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Revisiting visuo-spatial processing in individuals with congenital amusia

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Abstract

Congenital amusia is a lifelong developmental disorder of pitch, not only specific to music. Several studies have explored whether amusia impacts spatial processing, as pitch perception is associated with spatial representations in nature. However, to date, the results were still inconclusive, with some researchers claiming amusics have general spatial processing deficits while others not. To better understand this question, the present study examined some basic capabilities of spatial processing via Corsi Blocks task and the mental rotation task. Additionally, it has been documented that the processing of spatial representations normally shares cognitive mechanisms (e.g., the perception of magnitude precision) with melody memory, a pitch short-memory (span) task was also conducted. Eighteen amusics and 18 controls participated in the experiments. The results showed that in Corsi Block task, amusics' performances were comparable to the musically intact controls, suggesting that amusics possess intact visual short-term memory. However, poorer performance on the mental rotation task indicates that amusics have poor spatial awareness. Furthermore, the results also showed a strong association between pitch memory capacity and mental rotation accuracy, confirming that they shared certain underlying cognitive mechanisms like the perception of magnitude precision, probably contributing to their deficits in pitch memory and spatial processing.

Index Terms: congenital amusia, spatial processing, pitch short-term memory, visual short-term memory

1. Introduction

Most humans are born with the potential to perceive, appreciate, and produce music, without conscious effort and musical training [1], [2]. Despite a lack of musical training, adults display a high-level competence in musical perception, memory, and production [3], [4]. However, a few individuals are profoundly impaired in the musical domain without having any other hearing difficulties [5] and brain injury [6]. This disorder is termed congenital amusia (henceforth, amusia) [7]. And it is estimated that approximately 1.5% of the population suffers from amusia [8].

Amusia is a lifelong developmental disorder involving difficulty in processing certain aspects of music which has generally been associated with pitch discrimination deficits [9] and sometimes with temporal processing deficits regarding meter [10]. Individuals with amusia also have difficulties in discriminating melodies without lyrics, and are unable to identify tunes, as well as exhibit impaired performance on tasks involving pitch height discrimination [11]. In addition, strong evidence showed that amusics suffer from a broad disorder of processing fine-grained pitch features [11] that has the effect of disrupting downstream musical processing, for example, melody [12]. Researchers have found that amusia affects pitch pattern/direction and pitch memory, which is a building block for the representation of melodic contour [13]. In sum, the core deficit in amusia concerns the processing of pitch.

In the meanwhile, numerous studies also investigated the relationship between music and other domains in amusia, such as speech, memory, and visuo-spatial abilities. The impairment of language in amusics is mainly manifested in lexical tone perception [14], [15], intonation processing [16], [17], and emotional status identification [18], in which pitch widely serves as a cue. In addition, amuiscs show deficits in short-term memory for nonverbal, auditory sequences [19]. This deficit has been linked to anomalous fronto-temporal connections [20], which could hinder the process of integrating pitch sequences that play an important role in melodic and speech perception. These findings provided strong evidence supporting that amusics have deficiencies in speech processing and memory.

However, the studies on the association between musical processing and spatial skills in amusics have shown conflicting results. For example, Douglas and Bilkey [21] reported that amusics performed worse on a classic mental rotation task compared to musically normal participants. This apparent deficit in spatial processing suggested that amusics had a problem with a shared mental representation of pitch and space [21]. However, Tillmann et al. [2] replicated the task and found that the performances of amusics did not differ from controls, indicating that neurocognitive impairment in amusia does not influence spatial processing. Similar null results were also found in the study of Williamson et al. [22]. Based on these results, it seems that the different performances of amusics on the mental rotation task were a key factor attributing to the inconclusive findings regarding their spatial processing. According to the analysis of the three studies, the mental rotation in Douglas and Bilkey's study [21] was more challenging than the two others, as it involved the unfamiliar rotation degrees, such as 20°, 40°, 80°, 100°, 140°, as well as 160°. Apart from this, Tillmann et al. [2] and Williamson et al. [22] seem to underappreciate the correlation between the results of both the mental rotation and the melody memory found in Douglas and Bilkey's study [21]. Based on these findings, the current study aims to revisit the hypothesis that there is a correlation between pitch and spatial processing in amusia.

