Sound and Posture: an Overview of Recent Findings

Lennie Gandemer[1,2], Gaëtan Parseihian[1], Christophe Bourdin[2], and Richard Kronland-Martinet[1] *

[1] LMA, CNRS, UPR 7051, Aix-Marseille Univ, Centrale Marseille, 13402 Marseille, France
[2] Aix Marseille Univ, CNRS, ISM UMR 7287, 13288, Marseille, France
gandemer@lma.cnrs-mrs.fr

Abstract. Even if it has been neglected for a long time, the sound and posture domain seemed to arouse an increasing interest in recent years. In the present position paper, we propose to present an overview of our recent findings on this field and to put them in perspective with the literature. We will bring evidence to support the view that spatial cues provided by auditory information can be integrated by human for a better postural control.

Keywords: Posture, Sound spatialization, Auditory Perception, Acoustic Space

1 Introduction

It is well known that human upright stance control leans on the integration by central nervous system of various sensory cues [1]. The role of visual, vestibular and proprioceptive inputs has been well documented, leading to complex multisensory models of postural control (e.g., the Disturbance Estimation and Compensation model, [2]). The role of audition in postural control received less interest, in spite of a couple of earlier studies on this issue tending to exhibit an effect of sound on posture [3, 4]. However, this topic seems from now on to arouse an increasing interest, as a couple of studies emerged in the last years [5–10]. All these studies, which were conducted in different contexts, tended to show that sound can influence posture, and more precisely that auditory information can be integrated by human subjects to decrease their postural sway.

In the framework of a project involving two laboratories, one specialized in acoustics and the other in movement sciences, we conducted several studies on the role of auditory perception in postural control. In the present paper, we propose to present these studies and to put them on perspective with the existing literature, to better understand how sound is integrated in the postural control

* This work was funded by the French National Research Agency (ANR) under the SoniMove: Inform, Guide and Learn Actions by Sounds project (ANR-14-CE24-0018-01).

process[3]. Our goal is not to describe in details all the studies we conducted, as there are already a couple of pending publications, but rather give an overview of the emerging field of sound and posture, exploring various hypotheses concerning the attributes of sound which are useful for postural purposes. In particular, we will bring evidences to support the view that **human can use spatial content of auditory information for postural control.**

Before the presentation of our contributions, we will start by a state of the art of the sound and posture emerging domain. Then, we will present the results of our investigations on the influence of moving sound sources (sections 3, 4, and 5) and static sound environment (section 6) on human posture. The first study we will describe investigated the role of an rotating auditory stimuli around subjects (section 3). In a second study involving the same rotating sound stimuli, we investigated the influence of subject's focus of attention on their postural responses. Then, in a third moving sound study, we manipulated the various attributes of sound source movement (section 5). Finally, we built different kind of static sound environment to better understand the role of spatial information bring by auditory space (section 6).

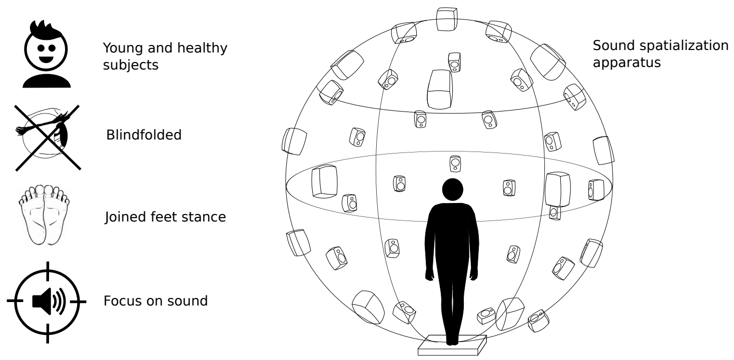

Fig. 1. Spatialization apparatus and experimental paradigm of the various studies presented in this paper

[3] Note that in this paper, we will focus on studies using comfortable level of auditory stimulation. We won't talk about studies using high intensity noise to activate vestibular system, as in [11] or [12]. We won't neither mention studies using sounds that convey emotion (e.g., threatening sounds, or music [13, 14]).

2 State of the art

In this section, we propose to give a quick overview of the sound and posture literature. This literature is not large and may at first glance appear contradictory. Here, we will show that different approaches are responsible of the differences in the various studies.

Loss of hearing

To our knowledge, the first studies concerning the role of audition in the postural control concerned the influence of auditory loss on postural sway. In 1985, Era and Heikkinen [4] showed that the postural sway of young adults who had been exposed to noise in their work was more pronounced than those who had not been exposed. This results was confirmed two years later, in a study by Jununten et al. [3] investigating the influence auditory loss in soldiers on their postural control. The soldiers, who had been exposed to high-energy intermittent noise from firearms, showed significantly more body sway than the control group; moreover, subjects with more severe hearing loss exhibited more sway than those with less severe hearing loss.

