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Audio-Corsi: a novel system to evaluate audio-spatial memory skills*

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Abstract— **Spatial memory (SM) is a multimodal representation of the external world, which different sensory inputs can mediate. It is essential in accomplishing everyday activities and strongly correlates with sleep processes. However, despite valuable knowledge of the spatial mechanisms in the visual modality, the multi-sensory aspects of SM have yet to be thoroughly investigated due to a lack of proper technologies.**

This work presents a novel acoustic system built around 3D audio spatial technology. Our goal was to examine if an afternoon nap can improve memory performance, measured through the acoustic version of the Corsi Block Tapping Task (CBTT), named Audio-Corsi. We tested five adults over two days. During one of the two days (Wake), participants performed the Audio-Corsi before (Pre) and after (Post) a wake resting period; while the other day (Sleep), participants performed the Audio-Corsi before (Pre) and after (Post) a nap. Day orders were randomized. We calculated the memory span for the Pre and Post session in both the Wake and Sleep days. Preliminary results show a significant difference in the memory span between the Wake and Sleep days. Specifically, memory span decreased between the pre-and post-test during the wake day. The opposite trend was found for the sleep day. Results indicate that SM can be improved by sleeping also in the acoustic modality other than the visual one.

Clinical Relevance— **The technology and procedure we designed and developed could be suitable in clinical and experimental settings to study high-level cognitive skills in the auditory sensory modality and their relationship with sleep, especially when vision is absent or distorted (i.e. blindness).**

I. INTRODUCTION

The brain must build multimodal representations of the surrounding space to interact with it and to accomplish daily activities such as way-finding and object localization. SM is pivotal in these processes. Moreover, besides having a crucial role in everyday activities, SM strongly correlates with sleep mechanisms. It is well-known that spatial information is processed during sleep. Previous works highlighted improved spatial performance in navigation tasks [1] and the retention of visual spatiotemporal sequences [2] after sleep. Furthermore, sleep consolidates hippocampus-dependent spatial maps and supports the acquisition and maintenance of the spatial relations among the objects within an environment [3]. However, although evidence showed that spatial signals are processed independently from the input sensory modality [4] and that many sensory signals interplay to provide a coherent external world model, SM processes are mainly investigated in the visual domain. One of the procedures most used in experimental and clinical settings for evaluating visuo-spatial skills along with learning disabilities in children, dementia, and other cognitive and neurological diseases or delays is the CBTT [5]. Previous work demonstrated that visuospatial performance measured with CBTT improves after sleep [6]. The CBTT original apparatus consists of a board with nine blocks irregularly arranged on its surface. The experimenter taps to a series of blocks and the subject is asked to repeat the sequence, in the same presentation order, by touching the corresponding blocks. In addition to the physical versions of the task, many computer based-forms of the CBTT have been designed [7] such as the haptic Corsi [8], the walking Corsi [9], and the the e-Corsi [10].

Regarding evaluating memory skills in the acoustic sensory domain, the most common tasks currently employed in clinical practice require the verbal recalling of digits or object names. Examples of these tasks are the *Digit Span forward* and the *Learning Names* (both subtests of the WISC III intelligence test), the *Listening Span task* [11] and the *Word Test for Children* [12]. However, there is still a lack of systems and technologies to evaluate and recover spatial auditory memory skills. The study of the influence of spatiality in mnestic abilities indeed requires specific and complex hardware or software, such as numerous speakers or dedicated virtual acoustics. Along this line, auditory versions of the CBTT mentioned above have been developed through either real speakers or virtual acoustic sources [13] [14] but they required, along with the auditory devices, a visual representation of the board and the squares of the original CBBT apparatus. Consequently, these auditory CBTT are not usable by visually impaired and especially blind individuals.

The current study presents a novel system based on 3D audio spatial technology employed in an audio-spatial memory task named Audio-Corsi (i.e., the acoustic version of the CBTT). We know that sleep improves visuo-spatial memory skills [6], but it is not clear yet whether this is also valid for audio-spatial mnestic abilities. We verified the efficacy of the Audio-Corsi in a task-nap-task paradigm by testing five participants pre- and post-nap and pre- and post-wake rest period. We hypothesized that, as known for visuospatial, also audio spatial performance increases after a period of sleep than a period of baseline, given the supramodal nature of spatial memory processes. The Audio-Corsi device simplifies the procedures and opens up new research and clinical studies, especially in the case of a visual disability (e.g., blindness).

