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论文题目： The effect of environmental acoustic enrichment and light deprivation on sound localization

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## Summary

In recent years, cross-modal plasticity has been a popular topic in the field of cognitive neuroscience. In visually impaired and blind individuals, this is a topic of particular interest as plasticity allows improved interpretation of auditory stimuli and localisation of sound in the absence of visual cue. Pioneer studies performed by Boroojerdi et al. found that in normally sighted individuals, the primary auditory cortex can be activated after 45 minutes' visual deprivation using Transcranial Magnetic Stimulation (TMS) (Boroojerdi et al., 2000). The auditory system adapts to a range of changes in the blind, the myopic and normal sighted individuals. (Dufour et al.,2000, Lewald et al.,2007). It has been suggested that in the absence of visual input, the occipital lobe recruit auditory nerves. However, currently there are limited research on how different acoustic environments can affect individual's ability to localize sound following visual deprivation. This study shows that environmental acoustic enrichment triggers a marked improvement in sound localization in visually deprived individuals. A 2×2 factorial experiment was designed using classic music as an enriched acoustic environment. Our results show that there is significant improvement in sound localization when visually deprived individuals are exposed to this environment. This is not seen in individuals exposed to normal background acoustic environment. In addition, there is an increase in errors in sound localization peripheral azimuths, compare with central azimuths, consistent with existing literature.

**Keywords:** sound localization, environmental acoustic enrichment, cross-modal plasticity

# Content

# Introduction

In the past decades, there has been extensive research in how blind individuals adapts to their environment, including changes in the processing of auditory, tactile stimuli, their short-term memory, etc. It was long believed that the whole sensorium degenerates in the blind. However, recent evidence, most notably from three-dimensional spatial mapping tasks performed by blind and sighted individuals showed that the blind with no residual vision showed comparable, or even better performance in these tasks, especially in those requiring mono-aural abilities (Lessard et al. 1998). This study showed that vision is not an imperative for auditory spatial localization, and that blind people develop compensation for their absence of vision.

During the past few years, studies in auditory spatial localization ability in the blind progressed rapidly. Substantial neurocognitive evidence emerged via neuroimaging. Transcranial magnetic stimulation (TMS) is one of the most established methods to elicit the underlying mechanism. Using TMS, Cohen et al. showed that despite the fact that blind individuals could not see, the occipital lobe responsible for optesthesia, remained active (Cohen et al., 1997). It was suggested that the occipital lobe recruit non-visual nerves to provide a compensation for the loss of vision. This is an example of cross-modal plasticity and requires extensive remodelling (nerve growth factors, microenvironments, etc.) and long-term adaptations in the cerebral cortex.

Cross-modal plasticity exists in all individual and lifelong visual deprivation is not a prerequisite for superior auditory spatial localization. A vast majority of the previous studies chose sighted people without being blindfolded as control, comparing with the blind. However, for a sighted individual, his or her other perceptual and non-perceptual consciousness can help with localizing sound, and the difference observed in auditory spatial localization would be confounded. Eyes, for example, serve as an aid of the trunk while turning around even though subjects could not see the exact place of the sound source (Tabry et al. 2013).

Short-term visual deprivation enhances the auditory concept of space. Through neuroimaging, scientists have detected an increase in the sensitivity of visual cortex to light stimuli after as little as 45 minutes' visual deprivation (Boroojerdi et al. 2000). Further experiments showed that in sighted individuals, being blindfolded and deprived of visual stimulation for as little as five-day, the brain adapts in a similar manner as those who are born blind (Kauffman et. al 2002), although the adaptation disappears within a day of regaining normal vision. Other studies have shown that both the born and early blind develop compensatory mechanisms. Even acutely myopic individuals could form preeminent space concepts just like blind individuals (Dufour et al. 2000).

Lewald et al. have found that in sighted individuals, short-term visual deprivation led to better auditory spatial localization abilities, whilst individuals were exposed to an "acoustically enriched environment" created by chatting (Lewald et al.,2007). It was however, unclear whether acoustic enrichment contributed to enhanced auditory spatial localization. We wanted to investigate whether the type of auditory environment in visually deprived can affect their auditory spatial localisation abilities.

This study is based on the pilot study before submission in 15th September 2017, from which the experimental procedure and data analysis approaches were applied. However, the previous study was refined by using within-subjects design rather than between-subjects. This new design eliminates the effects of individual difference in abilities of acoustic localization. The design also aims to weaken the impact of interaural distance on the result by increasing the distance between loudspeaker and subjects. A new study was conducted, and this article would concentrate on the effect of environmental acoustic enrichment and light deprivation for each individual.

