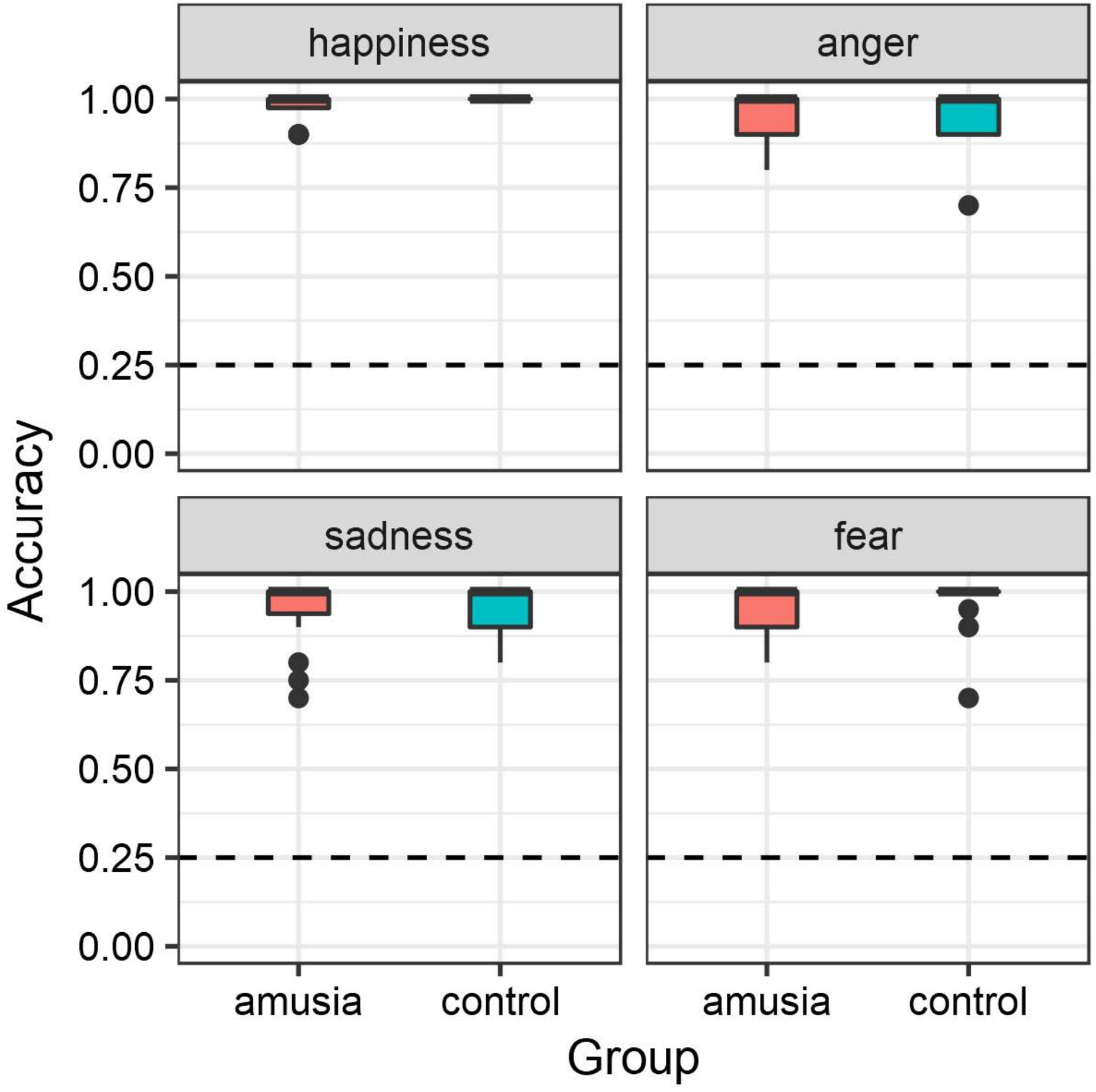
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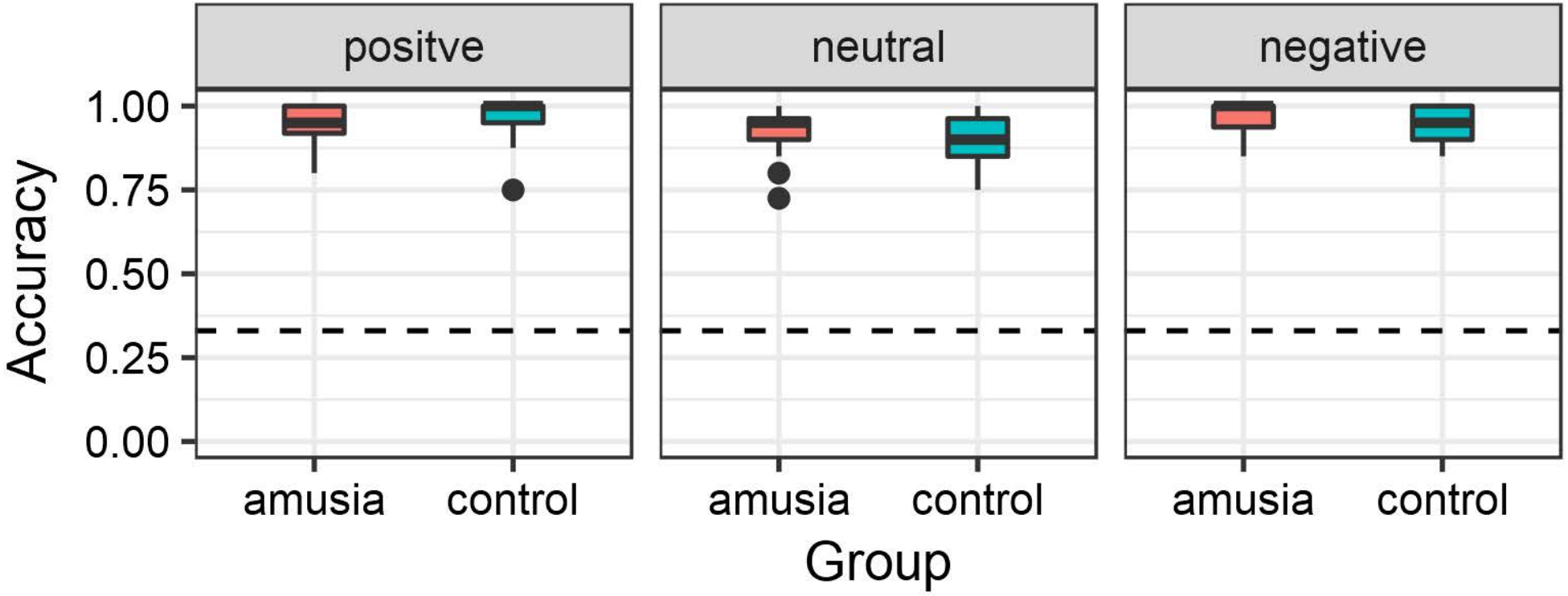
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Group