The hypothesis of an association between pitch and space can date back to Stumpf [23]. Several studies suggested the relationship between pitch height and vertical location [24], [25], i.e., higher-frequency pitches were assigned to right/up

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positions and lower-frequency pitches were assigned to left/down position in mental space [26]. The research of Rusconi et al. [27] demonstrated that pitch height was internalized as a spatial representation that affects performance and cognition and termed it the Spatial-Musical Association of Response Codes (SMARC) effect. In light of these findings, representations of pitch may be fundamentally spatial in essence. Furthermore, it has been documented that musical expertise could improve visuo-spatial processing [21]. Therefore, it warrants a study to revisit the question about whether amusia represents the part of the population with deficits in spatial processing.

Spatial processing is defined as the ability to perceive and intergrade information related to spatial location [28] including spatial location memory, object orientation recognition and dynamic spatial transformations [22]. Therefore, two visuo-spatial tests would be utilized to investigate these capabilities of spatial processing in amusics. To test the memory for a sequence of spatial locations, we conducted Corsi Block task used by Williamson et al. [22], as it meets the demands for measuring this capability by increasing the length of the sequence and presenting squares at different locations [29]. Additionally, we adopted the mental rotation task used by Tillman et al. [2] and Williamson et al. [22] to assess the abilities to recognize object orientation and interpret dynamic spatial transformations. Because its processing involves the reasoning basis of spatial processing, consisting of spatial representation and location, motion representation, as well as dynamic analysis [30]. Furthermore, a pitch short-memory (span) task was carried out to explore whether pitch and visuo-spatial have a shared cognitive framework. Based on these findings, we expected to observe poorer performances of amusics than controls on one or other of these two visuo-spatial tasks, allowing us to better determine the nature of any potential spatial processing impairment in amusia.

2. Method

2.1 Participants

Table 1: *Demographic characteristics of the amusic and control participants*

Characteristic	Amusics	Controls
Male / Female (Total)	11 / 7 (18)	12 / 6 (18)
Age (Range)	23.3 ± 3.3 yr (19-33 yr)	20.5 ± 2.5 yr (18-26 yr)
MBEA, Mean (*SD*)		
Scale	59.9 (7.7)	96.2 (3.4)
Contour	61.7 (10)	95.9 (3.5)
Interval	59 (8)	95.2 (4.5)
Rhythm	71.5 (13.5)	96.4 (3.4)
Meter	50.7 (17)	84.2 (14.3)
Memory	76.4 (12.3)	96.3 (5.7)
Global	63.1 (6.6)	94.1 (3.1)

A total of 36 participants (18 amusics and 18 matched controls) took part in all aspects of the experiment. They were all native Mandarin speakers, right-handed, and with no hearing impairment or neurological illness. Additionally, none had any background in musical training. Amusics and controls were selected according to the Montreal Battery of Evaluation of Amusia (MBEA) [31]. It consists of six parts: three of them are pitch-based tests (Scale, Contour, Interval), two of them are duration-based tests (Rhythmic and Metric Tasks), and the last one is Memory Task. In the MBEA test, none of amusics scored higher than 70 in the global score, which is the mean of all six subtests, whereas all controls scored 89 or higher. Amusics' global scores were significantly lower than controls', $t(34) = 18.03$, $p < 0.001$, based on independent-sample t-tests. Furthermore, amusics also performed significantly worse in all subtests than controls (all $p < 0.001$). Participants' characteristics are summarized in Table 1. For this study, all participants provided written consent forms for review and approval by the Human Subjects Ethics Sub-committee of Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences.

2.2 Pitch short-term memory (span) tasks

Prior to the visuo-spatial tasks, the short-term pitch memory span test was administrated to all participants. For a description of the design and procedure of this task, please refer to the study of Williamson and Stewart in 2010 [32].