# Methods

## Participants

This is a controlled experiment with 6 student volunteers, 4 girls and 2 boys (mean age 15.8 years, range 15-17 years). All participants are right-handed healthy middle school students with normal or corrected-to-normal vision, and no history of neurological disease. Audiometric assessments were performed for all participants and showed normal and comparable hearing in both ears. They gave written consent for taking part in the experiment. A guideline was given, including a brief introduction of the experiment and the rules they needed to obey.

## Equipment

The experiment was conducted in a sound-proof and anechoic room. For each participant, his/her ears were adjusted to the height levelled with the speakers used in the experiment.

A laser pointer was fixed to a bicycle helmet, calibrated to point to the line of zero azimuth while the participant sits up straight, with the back firmly against the chair. 6 identical blindfolds with were given to subjects previously, no light was reported to be perceived under normal illumination. Acoustic stimuli were 1kHz, -6dBFS×10 times, duration 0.4 s, generated from the website *wavtone.*

Large blank panels were mounted on the floor, forming a semicircle with radius of 2 m with the centre, which is the midpoint of the subject's interaural segment. The positions with a constant angular separation of 15 ° where acoustic stimuli were played were marked on the top of the panels. One position was straight ahead of the subject (named "zero point"), 6 were on the left, and 6 were on the right (Fig. 1.). During sound localization sessions, the experimenter, wearing soft-soled shoes, moved loudspeaker to different marked points to play acoustic stimuli.

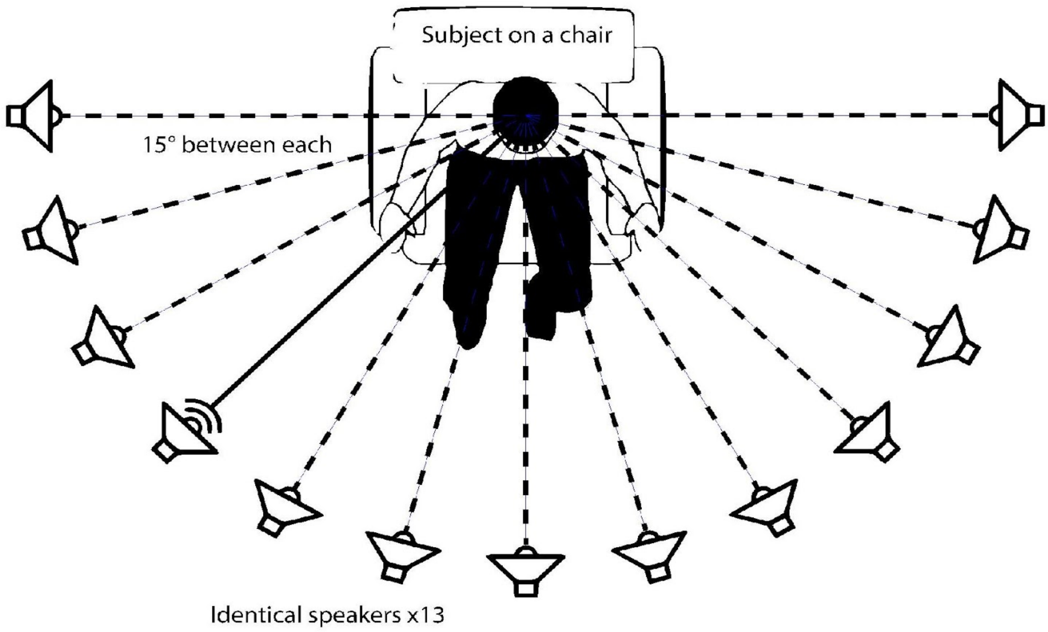
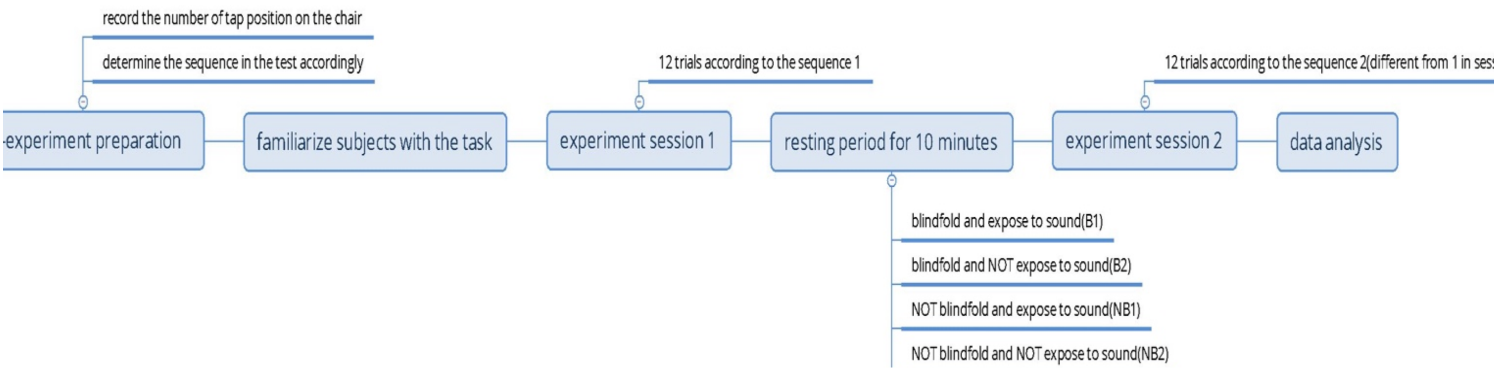