Similar results were obtained later, with workers [15] and congenitally deaf children [16] or adults [10]. But the most numerous studies concerned hearing loss in the elderly and its association with an increased risk of falling (e.g. [17] and [18]). Some authors suggested that this association might be explained by a global age-related loss of vestibular function, in which auditory loss is simply a marker for vestibular losses leading to imbalance. However, a recent study by Rumalla et al. [7] compared the postural sway of hearing-aid users, in aided (aid switched on) or unaided (aid switched off) conditions. Postural performance of subjects was significantly better in the aided than the unaided condition which proves the benefits of having auditory input fully available.

Finally, a study conducted by Kanegaonkar et al. [19] compared the postural sway of subjects in various auditory environment: normal room *vs* soundproof room, wearing ear defenders or not, eyes closed *vs* eyes open. With their eyes open, subjects exhibited a greater sway when there were set in the soundproof room *vs* in a normal room, or wearing ear defenders *vs* without ear defenders.

Thus, all these studies tend to show that the **lack of auditory input results in subjects exhibiting a poorer postural control**. It suggests that humans integrate sound in their postural control process, opening the way to studies on sound and posture interactions. However, we will see in the following that the influence of sound on posture has been little studied to date.

The sound helps to stabilize...

Firstly, a couple of studies involving static sound stimulation exhibited a decrease of sway in presence of sound stimuli. In a study conducted by Easton et al. [20], subjects were set in a tandem Romberg stance (heel-to-toe position) with two sound sources on both sides of their head, eyes open *vs* eyes closed. Authors reported a decrease of sway of 10% of subjects in presence of auditory cues vs 60% in presence of visual cues. This study highlighted the slightness of sound effect when compared to vision. In a more recent study also involving subjects in tandem Romberg stance, authors showed a decrease of sway of 9% of subjects exposed to a pink noise sound source facing them [8].

Then, other studies focused on the role of moving sound sources. In a study conducted by Deviterne et al. [21], authors used sound stimuli rotating around old subjects. They compared two types of rotating stimulations: a "non-meaningful auditory message" (440 Hz continuous tone) and a "meaningful auditory message" (a short recorded story). In the "meaningful auditory message" condition, subjects were asked to carefully listen to the story, and they were questioned afterwards about details in the story. The results showed a stabilization of the subjects only in this meaningful condition: authors concluded that the attention paid to the sound forced the subject to take into consideration the regularity and rotation of the stimulation, which provided them an auditory anchorage and so facilitated posture regulation. Another study conducted by Agaeva and Altman [22] used moving sounds played by an arc of loudspeakers in the sagittal plane. With sound moving back and forth, subjects exhibited a small reduction of their postural sway, and tended to slightly lean forward in presence of the sound.

In all these studies, sound stimuli were presented through loudspeakers. Thus, the auditory stimulations could provide spatial information on the space surrounding subjects thanks to auditory cues; authors generally explained their results in terms of **auditory anchorage effect**: **the sound sources provide landmark through the spatial information it conveys**, which allows subjects to decrease their body sway.

Two more studies were conducted with headphones: when it is presented through headphones, the auditory stimulation is not independent on the subject's movement. Thus, in that case, sound does not provide spatial cues on the environment surrounding subject: this could explain why a study by Palm et al. [23] did not highlight any postural sway differences between a condition without headphones and a condition with headphones playing background noise. However, a more recent study by Ross and Balasubramaniam [6] exhibited a significant reduction of subjects body sway when exposed to auditory stimuli through headphones. In this study, postural sway of subjects wearing noise reduction headphones has been compared in two conditions: a pink noise *vs* no sound played by headphone. Here, the reduction of sway cannot be considered as the result of the integration of auditory cues. Authors hypothesized that their results could be due to the "stochastic resonance" phenomenon. Stochastic resonance is a phenomenon that occurs when a sensory signal containing information is subthreshold, that is, too weak to be detected and integrated by central nervous system. In that case, adding noise (a signal which does not contain information) to the initial sensory input amplifies the whole signal which can pass over the threshold and then be integrated. This phenomenon is well known with proprioception: subsensory vibrations applied to the soles of the feet have been shown to reduce postural sway [24]. Ross and Balasubramaniam hypothesized that this phenomenon could also occur with audition. Even if this lead is interesting, we can object that in their experiment, there was no initial auditory information to be enhanced by adding noise. Indeed, subjects wore headphones "designed to reduce noise from any other external source": thus, in both silent and noise condition, there was no auditory information from the environment reaching subjects' ears. However, these results suggest that **more complex multisensory phenomenons** could be involved in the interactions between posture and auditory perception.

... but sound can also destabilize

Then, a few studies in literature missed to highlight a subject reduction of sway when exposed to sound stimuli. In a study conducted on young and older subjects exposed to rotating stimuli rendered in binaural technique, authors showed that the lateral body sway of the elderly group was more influenced by the lateral moving auditory stimulation than that of the young group [25]. But they did not compare postural regulation of subjects with and without sound, which makes the comparison difficult with the studies previously described. Another study conducted by Ha Park et al. addressed the influence of sound of various frequencies and amplitudes on postural stability [26]. They highlighted a significant increase of sway when sound frequency increased. But here again, there was no reference condition without sound stimulation allowing to compare this study with those of the previous section.