2.3 Visuo-spatial tasks

2.3.1 Corsi Blocks task

Design. This task was adopted from Orsini et al. [33]. Nine irregularly positioned blue squares were arranged at fixed points on the black screen in order to create a similar Corsi board.

Procedure. The procedure ran on PEBL [34]. On each trial, the squares would be lit up one at a time in sequence. Then participants were instructed to click on each square in the same order that they were given. The Procedure started with a sequence length of 2 and each sequence length was presented with two trials. The length of the next trial would increase by one whenever participants got at least one of the two trials of a given length correct. If participants incorrectly recalled two sequences of a given length or if two sequences of the length of 9 were correctly recalled, the test would stop. This span score was automatically calculated. Before the formal test, participants were given three practice trials at the length of 3 to familiarize them with the procedure.

2.3.2 Mental rotation task

Design. The stimuli were derived from a collection of 3D jpeg images create using the original Shepard-Metzler figures [35]. The experiment consisted of 32 trials in which two jpeg images are displayed on screen side-by-side. On half of these trials, the two images were identical (hereafter same trial), but on the other 16 trials, the two images were mirror images (hereafter different trials). In both the same and different trials, 16 original images were selected at random; four images rotated by 0°, four rotated by 60°, four rotated by 120°, and four rotated by 180°. Each rotation degree contains four images, of which two rotate in x axis and two in y axis. Four additional trials (one at each degree of rotation; two in x axis, and two in y axis) was created to serve as practice trials to familiarize the participants with the procedure.

Procedure. The experiment ran on MATLAB (2016). The participants were instructed to determine whether the two images were the same or different by pressing "F" (same) or "J" (different) on a keyboard. Images were defined as "different" if rotation could not align them. On each trial, a central fixation was displayed for 3000ms and were then presented with two images. After making the response, participants pressed the spacebar, then the next trial will begin. Following the practice trials, each participant was instructed moved to the main task. The trials' order was randomized for each participant and no feedback was provided regarding accuracy or response time (RT). The whole process of the experiment took approximately 20 minutes. Results were collected in terms of accuracy and RT.

2.4 Data analysis

For short-term pitch memory task and Corsi Blocks task, span score was analyzed. Span score referred to the length of a sequence that a participant can remember. For mental rotation, accuracy and RT were analyzed. Accuracy was the number of correctly identified trials per participant. RT was determined by measuring the offset of the trial until a response was made by a participant.

Independent-sample t-test was conducted on the pitch short-term memory span and Corsi Block span (visual short-term memory span). For accuracy of mental rotation, general linear mixed-effects models were fitted. In our model selection process, we used backwards elimination of non-significant effects. In the full model, *group* (amusics and controls), *rotation degree* (0°, 60°, 120° and 180°) and *axis* (*x* axis and *y* axis) were fixed factors, as well as interaction between them, and random effects were intercepts of *subject, gender,* and *pair type* (same and different). Based on Bayesian Information Criterion (BIC) values and Akaike Information Criterion (AIC) values, the optimal model was estimated. For statistical analysis of mental rotation's RT, linear mixed-effects models were computed. The procedures were same as those described in the above. The analysis above were performed with R (R Core Team, 2014), using the *lme4* package, *emmeans* package, and the *tidyverse* package. Finally, correlation coefficients analysis was performed among the three tasks using *BruceR* package.

3. Results

3.1 Pitch Short-term Memory Task

For the average pitch short-term memory span, the amusic group (M = 5.35, SD = 1.76) showed a significant smaller capacity of pitch memory than controls (M = 7.10, SD = 1.47) $t(34) = 3.23$, $p < 0.01$.

3.2 Visuo-spatial tasks

3.2.1 Corsi Blocks task

For the average group performance data of Corsi block task, no significant group (amusic M = 5.92, SD = 0.974; control M = 6.03, SD = 0.992) difference was found for this task $t(34)$ = 0.34, p = 0.73.