Fig. 1. Subject and loudspeaker




a diagram showing the procedure of the whole study

## Procedure

Each subject was tested in four separate experiments in all, Blindfolded Experiment 1(B1), Blindfolded Experiment 2 (B2), Non-blindfolded Experiment 1 (NB1), and Non-Blindfolded Experiment 2 (NB2). Experiment 1 refers to B1 and NB1, Experiment 2 refers to B2 and NB2, Experiment B refers to B1 and B2, Experiment NB refers to NB1 and NB2. All the four experiments for each participant consisted two sound localization session and a resting session, Experiments differed only in the latter. The whole experiment was videotaped, from which raw data were collected.

**Sound localization session:**

All participants wore blindfold during the two sound localization sessions. Each session consisted of each participant being tested on 12 points. Prior to the experiment, sound stimuli were played at zero point by one experimenter, and subjects were asked to turn their heads toward their dead ahead, while another experimenter adjust the helmet accordingly, until the laser point directly at the marked zero point.

Stimuli positions changed in pseudorandom orders set previously in each session (Fig. 2.), the sequence in session 1 (sequence 1) was different from that in session 2 (sequence 2). Each sound localization session began with a sound stimuli from zero position, followed by the sound burst to be localized. Before experiment, all the participants were told to turn their heads toward their perceived sound source. They were allowed to turn their shoulders, but movements of legs and feet were not permitted. At each position, participants had three seconds to respond, and were asked to hold their heads for a second, after which the experimenter would guide the participant to return to zero point to start a new trial. Therefore, 0 degree was the set point and was not included in statistical analysis. Azimuths were collected by watching back the video and all the data were recorded in Microsoft Excel.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sequence A | -75° | -30° | +60° | +15° | -15° | +75° | -60° | -90° | -45° | +45° | +90° | +30° |
| Sequence B | -30° | -60° | -75° | -15° | +90° | +60° | +75° | +45° | -30° | +15° | -45° | -90° |

Fig. 2. Table of stimuli position sequence in two sessions

**Intervention: blindfold and environmental acoustic enrichment:**

After the first sound localization session, participants were given a 10-minute resting period. A factorial design was used, factors included were blindfold vs. non-blindfolded (Experiment B vs. Experiment NB), exposed to classical music vs. not exposed to sound (Experiment 1 vs. Experiment 2). In Experiment B, participants wore the blindfold during the resting period; while in Experiment NB, participants did not wear blindfold during the resting period. During the resting period of Experiment 1, participants were guided to a soundproof room (resting room 1) with melodious classical music in the background playing at 50 dB, providing environmental acoustic enrichment; while in the resting period of Experiment 2, participants were guided towards another sound-proof room (resting room 2) and asked to put on earplugs. Between sessions 1 and 2, all subjects were kept awake and supervised by the experimenter.

# Results

Data was recorded and analysed with Microsoft Excel 2015. The average of three repetitions were calculated. Deviation from the true value was determined as "loss" of accuracy of localization (unsigned). + and - at the same absolute azimuth was considered to be of the same effect and were combined for analysis (the absolute azimuth n° refers to both position +n° and -n° hereinafter). Non-paired two tailed T-tests assuming equal variance were used to analyse differences in the means. Significance level set as $p<0.05$.