In two more studies, involving respectively static and moving sounds rendered with four loudspeakers, Raper and Soames exhibit a disturbing effect of sound on subjects posture [27, 28]. Sound stimuli were pure tone and background conversation. Similarly, a recent study conducted by Gago et al. [9] exhibited a disturbing effect of background noise on postural regulation of standing subjects. In this study, authors compared, among other conditions, the postural regulation of subjects wearing ear defenders or not. Subjects were set in a quiet laboratory, with a normal level of background noise. Authors concluded that the background noise was not informative, and thus may have created more distraction than a total lack of auditory information.

Thus, the **nature of the sound source** might be a determinant factor explaining the differences in the literature on sound and posture. It seems that when the sound does not appears to be informative, it is not integrated in the postural control process.

Our framework

The exploration of the sound and posture literature shows that the results are highly dependant on experimental conditions. In all the following, the studies we will present were conducted with almost the same paradigm, schematically represented in Figure 1. In a general point of view, we investigated the **static upright stance** of **young and healthy subjects**, **blindfolded** and standing with their **feet well joined**. The deprivation of visual cues as well as the joined feet stance allowed to set subjects in a slightly uncomfortable postural situation, inducing increased postural sways and the need to actively control the posture. This also allows to better observe the expected effects of the auditory stimuli exposure. Subjects' postural sway was measured using a **force platform**, and sound stimuli were produced using **sound spatialization techniques** in an **auditory CAVE** (a spherical loudspeakers array surrounding the subjects presented in [29]). Subjects were asked to **stand still**, and their task was to **focus on sound stimuli**.

3 First experiment: when a moving sound stabilizes

In a first experiment described in [5], we addressed the role of a rotating sound source on the postural sway of standing subjects. Twenty young subjects, standing in the dark on a force platform, were exposed to a pink noise sound source rotating around them at various speeds. Subjects were asked to stay still while focusing on the moving sound itself (counting the number of laps completed by the sound source).

Our first hypotheses were based on studies manipulating visual information for postural control. Moving visual stimuli are known to induce postural responses [30]. Similarly, we thought that a moving auditory stimulus could induce postural sway. Moreover, a rotating sound can possibly induce circular vection (illusory self-motion) [31]. We wanted to explore the postural response of subjects exposed to circular vection, as it is known that vection go along with postural responses [32].

However, subjects did not experience any vection. On the contrary, our results demonstrated that they rather **decreased their postural sway when confronted to rotating auditory stimuli**. Indeed, subjects' amplitude of sway as well as mean sway velocity decreased in presence of rotating sound, when compared to the reference conditions (without sound or with a static sound source facing them). The decrease of the sway went to 30% with the quickest rotating sound. These counter-intuitive results suggests that auditory information, which is by nature very different from visual information, may be processed and integrated in a different way.

Then, these results raised numerous questions and hypotheses: Did the subjects build a more stable representation of acoustic space using this surrounding rotating sound source? If so, what would have happened with less regular displacements of the sound? What about the role of subjects counting task and sound-focus task? Did the perception of moving auditory sources activate movement control centers? Could we get the same results with a rich static sound environment?

The first question we chose to address is the role of the subjects' focus of attention in the effects observed with a rotating sound. Indeed, the instructed focus of attention of subjects is known to play a role on their postural responses [33]. In our rotating sound study, subjects were asked to focus on sound source displacement and to count number of laps completed by the sound source. Thus, the reduction of postural sway could have been due to this task implying an external focus of attention and a slight cognitive load.

4 Focus on sound: a tree hidding the wood

In a second study (currently under review), we addressed the role of attentional focus in the integration of dynamic sound information for postural purposes. To this end, we followed a procedure very similar to the first rotating sound study described section 3: we produced the same rotating auditory stimuli around blindfolded subjects (n=17) in the same stance, and the same reference auditory conditions (without sound and with one static sound source facing subjects). We then compared their postural regulation when completing three different tasks:

- a **postural-focus** task: stay still, focusing on postural control (a single reference postural task)
- a **sound-focus task**: stay still, focusing on sound (dual-task: the same than in section 3)
- a **mental arithmetic task**: stay still while counting backward by 7 (purely cognitive dual-task)

Unsurprisingly, the effect of sound condition on postural sway described in the previous experiment was observed again in the sound-focus task, which corresponds exactly to the same task than the first experiment (see the gray bars Figure 2.a). However, in the two other tasks (postural-focus task and mental arithmetic task), results showed that sound conditions have no longer significant effect on postural control. This could have been explained in two ways: 1- subjects necessitated to allocate more attention to sound to be able to integrate auditory information or 2- subjects did not integrate sound and their decrease of sway in the sound-focus task is only due to the cognitive counting task, not present in the two reference conditions without sound and with a static sound. The results obtained in the two other tasks support the first explanation. Indeed, in the mental arithmetic task (which is purely cognitive) the subjects exhibited a significantly higher sway velocity than in the two other tasks (see Figure 2.b), associated with a small amplitude of sway, whatever the sound condition. This "freezing" behavior, different from subjects' behavior in the two other tasks, is consistent with what have been observed in the literature when subjects are exposed to cognitive loads [34]. Moreover, subjects exhibited a significantly smaller velocity of sway in the sound-focus task than in the reference postural-focus task, which proves that they integrated the auditory information in the former and not in the latter.