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II. MATERIALS AND METHODS

A. Experimental Setup

The sound spatialization for the Audio-Corsi was created with the 3D Tune-In Toolkit, an open-source library for real-time binaural audio spatialization and for the creation of virtual three-dimensional soundscapes hearable with a pair of headphones [15]. The binaural signal is generated through the convolution between a head-related transfer function (HRTF), and a mono signal. The parameters of the spatialization are programmable within the toolkit. In this study, we did not add reverberation to the rendering and the HRTF employed was measured from a Kemar dummy head mannequin. Furthermore, no head tracker was employed. We used six virtual acoustic sources, in line with previous studies[16], [17], and displaced them according to Figure 1. The sounds were emitted from six distinct locations: forward-right and forward-left locations were simulated by an interaural intensity difference of 7 dB (about 54 and 61dB SPL for the left and right ears). Right and left positions were simulated by an interaural difference of 12dB (approximately 65 and 53dB SPL for both ears), while the interaural difference in the frontal position was equal to 0 dB (about 67dB SPL for both ears). Finally, the back position was simulated with an interaural difference of 2dB (approximately 54 and 52dB SPL for the left and right ear). In a binaural acoustic environment, rear and back sound discrimination is difficult if the sounds are spatially aligned. To solve this issue, we rendered the stimulus in the back location slightly to the right. The spatialization was performed in real time using the Toolkit’s Test Application.

To register the responses, we employed an Arduino-Uno-based keyboard, designed in AutoCAD [17] (see Figure 2 for details) design and developed by ourselves. The six red buttons on its surface, which also hosted the needed electronic components, replicate sounds’ positions in the virtual environment. The blue button in the center matches the head in the Toolkit and is used as the reference point. The keyboard is controlled by an Arduino Uno connected to the PC with an USB cable that allows for serial communication. Arduino Uno logs the button pressed by the user with a pull-down resistor configuration (see Figure 3 for details).

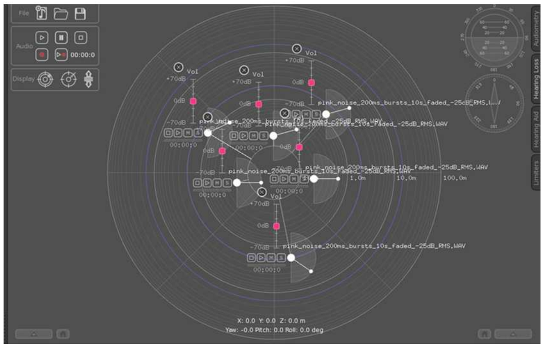

Figure 1: Sounds’ dispositions in the virtual environment.

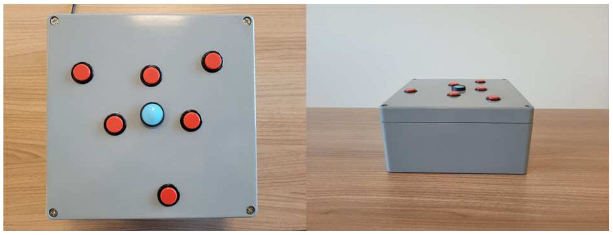

Figure 2. Assembled keyboard. The red buttons represent the positions of the six virtual sounds while the central blue button is the reference point.

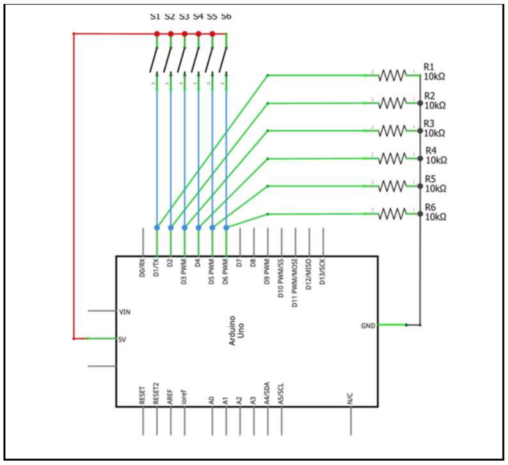

Figure 3. Keyboard circuit schematic.