3.2.2 Mental rotation task

Figure 1 shows the mental rotation task accuracy of amusics and controls. The optimal model for its data analysis included *group, rotation degree, axis* and two-way interaction between *rotation degree* and *axis* as fixed effects, and *subject* and *pair type* as random effects. The results showed there were significant main effects of group, $\chi2(1) = 8.4647$, $p < 0.01$, rotation degree, $\chi2(6) = 56.879$, $p < 0.001$, and axis, $\chi2(4) = 28.311$, $p < 0.001$. The two-way interaction between rotation degree and axis was also significant $\chi2(3) = 12.274$, $p < 0.01$. Post hoc analysis of the interaction between rotation degree and axis were performed using *emmeans* package in R. For the accuracy on rotated around *x*-axis, the results revealed that there were significant differences about images rotated by 0° and 180° (p < 0.0001), images rotated by 60° and 180° (p < 0.0001), as well as images rotated by 120° and 180° (p < 0.01), and slight difference between images rotated by 0° and 120° (p < 0.05). For the accuracy on rotated around *y*-axis, however, only images rotated by 0° were slightly different from those with images rotated by 120° (p < 0.05). Apart from these, there was a significant different in accuracy for the 180-degree rotation of the image around *x*-axis and y-axis (p < 0.0001). No other effects were significant.

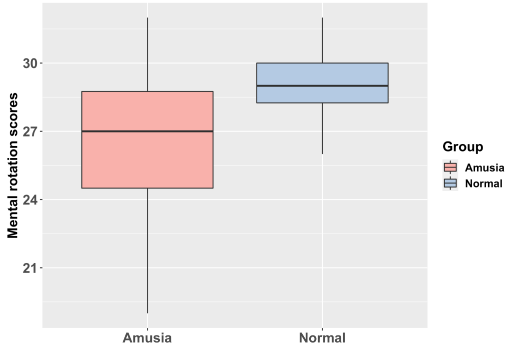

Figure 1: *The mental rotation accuracy of the amusic and control groups.*

Figure 2 shows mental rotation RT of amusic and control groups. The appropriate model for its data analysis included *group*, *rotation degree, axis* and three-way interaction were all included as fixed effects, with *subject* as random effects. It was found that group ($\chi2(8) = 22.533$, $p < 0.01$), rotation degree $\chi2(12) = 124.66$, $p < 0.001$, and axis ($\chi2(8) = 66.266$, $p < 0.001$, had significant main effects, and the three-way interaction was also significant ($\chi2(10) = 45.2$, $p < 0.001$).

Post hoc analysis (*emmeans* package) indicated that RTs in the aspect of rotation degree differed significantly between images rotated by 0° and 60° (p = 0.0001), 0° and 120° ($p < 0.0001$), 0° and 180° ($p < 0.0001$), as well as 60° and 120° ($p < 0.0001$). Also, there was a slight difference between 60° and 180° ($p < 0.05$). No other effects were significant.

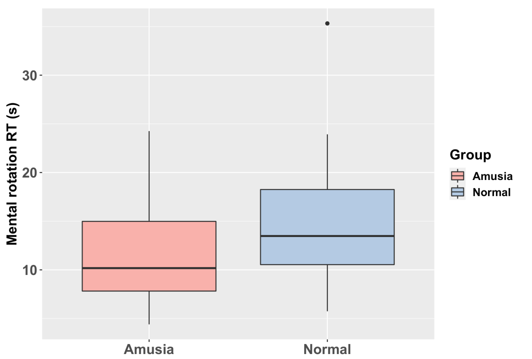

Figure 2: *The mental rotation RT of the amusic and control groups.*

3.3 Correlation results

There was a significant correlation between short-term pitch memory span and mental rotation task (r = 0.34, p = 0.046), while no correlations between short-term pitch memory span and Corsi Blocks task (r = 0.26, p = 0.121), as well as Corsi Block task and the mental rotation task (r = 0.03, p = 0.858).

4. Discussion

It has been documented that pitch height is related to space in fundamental mental representations in the brain [26]. According to this hypothesis, individuals with amusia who are with pitch perception disorders might also encounter problems with spatial processing. The present study employed two widely-used tests (Corsi Blocks task and the mental rotation) to assess the basic competencies involved in spatial processing in amusia. We found no difference between amusics' and controls' performance on Corsi Block task. However, for the mental rotation task, there were notable differences in accuracy between them which indicated that amusics suffered from difficulty with spatial processing.