Thus, with this second experiment, we showed that the **subjects stabilization** observed in our first rotating study(section 3) was **not due to their counting task**, but rather to the integration of auditory information. We also showed that **focus on sound is necessary to allows subjects to integrate this auditory information**. The results of our two first rotating sound studies could be related to the results of the earlier study by Deviterne et al. [21] in

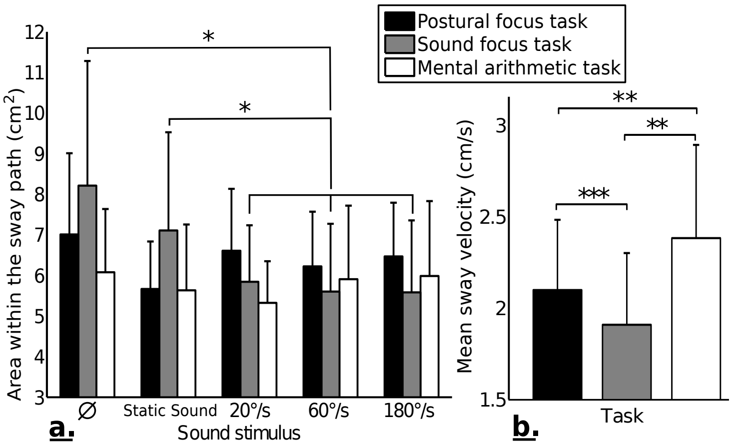

Fig. 2. Results of the rotating sound study with various focus of attention of subjects. Mean on 17 subjects. **a.** Area within the sway path across the five sound conditions and the three tasks. **b.** Mean sway velocity across the three tasks. Bars represent the 95% confidence interval.

which authors compared the effect of two types of rotating stimulations around subjects: a "non-meaningful auditory message" (440 Hz continuous tone) and a "meaningful auditory message" (a short recorded story). In "meaningful auditory message" condition, subjects had a similar sound-focus task: they were asked to carefully listen to the story. Similarly to our study, their results showed a stabilization of the subjects only in this sound-focus task. Authors concluded that the attention paid to the rotating sound forced the subject to take into consideration the regularity and rotation of the stimulation, which provided them an auditory anchorage allowing to improve their posture regulation. Similarly, we postulate that **allocating more attention to the sound favors the integration of auditory information** for postural purpose. For that purpose, to stimulate the potential effects of sound on posture, we chose to give subjects a sound-focus task in all the following studies.

Of course, this very interesting and new effect of sound stimulation on postural control remains of small amplitude, mainly when referred to possible effects of vision on posture. For example, in the study by Easton et al. [20] conducted with subjects standing in between two static sound sources, eyes closed versus eyes open, authors showed a decrease of sway of 10% with auditory cues against 60% with the visual cues. In comparison, our results suggesting a decrease of sway amplitude of about 30% with sounds appears as the only study which such results. The explanation may lead to the typology of the sounds used and to the way we produced the auditory stimulation. It is now clear that the quality of our innovating experimental device could be part of the explanation. The following experiments will question these points, exploring the various attributes of sound possibly involved in the stabilization.

5 Dissecting movement: space vs morphology

A sound source which is moving in space provokes variations of the acoustic cues (interaural time difference, interaural level difference and head related transfer function) human uses to localize it [35]. Such variations represent what is traditionally labeled as the **spatial attributes** of a moving sound. But a moving sound source also intrinsically contains information on its own movement: its spectral content will be modified by the Doppler effect, filtering due to the air absorption, or changes in the ratio between direct sound and reverberate sound [36]. It is what we will call here the **morphological features** of a moving sound source.

In real world, dynamic as well as morphological features of a moving sound source are mixed up. A sound source moving in space induces modifications of its spatial and morphological attributes. Experimentally, we can separately synthesize these both attributes. We can then apply various attributes to a static source to evoke movement. On the one hand, there are various sound spatialization techniques allowing to control the spatial displacement of virtual sound sources. In our rotating sound studies we used a sound spatialization technique called High Order Ambisonics (see [29]). On the other hand, it is possible to implement separately each morphological feature linked to one movement. For example, by applying the equivalent Doppler effect of a moving sound source to a static sound rendered in mono, we can easily create a strong source movement impression [37].

In our first rotating sound study, we showed that a rotating sound source around subjects induced a decrease of their body sway. To explain this stabilization, we can formulate two hypotheses:

– the stabilization provoked by the rotating sound could be due to **changes in the spatial cues**, which are integrated by our auditory system and give spatial landmarks which can be used to stabilize. In this case, we can wonder in what extend the regularity and predictability of the trajectory is important to allow stabilization.
– more simply, postural responses to the rotating sound could be due to the **motion perception** in general. As our postural control is managed by motor control areas, a moving sound perception could possibly activate brain areas linked to the movement. In this latter case, the only evoked movement simply by morphological treatments of sound could be sufficient to induce postural changes.