B. Audio-Corsi

The Audio-Corsi test was inspired by the CBTT [18]. In the Audio-Corsi [16], [17] the participants were asked to repeat sequences of sounds of increasing length. In this work, we used a pink noise sound lasting 2.5 seconds and presented binaurally through the headphones from all six locations. Before starting the experiment, the participants were all blindfolded and asked to touch the keyboard without time constraints. After this first haptic exploration, they started to freely press the six red buttons for three minutes while listening to the corresponding sounds. After each touch, they had to return to the reference point. This exploration served to help the subjects discriminate among the six locations and to reduce localization and perceptual errors in sequence recalling. After the exploration, they listened to the sounds individually and were asked to press the corresponding button to check whether they understood the virtual environment correctly. The test began immediately after this check. The subjects listened to sequences of sounds of increasing length, from two up to nine sounds. They were presented with three sequences per length. If at least one out of the three sequences was correctly recalled, the experimenter communicated the increase in sequence length. However, he did not provide any feedback on participant performance during the task. In the listening phase, they maintained the dominant hand's index finger on the reference point. In the recalling phase, they pressed the buttons with the same finger, following sequence presentations. Even though the test did not have a fixed duration, it lasted 20 minutes on average.

C. Experimental Protocol

Five healthy participants aged between 25-35 years of age were recruited. They reported being free of sleep medications, psychiatric and physical illnesses. They also have a PSQI (Pittsburgh sleep quality index) ≤ 6. All participants were instructed to abstain from alcohol, caffeine, and smoking and avoid physical activity in the morning on the testing days. Moreover, they were asked to go to bed around 11:00 pm at night and wake up around 7:00 am in the morning. All subjects participated in two consecutive days of testing, the wake day and the sleep day, which were randomized between subjects. Three subjects started with the sleeping day, and two with the waking day. All participants performed the Audio-Corsi task, on both days at 1:00 pm and were retested at 3:30 pm after having given their written consent and filled out the Stanford Sleepiness Scale (SSS). They were informed of the day assignment (wake or sleep) after the Audio-Corsi. During the next retention interval, participants lied down for a 90-minute sleep opportunity if they have been assigned a sleep day. Otherwise, participants remained awake in the laboratory and filled out some questionnaires, read, or worked at PC. During the nap, participants slept in a bed placed in a darkened and silent room. They were asked if they had a dream at the awakening. To evaluate the possible correlation between memory performance and dream activities, participants also filled out the Dream Recall Frequency Scale (DRFS), Van Dream Anxiety Scale (VDAS), and some questions about the sensory composition of their dreams. Following a 20 min break, subjects filled out the SSS and were then retested on the Audio-Corsi. During the retest, the exploration phase was removed, and only the check was maintained before the task.

D. Data Analysis

Performance changes were measured by comparing the memory span in the pre- and post-test. The memory span is a neuropsychological parameter for identifying spatial memory skills and deficits. It was calculated considering previously validated procedure [19], [20]. The number of sequences correctly recalled for all sequence lengths was summed and divided by 3 (i.e. the number of trials per sequence length), using the following equation (1):

$$\sum_{i=1}^{9} \#corr.subtrials(i) * \frac{i}{3} \qquad (1)$$

Where i is the sequence length. This is a more sensitive measure than the classical memory span of the length of the longest sequence recalled. Indeed, the correct sequence for each length, counted as 1/3; then, the total number of thirds was added up to provide a span score. We supposed that all participants perform the task with a single sound, so the memory span score is included in the interval from 1 to 45 (the maximum sequence length tested was nine).