## Mean loss

Mean loss of each Experiment was calculated and compared for each absolute azimuth in both sessions, totalling 6 azimuths × 4 Experiments × 2 sessions. Mean loss for each azimuth were compared in pairs, using non-paired two tailed T-test.

Mean loss increases as stimuli move from central (15°) to the most peripheral (90 °) position on average (Fig. 3.) indicating that people localized central auditory stimuli better than peripheral ones. Particularly, mean loss in 75° (=6.375) differs significantly from that in 30° (=4.354, p=0.00269) and that in 15° (=3.083, p=0.000293). Similar picture can be seen the comparisons between mean loss in 60° (=5.802) and 30° (p=0.0315) as well as 15° (p=0.00226).

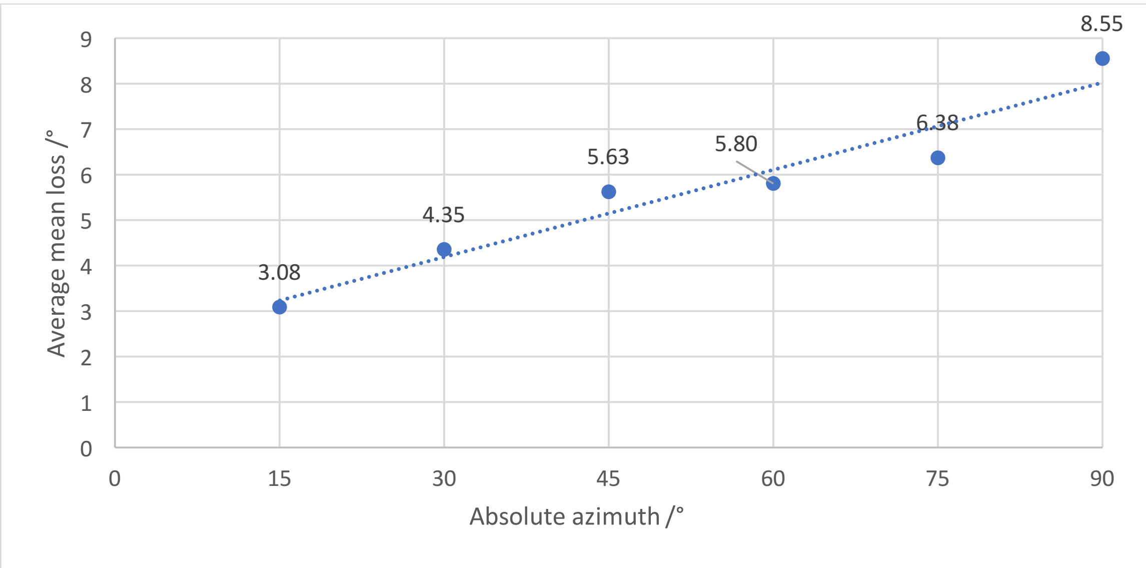



Fig. 3. Average mean loss for each azimuth.

## Delta loss

The loss in session 1 was subtracted from loss in session 2 to get the value delta loss (signed), showing improvement or regression after the intervention of different acoustic environment and visual deprivation. Delta loss for each absolute azimuth were also calculated (6 azimuths × 4 Experiments × 6 participants). All the statistical comparisons of delta loss were made in pairs, totalling 6 pairs (B vs. NB, B1 vs. B2, NB1 vs. NB2, 1 vs. 2, B1 vs. NB1, B2 vs. NB2).

Delta loss in Experiment B (B1 & B2) differs significantly from that in Experiment NB (NB1 & NB2) at peripheral azimuths, 90° (p=0.0226), 75° (p=0.0467), 60° (p=0.0346). In all three cases, the progress made in sound localization accuracy of Experiment B was greater than that in Experiment NB (Fig. 4.1.), which demonstrates a specific effect of light deprivation on acoustic spacial localization.