To explore concomitantly these two hypotheses, we decided to dissect the rotating sound scenario which produced the better stabilization in our first studies, separating spatial from morphological features of sound. For that purpose, we compared postural regulation of subjects exposed to 1 - a dynamic rotating sound, synthesized with sound spatialization and morphological features: "**morphologico-spatial**" condition or 2 - a morphological-evoked movement rendered in mono: "**morphological**" condition. In this latter condition, the Doppler effect equivalent to the one produced for the "morphologico-spatial" condition was applied to a static sound source rendered in mono, to give the impression that the sound source was traveling on the same trajectory.

Two different trajectories were implemented in each sound-feature condition. The first trajectory, regular and **predictable**, was a circle on the horizontal plane (at ear level) shifted to the right. The second was a **pseudo random trajectory**, rotating around subject at the same average speed but following a more chaotic and random path (cf Figure 3).

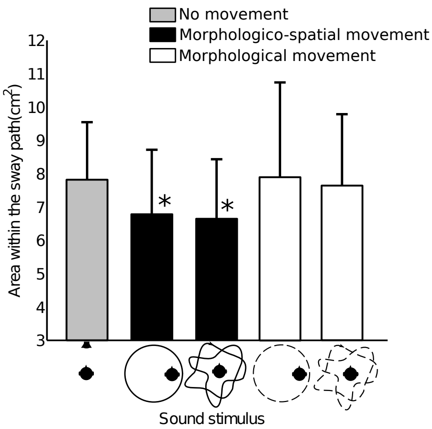

Fig. 3. Results of the spatial VS morphology study: area within the sway path across the various sound stimuli. Mean on 21 subjects. Bars represent the 95% confidence interval. The stars (*) represent a significant difference from the reference condition without movement.

The results, partly presented in Figure 3, showed that the morphological-evoked movement did not lead to a decrease of sway, but to an amplitude of sway comparable to the static sound reference condition. On the contrary, the two trajectories with spatial displacement induced a decrease of sway, significantly different from the reference. Moreover, there was no differences between the two morphologico-spatial trajectories, which seems to show that the predictability and regularity of trajectories were not a determinant factor in the integration of sound by the subjects. This third experiment allowed to validate the first hypothesis on sound movement we formulated: stabilization provoked by the rotating sound is due to the **variation of spatial cues**. Thus, it seems to confirm that the spatial attributes of sound are the main features involved in subjects stabilization. We explore this hypothesis more in detail in the next section.

6 Static sound environment for postural stabilization

In the previous sections, we showed that a moving sound source around a subject can help him to stabilize, but that the precise movement of the trajectory is not of interest. Thus, we can hypothesize that subjects use the spatial cues they can get from the moving source. Therefore, we wonder to what extent the moving sound could be replaced by several static sources surrounding subjects. Indeed, static sources also provide spatial cues, and we can imagine that it would be at least as easy for subjects to build their representation or spatial surrounding environment from static spatial cues than from changing cues.

In this section, we will present two studies we conducted with static sound stimuli. The main idea behind these two studies was to investigate if subjects were able to construct a putative "auditory landmark" using spatial cues from static sound sources, and then reach the same stabilization effects than those observed with rotating sounds.

Construction of an auditory environment

In our first studies, we showed that one static sound source facing subjects was not sufficient to provide an important decrease of sway of subjects. Thus, we built a richer auditory environment with three recordings of ecological sources[4]: a motor, a fountain and a cicada. These 3 sources were positioned around subjects, and we compared postural sway of subjects (n=35) exposed to 1, 2 or 3 sources, and in the absence of sound. Subjects were asked to focus on sound, counting the number of sources surrounding them. This study was conducted in a normal room and in an anechoic soundproof room. Indeed, in an soundproof environment, there is no background noise: the reference condition is perfectly silent. Moreover, a single source provides more spatial information in a normal room (thanks to sound reflection in the space) than in an anechoic room. We wanted to know if the reduced information provided by sound in the anechoic soundproof environment could result in subjects exhibiting greater postural sway than in a normal room.

Subjects exhibited a decrease of their postural sway in presence of static sound sources, when compared to the reference condition without sound (Figure 4.a). Moreover, adding sources seemed to reinforce the decrease of sway, although this tendency was not found to be significant. The decrease of sway went to 10% with 3 static sources. This result is in accordance with other studies involving static sound stimuli. As mentioned before, Easton et al. [20] have reported a decrease of sway of 10% of subjects in tandem Romberg stance (heel-to-toe position) with two sound sources on both sides of subject head. In a more recent

[4] The sources are labelled "ecological" because they represent sounds which exist in nature, in contrast to more abstract sound source as pink noise

