Measuring threshold and latency of motion perception on a swinging bed

Maxime Guyon¹, Cyrielle Chea*,¹, Davy Laroche²,³, Isabelle Fournel⁴, Audrey Baudet⁵, Michel Toupet¹,⁵, Alexis Bozorg Grayeli¹,⁶*

¹ Otolaryngology Department, Dijon University Hospital, Dijon, France, ² INSERM CIC 1432, Plateforme d’Investigation Technologique, Dijon University Hospital, Dijon, France, ³ INSERM UMR1093, Cognition, Action et Plasticité Sensorimotrice, Université de Bourgogne Franche Comté, Dijon, France, ⁴ INSERM CIC 1432, Module Epidémiologie Clinique/Essais Cliniques, Dijon, France, ⁵ Centre d’Explorations Fonctionnelles Otoneurologiques, Paris, France, ⁶ CNRS UMR 6306, Le2i Research Laboratory, Dijon, France

* alexis.bozorggrayeli@chu-dijon.fr

Abstract

Introduction

Our objective was to develop and to evaluate a system to measure latency and threshold of pendular motion perception based on a swinging bed.

Materials and methods

This prospective study included 30 healthy adults (age: 32 ± 12 years). All subjects were tested twice with a 10 min. interval. A second trial was conducted 2 to 15 days after. A rehabilitation swinging bed was connected to an electronic device emitting a beep at the beginning of each oscillation phase with an adjustable time lag. Subjects were blindfolded and auditory cues other than the beep were minimized. The acceleration threshold was measured by letting the bed oscillate freely until a natural break and asking the patient when he did not perceive any motion. The perception latency was determined by asking the patient to indicate whether the beep and the peak of each oscillation were synchronous. The time lag between sound and peak of the head position was swept from -750 to +750 ms by 50 ms increments.

Results

The mean acceleration threshold was 9.2±4.60 cm/s². The range width of the synchronous perception interval was estimated as 535±190 ms. The point of subjective synchronicity defined as the center of this interval was -195±106 ms (n = 30). The test-retest evaluation in the same trial showed an acceptable reproducibility for the acceleration threshold and good to excellent for all parameters related to sound-movement latency.

Conclusion

Swinging bed combined to sound stimulation can provide reproducible information on movement perception in a simple and non-invasive manner with highly reproducible results.
Introduction

Today, there is no routine test to evaluate the vestibular input by the awareness of the body movements. Previous attempts to measure psycho vestibular parameters such as the perception threshold of body acceleration are based on complex and expensive systems which cannot be easily applied to all dizzy fragile or old subjects [1]. To evaluate the perception of circular movements in healthy subjects, Nooij et al. employed a MPI Cybermotion Simulator [2]. Sensitivity to vertical self-motion was evaluated in healthy volunteers on a similar device by Nesti et al. [3]. Other authors set up a Moog motion platform to detect dynamic tilt thresholds in patients with vestibular migraine [4] or a motor-driven linear sled on a 4.2-m track to assess linear movement perception [1]. The complexity of the setups, the duration of the examination, their cost and cumbersomeness hamper their clinical use in routine. In this view, a pendular movement on a rehabilitation swinging bed appears as a more accessible and probably a safer approach to the exploration of movement perception. Indeed, to our knowledge, none of these experimental platforms comply to the safety requirements for a routine clinical use in contrast to physiotherapy swinging beds.

Evaluating the movement perception has major potential applications. Falls in senior subjects have a major medico-economic impact and their prevention is a significant challenge for many health actors [5, 6]. The pathophysiology of balance disorders in the elderly is complex and probably variable from one patient to another [7]. Disturbances in functional connectivity, slower central processing and reaction to the disequilibrium are significant mechanisms in senior fallers among several others such as lower weight of vestibular input, lack of coordination, sarcopenia and inadequate reaction [7–10]. More generally, the awareness of the body movement is a prerequisite to adapted postural reactions and to rehabilitation in subjects with balance disorders. A decline of this capacity is observed with sedentary lifestyle and age [11]. This awareness can be characterized by several parameters (e.g., change of direction relative to the gravity vector, relative movement of body parts, change of location in space) among which, the perception threshold of body acceleration and the delay of this perception. Indeed, the impaired perception of fall timing appears to be related to the risk of fall in the elderly [12].

Measuring the delay of body movement perception is distorted by the delay in the subject’s response if it is manual or vocal. Hence, perception delays of different sensory modalities are compared to each other. Previous works have already demonstrated that this type of comparison for vestibular, visual and auditory stimuli provide consistent results in terms of processing delay at a conscious level [13]. These studies have shown that visual and auditory inputs are processed more rapidly than vestibular information [14].

Multisensory integration of visual, vestibular, proprioceptive, and auditory cues for movement perception is crucial in balance and seems to be affected by diseases such as vestibular migraine [15] or age [16]. We hypothesized that this integration could be assessed by exploring the synchronous perception of a sound and a passive body oscillation on a swinging bed. Measuring acceleration perception threshold has potential implications on understanding the mechanisms of dizziness and fall [17]. Threshold values are subject to significant variation depending on the plane of the stimulation and stimulus profile (sinus, linear, steps, etc.) [1].