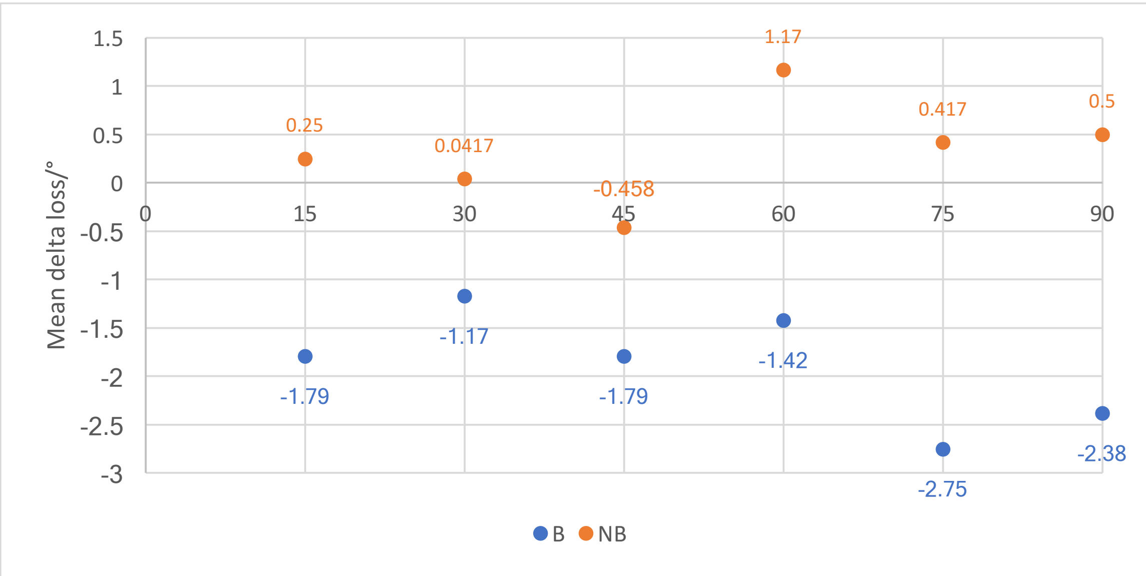



Fig. 4.1. Mean delta loss of Experiment B & NB for each azimuth.

Delta loss of B1and NB1 differ significantly at 90° (p=0.0500), 75° (p=0.0460) (Fig. 4.2.). Mean delta loss in B1 (= -2.76) is less negative than NB1 (= -0.667), which means whilst both Experiments were exposed to an enriched acoustic environment, being blindfolded contributed to improved acoustic localization, especially in peripheral and central azimuths.

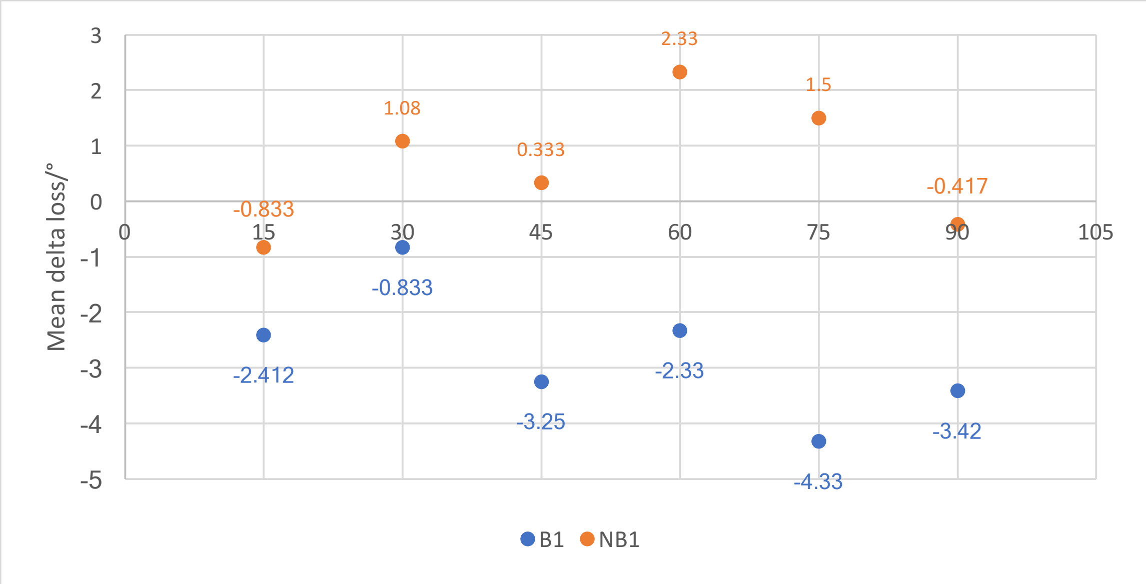



Fig. 4.2. Mean delta loss of Experiment B & NB for each azimuth.