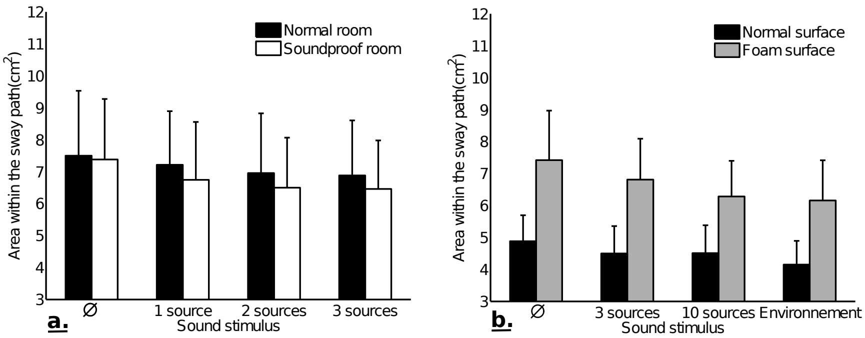

Fig. 4. Results of the amplitude of sway in the two static sources studies. **a.** First study: No sound, 1, 2 or 3 static sources; soundproof room vs normal room. Mean on 35 subjects. **b.** Second study: No sound, 3 sources, 10 sources or an immersive environment; firm surface vs foam surface. Mean on 30 subjects. Bars represent the 95% confidence interval.

study also involving subjects in tandem Romberg stance, authors showed a decrease of sway of 9% of subjects exposed to a pink noise sound source facing them [8].

Moreover, results of our study showed no differences of postural behavior between the normal room and the anechoic room. In a study conducted by Kanegaonkar et al. [19], authors also compared the postural sway of subjects in a normal room *vs* an anechoic room, eyes open *vs* eyes closed. They demonstrated that with eyes open, subjects exhibit a significant greater postural sway in an anechoic room than in a normal room. Similarly to our study, they found no difference between the two rooms when subjects' eyes were closed. We can hypothesize that when subjects are deprived from both visual and auditory information, their postural situation is too challenging, and their sensory information needs are reported on the other available modalities, probably considered as more "reliable" (proprioception and vestibular system).

This first static sound study confirms that the spatial cues provided by static sound sources can be integrated by subjects to decrease their postural sway. However, subjects reached a decrease of sway of 10% with 3 static sources, which is far less than the 30% of our first rotating sound study. The auditory environment built in this static sound study was quite simple. It only consisted of 3 sound sources spatially limited, that we could label "isolated": indeed, the sources were 3 recorded sounds played independently by 3 different loudspeakers. We can hypothesize that if we enrich the auditory environment, we will bring more information to subjects and thus allow them to better stabilize.

Toward a more immersive environment

For that purpose, in a last experiment, we decided to create richer auditory environments by means of two different approaches: firstly, adding other isolated sources, using more samples played by other loudspeakers. Secondly, by recording a real sound environment and then by re-synthesizing it in our auditory CAVE using ambisonics spatialization techniques. These techniques aim to recreate an auditory stimulation closer to natural listening. Thus, the auditory environment recreated in the spatialization apparatus was much more realistic and immersive than what we could create adding isolated sources on separate loudspeakers.

Thus, in this study, we used four different auditory conditions:

- a reference condition without sound
- 3 isolated ecological sources (same condition as the previous static sound experiment)
- 10 isolated ecological sources
- an immersive environment consisted of the same kind of ecological sources (fountain, motor sound and cicadas) recorded and re-synthesized in ambisonics.

Moreover, in this study, we decided to compare two surfaces conditions: subjects standing either on a firm surface (as in the other static sound experiment), or on foam. The foam is classically used in postural studies to reduce proprioceptive feedback from the plantar touch [38]. We were interested here in determining if less proprioceptive feedback resulted in sound having more influence on posture, or on the contrary in sound being ignored.

Not surprisingly, the amplitude of sway has been found to be far greater on the foam surface than on the normal firm surface. Then, the results showed a decrease of sway in all the sound conditions when compared to the no sound reference condition. More interestingly, the decrease of sway was significantly more important in presence of the immersive environment than with 3 or 10 isolated sources (Figure 4.b). In the immersive environment condition, the decrease of sway reached 15%. This results shows that the richer the auditory environment, the more subjects can integrate sound information to decrease their postural sway, which is in accordance with our hypothesis. Finally, these results were similar on both firm and foam surfaces.

Thus, with these two studies and several static sound studies in literature, we showed that the **spatial cues coming from the sound environment can be integrated by subjects, and help them to better stabilize**. In a study adressing the potential role of auditory information in spatial memory, conducted by Viaud Delmond et al [39], authors built a realistic auditory soundscape rendered in headphones. The soundscape was updated in real time according to subjects movements and displacements in 3D space, thanks to subjects tracking and advanced binaural technologies. Subjects were blindfolded and their task was to explore a delimitated area in order to find a hidden auditory target. In this study, authors showed that subjects were able to build a representation of space thanks to sensorimotor and auditory cues only, and then navigate and find their way in this environment in an allocentric manner. In our studies, subjects did not navigate in the space, but we can advance that they also built a spatial representation of auditory environment and used it as an auditory landmark that provided them cues to stabilize. Moreover, the richer the environment, the better the stabilization. We assume that the rotating sound source around subject provides numerous spatial cues to subjects, and thus could be seen as a rich sound environment too. This could explain the greater decrease of sway reached by subjects in these studies (around 30%).

7 Conclusion and perspectives

In this paper, we presented an overview of the recent studies conducted on the emerging topic of the influence of sound on posture.