For the visual short-term memory, we provided evidence that amusics performances were comparable to controls. The results were in line with the study of Williamson et al. [22]. In addition, similar results were found by Schaal et al. in 2015 [35] using Devanagari letters. The procedure of this task was consistent with the pitch memory task designed by Williamson and Stewart [32], in which participants were instructed to discriminate whether the letter-sequence pairs were identical or different. The findings confirmed that amusia established intact visual memory in the cognitive domain.

On the other hand, the present study suggested that there were no correlations between pitch memory span and visual memory span, therefore it might be two distinct memory patterns between them. Visual working memory can be defined as the ability to retain the amount of visual information. Its mental representations could position, shape, color, and text information [36], depending on the task and the kind of pattern, and this information also largely determines the visual working capacity [36]. While pitch as a specific aspect of musical processing, F0 is the underlying form that can be mapped into space through vertical or horizontal dimensions [27], namely, higher frequency pitches were assigned to right/up locations and lower frequency pitches were assigned to left/down location. According to these findings, we proposed that the cognitive processing mechanisms of visual and pitch working memory do not share the same underlying mental representations, and their processing is based on two distinct types of mental representations.

For the accuracy of the mental rotation task, amusics performed worse than controls, which was consistent with the results of Douglas and Bilkey's study, but incongruent with Tillmann et al.'s and Williamson et al.'s. This result indicated that individuals with amusics have poor spatial awareness [21]. In addition, Nunes-Silva et al. observed that individuals with amusia consistently underestimated the spatial magnitude of numbers on all scales in the number line task which evaluates spatial representation of magnitudes and they showed significantly worse performance on the symbolic magnitude task which evaluates the access to the internal representation of the magnitudes from symbolic notation [37]. Besides, strong evidence indicated that pitch perception deficits are caused by a general disorder of processing fine-grained pitch features [38] which has negative effects on pitch information during memory processing [39]. According to ATOM theory (a theory of magnitude) [40], both spatial magnitude representation and fine-grained pitch are a part of a generalized magnitude system that involves an individual's perception of magnitude precision. Given these findings, it appears that amusics' poor ability in magnitude precision leads to their deficits in pitch memory and spatial processing.

It is notable that there were significant positive correlations between pitch memory capacity and mental rotation accuracy in amusics, providing some evidence for Douglas and Bilkey's finding that spatial processing was related to melodic memory [21]. These findings confirmed that the cognitive mechanisms involved in the visuo-spatial processing are also utilized by pitch/melodic memory in the auditory modality. As mentioned, the ability in magnitude precision is likely shared by pitch memory and spatial processing in the cognitive system. Based on these findings, it is not difficult to comprehend the strong association between these two tasks.

Moreover, amusics' performances did not differ from controls in the two critical local domains of the rotation degree and rotation axis in the mental rotation task. Tillmann et al. and Williamson et al. also reported similar results which suggested that amusics might possess some capabilities related to the organization of object orientation and dynamic spatial transformations in the processing of space [2], [22]. Generally, a math education background would improve one's ability to perceive the precision of numerical representations to some extent [41], although amusics have problems with this ability which has a negative effect on spatial processing related to number representations [37]. Therefore, it doesn't appear too tricky to interpret that Mandarin-speaking amusics performed equally well as musically normal controls on these two aspects in the mental rotation task, since 60°, 120° and 180°, as well as the x-axis and y-axis were particularly familiar general knowledge of mathematics for them which did not require great precision of the magnitude.

5. Conclusions

The present study showed that amusics maintain some capabilities in visual short-term memory, and object orientation recognition, as well as the ability to perform dynamic spatial transformations. However, amusia might have impairments in certain spatial processing, including the perception of spatial magnitude representations which probably was attributed to their low ability of magnitude precision. Therefore, future work will concentrate on this topic to investigate the spatial processing of individuals with amusia cognitively. Taken together, our findings enriched the understanding of visuo-spatial processing abilities in amusia.

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7. References

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