As for Experiment B2 and NB2, participants received no acoustic stimulation (p=0.0403). At 15°, B2 showed significant improvement in sound localization compare to NB2, independent of the acoustic environment they were exposed to.

Comparing Experiment 1 and 2, the former showed significantly better sound localization than the latter (p=0.0459) at 90°. Whilst blindfolded, being exposed to an enriched auditory environment improves sound localization (Experiment B1 vs. B2), suggesting an enriched auditory environment could benefit constructing better spatial concept. (Fig. 4.3.) No significance was seen between Non-Blindfolded Experiments, NB1 and NB2.

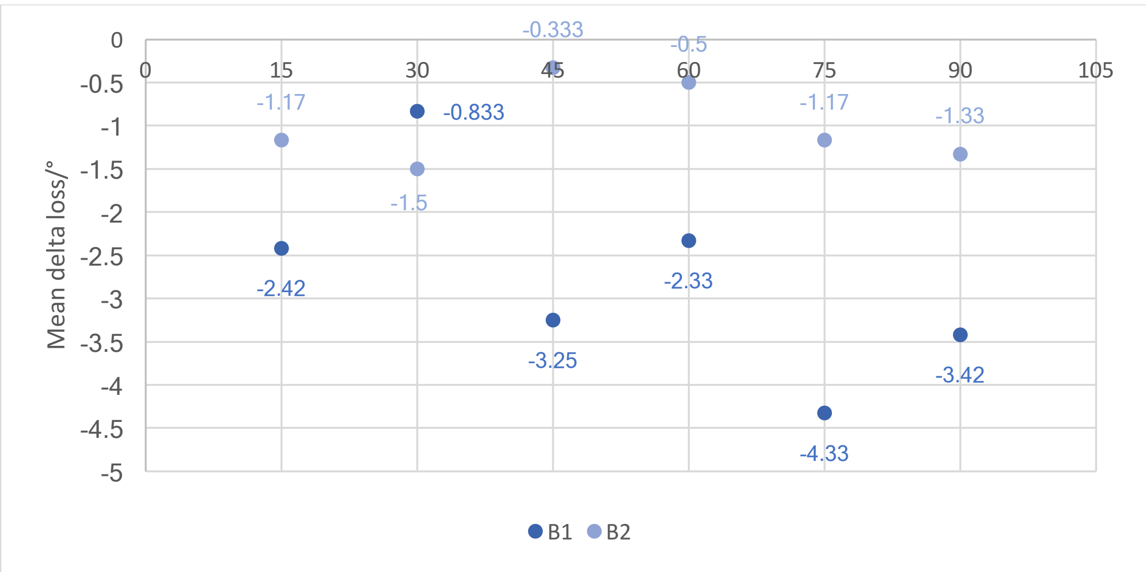



Fig. 4.3. Mean delta loss of Experiment B1 & B2 for each azimuth.

Visual deprivation affects auditory spatial localization especially in peripheral azimuths, regardless of the auditory environment the individuals were exposed to. Although, this is the most evident in blindfolded individuals exposed to classical music. Besides, subjects' responses to central auditory stimuli were better than peripheral stimuli, a universally observed phenomenon unaffected by visual deprivation or the acoustic environment.

# Discussion

## Better performances in central azimuths

The finding that sound localization is more accurate in central than peripheral positions were shown in other studies (Tabry et al. 2013, Lewald 2002) as well as our previous study. It was considered as a systematic error owing to the limitation of truncal rotation and also a potential impact of interaural distance. Even though we applied greater distance (2m) than our previous study, poorer performances in peripheral location are not eliminated. Further studies could use a semicircle with a range of radius, to investigate deeper its effect on peripheral acoustic localization.

## Visual deprivation on auditory spatial localization

This study is consistent with studies performed by Lewald et al. and Boroojerdi et al. (Lewald et al.,2002, Boroojerdi et al.,2000). Boroojerdi further showed that after 45 minutes of visual deprivation, auditory localization improved and correlated with higher excitability of the primary visual cortex. The result also confirmed the conclusion in the previous study that visual deprivation is the prerequisite of making marked progress in sound localization, and the acoustic environment whilst acclimatizing to being blindfolded could further improve sound localization.