The exploration of the sparse literature about sound and posture (section 2) showed that sound can play a role in the postural regulation. The results of some studies are somehow contradictory, which proves that there is a need to further investigate the field. First, numerous studies showed that the lack of auditory information (partial or total loss of hearing) results in a poorer postural regulation. Then, a couple of studies investigated the specific role of auditory stimulation on human posture. Some studies highlighted a stabilization effect thanks to sound: the main hypothesis which emerged from these studies is that sound can provide an auditory landmark helping people to stabilize. Other studies demonstrated that sound can also induce destabilization, which suggests that the nature of the auditory stimuli plays a role in the sound and posture interaction.

Through the five postural studies we conducted, we could confirm that subjects are able to use auditory information to better stabilize, when there are deprived of visual information. We explored the various attributes of sound that could possibly contribute to subjects' stabilization. We showed that forcing subjects to **allocate attention to the auditory stimulation favors the effects** of sound on posture (section 4). Then, we brought evidence to support the view that the **spatial cues provided by auditory stimulation are the main attribute of sound responsible of subject's stabilization**, either with a moving sound source around subjects (sections 3 and 5) or with a static sound environment (section 6). The richer the sound environment, the better the subjects stabilize.

Our studies continue to raise numerous questions. Firstly, the perception of 3D sound spatialization techniques (such as ambisonics we used in our studies) lacks research. We are convinced that a better understanding of how humans perceive 3D sound would help to understand how sound interacts with posture. That is why we are currently investigating the perception of sound trajectories in space. Then, now that we better understood how subjects lean on auditory information, it would be interesting to invert the approach and try to induce postural perturbations using perturbation of spatial sound environment. Then, we did not address the question of the nature of the sound source. The couple of studies in the literature which exhibited a destabilizing effect of non-informative stimuli (pure tones, background noise or conversation, or pure tones) suggest that subjects can use auditory information only if it provides spatial cues. In our studies, we used either static ecological sound sources, which provided spatial reference cues, or a moving abstract sound (pink noise) which provided spatial information thanks to its movement (variation of the spatial cues). Moreover, we forced subjects to pay attention to these auditory stimuli and thus probably to extract spatial information from the sound stimulation. Finally, our theory leaning on spatial attributes of sound does not explain how subjects can stabilize with an auditory stimulation played by headphones. As suggested in the section 2, they are probably more complex multisensory phenomenon which could be involved in sound and posture interactions.

All the results we presented here and all the raising questions associated show that the interaction between sound and posture is a promising area of research. Following the present overview, we are now convinced that auditory cues are a significant source of information for the postural control. Thus, auditory perception may be helpful for readaptation purposes, and for improvement of postural control in various fields, including sport, rehabilitation or sensory substitution for instance.

References

1. Maurer, C., Mergner, T. & Peterka, R. Multisensory control of human upright stance. *Experimental Brain Research* **171**, 231–250 (2006).
2. Assländer, L., Hettich, G. & Mergner, T. Visual contribution to human standing balance during support surface tilts. *Human movement science* **41**, 147–164 (2015).
3. Juntunen, J. *et al.* Postural body sway and exposure to high-energy impulse noise. *The Lancet* **330**, 261–264 (1987).
4. Era, P. & Heikkinen, E. Postural sway during standing and unexpected disturbance of balance in random samples of men of different ages. *Journal of Gerontology* **40**, 287–295 (1985).
5. Gandemer, L., Parseihian, G., Kronland-Martinet, R. & Bourdin, C. The influence of horizontally rotating sound on standing balance. *Experimental Brain Research* 1–8 (2014). URL `http://dx.doi.org/10.1007/s00221-014-4066-y`.
6. Ross, J. M. & Balasubramaniam, R. Auditory white noise reduces postural fluctuations even in the absence of vision. *Experimental brain research* **233**, 2357–2363 (2015).
7. Rumalla, K., Karim, A. M. & Hullar, T. E. The effect of hearing aids on postural stability. *The Laryngoscope* **125**, 720–723 (2015).
8. Zhong, X. & Yost, W. A. Relationship between postural stability and spatial hearing. *Journal of the American Academy of Audiology* **24**, 782–788 (2013).
9. Gago, M. F. *et al.* Role of the visual and auditory systems in postural stability in alzheimers disease. *Journal of Alzheimer's Disease* **46**, 441–449 (2015).
10. Mangiore, R. J. The effect of an external auditory stimulus on postural stability of participants with cochlear implants (2012).