III. RESULTS & DISCUSSION

Statistical analyses were carried out in R environment [21]. We compared the mean memory span of pre- and post- test in the both wake and sleep days. We fitted a linear mixed models (LMMs). The model fitting was undertaken using the *lmer* function of the lme4 package [22]. For the LMMs predictors were evaluated using Type III Wald χ2 tests as implemented in the *Anova* function of the car package [23]. We considered memory span as dependent variable. The effects and interactions of day (wake or sleep) and session (per or post) were evaluated in the LMMs. Contrasts of interest were further investigated with the *emmeans* function of the emmeans package [24] by obtaining estimated marginal means (EMMs). Effects were retained as significant when P <0.05 after Bonferroni correction. According to Wilkinson's notation [25], the models fitted, were:

Memory Span ~ Day * Session + (1|Subject)

The results showed a significant Memory Span X Day X Session interaction, χ2(1) = 18.38, P = 0.00002. Post hoc comparisons revealed a lower memory span in the post than pre session within the wake day, t(12) = -3,71, P = 0.003; as well as an higher memory span in the post than pre session within the sleep day, t(12) = 2,36, P = 0.04. Moreover, memory span was higher in the sleep than wake day within the post session, t(12) = 3,61, P = 0.004. Details are shown in Figure 4. Our study reveals that the memory span measured through the Audio-Corsi significantly decreases after wakefulness while increasing after an afternoon nap. Furthermore, we found a significant difference between the Wake and Sleep days, that is, a greater memory span in the post-session of the Sleep compared to the Wake day. These results are coherent with the results obtained with the CBTT [6], thus supporting the supramodal nature of spatial memory processes. Interestingly, four participants reported having a dream during the nap. Previous research associated the increase of spatial skills in post-sleep measured by visual CBTT to REM (rapid eye movements) sleep [6]. However, there is a low probability of reaching the REM stage during a nap, and the low oddity of the reported dream suggested a more non-REM sleep mentation. Considering the already reported relationship between dreams and memory [26], both dream activity and REM sleep could contribute to spatial learning. Further studies with polysomnography (PSG) might investigate these aspects.

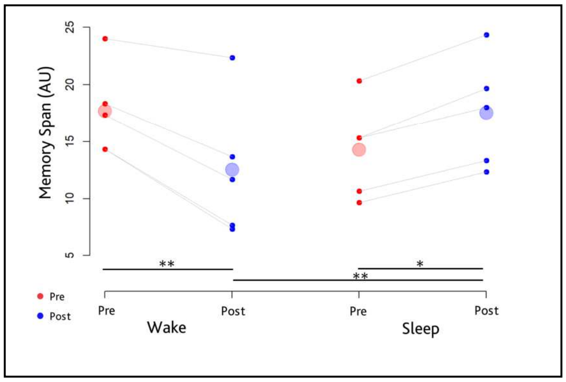

Figure 4. Plot shows the significant interaction between memory span and days and session. The dots represent the memory span during pre and post sessions, respectively red and blue, during the wake and sleep days. The smaller dots represent the single subject results, while the big ones with transparency color represents the mean. The stars represent the significance p value (* = p<0.5, **=p<0.01) after Bonferroni correction of the post hoc.

To verify the relationship between dream activity and spatial performance, in the current study, we correlated the memory span in the different sessions and days with the VDAS, DRFS and sharpness of sensory composition of their dreams in general. However, no significant interactions were found at this level. An increase in the sample will be necessary to deepen these aspects and to confirm the previous results. Future studies could focus specifically on the relation between REM sleep and spatial learning, versus dream activity and spatial learning and if acoustic training could be associated with an increase of occipital spindles cortex, as already seen in the CBTT [2]. This research could be useful to differentiate the sensory-specific reprocessing of information during sleep from the supramodal sleep-mechanisms.

IV. CONCLUSION

The Audio-Corsi is an effective technological solution for investigating auditory SM. Here we validated this paradigm to study acoustic spatial learning after a nap (i.e., a short period of sleep). The results highlighted that this technology could be an innovative solution to open up new research lines, from multisensory aspects of sleep processes to the role of dream activity in SM. The Audio-Corsi might also represent a novel way to implement cognitive training for blind individuals of all ages, whose SM abilities are strongly affected by the lack of visual experience.

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