One possible explanation is that peripheral auditory stimuli increases the total distance of the stimuli from the two ears, and the interaural distance begins to influence spatial localization. It has been suggested that in the horizontal plane, sound localization is dependent on the time difference the auditory stimuli arrives at each ear (Letowski T.R. et al. 2012).

On the other hand, this observed improvement limited to peripheral locations could be an artefact, mainly due to the small sample size of 6 participants. What's more, the stimuli itself cannot be regarded as a point, and the use of a laser pointer can magnify small, unintended deviations and is unreliable for this purpose (Tabry et al. 2013). For future studies, we aim to use computer programs and facial sensors to record localization, and improve the reliability of the recordings.

## Acoustically enriched environment on auditory spatial localization

We found subjects had the most significant improvement in sound localization in the Experiment, during whose resting session they were visually deprived and exposed to acoustic enriched environment. Two possible mechanisms may contribute to this phenomenon.

The first mechanism maybe that environmental acoustic enrichment improves sound localization, independent of visual deprivation. Numerous previous findings showed that classical music can induce positive emotions and activate limbic areas of the brain. This may enhance cross modal plasticity and improves the function of the auditory system, as shown in animal models (Beament et al. 2001, Gottfried Schlaug et al. 2005, Kilgard et al.1998, Weinberger 2007). When subjects are not visually deprived, classical music does not pose significant positive influences on sound localization as demonstrated in Experiment NB1 and NB2. This suggests the possibility that the acoustic environment and visual deprivation acts synergistically on sound localization. This should be investigated further by using a range of acoustic stimuli to enrich the auditory environment, and observe their effects on sound localization.

Another possible explanation could be that auditory stimuli recruits the visual cortex and enhance the neural connections between the visual cortex and the other cortices, improving sound localization, which has been shown in animal studies (Pascual-Leone et al. 2001, Falchier et al. 2002).

As have been stated by Beament "*the auditory cortex is so complex that the most we may ever hope for is to understand it in principle, since the evidence we already have suggests that no two cortices work in precisely the same way*" (Beament et al, 2001). This experiment has shown that an enriched acoustic environment improves sound localization in short-term visually deprived individuals. This has not been shown in previous studies and should be investigated further. This could translate to targeted rehabilitation for the blind, improving their ability to localize sound, and improve their quality of life.

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# 致谢页

**队员职务介绍：**

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**致谢：**

感谢参与实验的来自人大附中各个年级的同学们

感谢母校人大附中鼓励学生创新研究的开放氛围

**队员介绍：**

邓通，女，初、高中就读于中国人民大学附属中学理科实验班。从初中起，便产生了对自然科学的兴趣，总是自主思考学校课堂中所提到的延伸知识，并养成了一直关注生物学前沿、阅读科学杂志的习惯。高中积极参与学校大学先修及竞赛课程，并在2017年生物学联赛初赛中荣获一等奖，复赛中荣获省级二等奖。她课内成绩优异，曾被评为校级三好学生，“奋进自强”标兵、“突出特长”奖。在校内学习的同时，一直自学Cambridge international教材和大学生物课本，合理运用所学知识获得2017年英国生物竞赛全球银奖。在这些学习中，她加深了对生物学研究及发展的认知，并找到了自己对生物医学、神经生物学更深入的兴趣。此外，她是学校女足队的成员，多次代表学校参与比赛并屡次获奖。她也爱好跳舞，师从于中国踢踏舞王朱海峰老师，并曾两次与其在中国国家大剧院同台表演。

叶博辰，男，初、高中就读于中国人民大学附属中学理科实验班。他爱好科学，擅长创新和自主探究。从初中以来，参与学校机器人社团，自己研究电子工程项目。曾获北京学生科技节电子信息比赛一等奖。2015 年 9 月 24 日成立人大附中电子工程社——一个集电子、机械、网络等方面爱好者为一体的综合性平台。他主动申请学校实验室，领导队友们进行创新研发工作。所做产品曾参与各大比赛，其中在金鹏科技论坛中获得海淀区一等奖。他被选为海淀区少年科学院小院士，并被评为校级“创新人才”。此外，他爱好心理学学研究，曾自学五本心理学书籍，有自己的学科见解。在钻研兴趣的同时，他课内成绩优秀，曾获“学习标兵”称号。在学业以外，他也曾参与校演讲比赛并进入决赛；他还爱好摄影，熟练掌握图片处理软件，作品曾参加“一心一意”美术展。休息时间热爱锻炼，喜欢骑行、羽毛球，熟练掌握各种滑板花式。