11. Mainenti, M. R. M., De Oliveira, L. F., De, M. A. D. M. T., Nadal, J. *et al.* Stabilometric signal analysis in tests with sound stimuli. *Experimental brain research* **181**, 229–236 (2007).
12. Alessandrini, M., Lanciani, R., Bruno, E., Napolitano, B. & Di Girolamo, S. Posturography frequency analysis of sound-evoked body sway in normal subjects. *European Archives of Oto-Rhino-Laryngology and Head & Neck* **263**, 248–252 (2006).
13. Forti, S., Filipponi, E., Di Berardino, F., Barozzi, S. & Cesarani, A. The influence of music on static posturography. *Journal of Vestibular Research* **20**, 351–356 (2010).
14. Ross, J. M., Warlaumont, A. S., Abney, D. H., Rigoli, L. M. & Balasubramaniam, R. Influence of musical groove on postural sway. *Journal of experimental psychology. Human perception and performance* (2016).
15. Kilburn, K. H., Warshaw, R. H. & Hanscom, B. Are hearing loss and balance dysfunction linked in construction iron workers? *British journal of industrial medicine* **49**, 138–141 (1992).
16. Suarez, H. *et al.* Balance sensory organization in children with profound hearing loss and cochlear implants. *International journal of pediatric otorhinolaryngology* **71**, 629–637 (2007).
17. Viljanen, A. *et al.* Hearing as a predictor of falls and postural balance in older female twins. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* **64**, 312–317 (2009).
18. Lin, F. R. & Ferrucci, L. Hearing loss and falls among older adults in the united states. *Archives of internal medicine* **172**, 369–371 (2012).
19. Kanegaonkar, R., Amin, K. & Clarke, M. The contribution of hearing to normal balance. *Journal of Laryngology and Otology* **126**, 984 (2012).
20. Easton, R., Greene, A. J., DiZio, P. & Lackner, J. R. Auditory cues for orientation and postural control in sighted and congenitally blind people. *Experimental Brain Research* **118**, 541–550 (1998).
21. Deviterne, D., Gauchard, G. C., Jamet, M., Vançon, G. & Perrin, P. P. Added cognitive load through rotary auditory stimulation can improve the quality of postural control in the elderly. *Brain research bulletin* **64**, 487–492 (2005).
22. Agaeva, M. Y. & Altman, Y. A. Effect of a sound stimulus on postural reactions. *Human Physiology* **31**, 511–514 (2005).
23. Palm, H.-G., Strobel, J., Achatz, G., von Luebken, F. & Friemert, B. The role and interaction of visual and auditory afferents in postural stability. *Gait and Posture* **30**, 328–333 (2009).
24. Priplata, A. *et al.* Noise-enhanced human balance control. *Physical Review Letters* **89**, 238101 (2002).
25. Tanaka, T., Kojima, S., Takeda, H., Ino, S. & Ifukube, T. The influence of moving auditory stimuli on standing balance in healthy young adults and the elderly. *Ergonomics* **44**, 1403–1412 (2001).
26. Park, S. H., Lee, K., Lockhart, T., Kim, S. *et al.* Effects of sound on postural stability during quiet standing. *Journal of neuroengineering and rehabilitation* **8**, 1–5 (2011).
27. Raper, S. & Soames, R. The influence of stationary auditory fields on postural sway behaviour in man. *European journal of applied physiology and occupational physiology* **63**, 363–367 (1991).
28. Soames, R. & Raper, S. The influence of moving auditory fields on postural sway behaviour in man. *European journal of applied physiology and occupational physiology* **65**, 241–245 (1992).

29. Parseihian, G., Gandemer, L., Bourdin, C. & Kronland-Martinet, R. Design and perceptual evaluation of a fully immersive three-dimensional sound spatialization system. In *International Conference on Spatial Audio (ICSA) : 3rd International Conference* (2015).
30. Laurens, J. *et al.* Visual contribution to postural stability: Interaction between target fixation or tracking and static or dynamic large-field stimulus. *Gait & posture* **31**, 37–41 (2010).
31. Lackner, J. R. Induction of illusory self-rotation and nystagmus by a rotating sound-field. *Aviation, Space, and Environmental Medicine* (1977).
32. Guerraz, M. & Bronstein, A. M. Mechanisms underlying visually induced body sway. *Neuroscience letters* **443**, 12–16 (2008).
33. Mitra, S. & Fraizer, E. Effects of explicit sway-minimization on postural–suprapostural dual-task performance. *Human movement science* **23**, 1–20 (2004).
34. Stins, J. F., Roerdink, M. & Beek, P. J. To freeze or not to freeze? affective and cognitive perturbations have markedly different effects on postural control. *Human movement science* **30**, 190–202 (2011).
35. Blauert, J. *Spatial hearing: the psychophysics of human sound localization* (The MIT press, 1997).
36. Merer, A., Ystad, S., Kronland-Martinet, R. & Aramaki, M. Semiotics of sounds evoking motions: Categorization and acoustic features. In *Computer Music Modeling and Retrieval. Sense of Sounds*, 139–158 (Springer, 2008).
37. Kronland-Martinet, R. & Voinier, T. Real-time perceptual simulation of moving sources: application to the leslie cabinet and 3d sound immersion. *EURASIP Journal on Audio, Speech, and Music Processing* **2008**, 7 (2008).
38. Patel, M., Fransson, P., Lush, D. & Gomez, S. The effect of foam surface properties on postural stability assessment while standing. *Gait & posture* **28**, 649–656 (2008).
39. Viaud-Delmon, I. & Warusfel, O. From ear to body: the auditory-motor loop in spatial cognition. *Frontiers in neuroscience* **8**, 283 (2014).