We hypothesized that we could measure a reproducible threshold on the swinging bed during deceleration. From a practical standpoint, measuring 2 potentially important parameters (synchronous perception of sound and movement and acceleration perception threshold) on the same device and with the same setup would be interesting in a clinical setup.

The aim of this study was to develop a system to measure the delays for which sound and body movement were perceived as synchronous, and the threshold of acceleration perception.
on a safe device applicable to clinical routine and to evaluate its tolerance and reliability in healthy adults.

**Materials and methods**

This monocentric pilot study was conducted on 30 healthy young adults in a tertiary referral center for balance disorders. We estimated the population size, by setting $\alpha = 0.05$, $\beta = 0.1$, the value of Cronbach's alpha at null hypothesis $= 0$, and the expected value of Cronbach's alpha $= 0.7$. The population size was estimated at 24 according to Bujang et al. [18] and increased to 30 to account for potential lost to follow-up at the retest. The population included 16 men and 14 women with a mean age of 32 years (range: 20–61). Subjects with past medical history of balance disorders or hearing disabilities were excluded. The protocol was reviewed and approved by the institution's ethical committee (CPP Est III) and a written consent was obtained from all subjects. We have complied with APA ethical standards in the treatment of the subjects.

A total of 4 tests was designed for each subject and each parameter. After inclusion, subjects underwent a trial of test and retest measuring the latency and the acceleration threshold of movement perception on a swinging bed. A 10-minute interval separated the test and the retest. A second test-retest trial was carried out several days after the first (mean delay between trials $13\pm 2.1$ days, range: 2–50), on the same group. Four subjects were lost to follow-up for the second trial.

**Experimental set-up**

Subjects were placed on a swinging bed suspended to a 2.5 m-high gantry (Fig 1). Sound and friction were minimized by ball-bearings on the rotation axis. The radius of the oscillation was 2.4 m. Preliminary tests showed a 1% variation of this radius as a function of the weight of the subject. The swinging movement was initiated by a manual backward traction of the bed and a silent release. For the measurement of acceleration threshold perception, the amplitude of this initial displacement was controlled by a laser beam projected on a scale (millimetric resolution) on the ground. To measure the latency of the movement perception, an infrared detector was placed on the ground to detect the passage of the bed at its lowest point at each cycle. This device was connected to a processor and a loudspeaker inside the detector box and approximately 1.5 meters from the subject's ears enabling the system to produce a beep (5 ms, 80 dB SPL) at the beginning of each oscillation (subject's head at its highest position, peak). Considering the speed of sound (343 m/s), this distance created a 4 ms delay. During the first 3 bed passages in front of the infrared detector (half cycles), the device measured and averaged the half cycles of the oscillation. Then, the system began to emit a beep with a negative or a positive time lag based on this calculated period. The oscillation period of this compound pendulum is stable for small oscillations (1–2 rad) as in our case. In this way, the position of the head could be estimated and anticipated with precision. The delay between the peak and the beep could be adjusted by the operator with 50 ms increments.

**Measurement protocol**

The subject was installed on the bed on his/her back comfortably and blinded by a mask. Arms were placed along the body and the legs were stretched. The nose pointed to the ceiling. In preliminary experiments, 5 volunteers tested the device for the possible perception of the wind but could not perceive any related tactile or auditory cue during the swinging movements. Acceleration thresholds were determined by a descending method: The bed was pulled 8 cm backwards and released silently. The subject was asked to notify the operator immediately.
when he/she felt that the bed was immobile. At that time, the operator measured the maximal deviation of the bed from the equilibrium point in cm using the laser projection on the scale placed on the ground. This deviation ($d$, in meter) was converted to maximal tangential acceleration ($a$, cm/s$^2$) by the following formula: $a = 9.81 \times (d/2.4) \times 100$.

To measure the movement perception delay, we evaluated the range of sound-peak delays which produced a synchronous perception. The bed was pooled backward from its equilibrium point and released. The delays between the beep and the peak were swept from -750 to +750 ms in 50 ms increments. Only backward peaks were used generating only one beep per cycle and allowing a larger time lag exploration. For each lag increment, 3 or more oscillation periods were presented as required by the subject. We chose the peak because it corresponds to the maximum absolute value of deceleration. The peak also corresponds to a change of direction. Describing it to the patients as the “peak” appeared to be easy to understand for the subjects. The range was defined based on preliminary tests to cover the range of synchronous perception delays. The patient was asked to indicate whether the sound and the peak were synchronous. A synchronous perception was noted for a range of delay values defining a synchronous perception interval (SPI, Fig 2). We defined a sound-peak (SP) threshold at the lower limit and a peak-sound (PS) threshold at the upper limit of this interval. Each of these
thresholds was defined by an increment yielding a positive response followed by 2 negative responses to the following increments. For sound-movement synchronicity, each bed release was followed by 8–10 supra liminary oscillations. Each bed release generally allowed testing 2 time-lags. The tolerance of the procedure was evaluated by an auto questionnaire (stress, nausea, discomfort). The mean test duration was approximately 20 minutes.

**Statistical tests**

Values were expressed as mean ± Standard Deviation (SD). The normality of the distribution was tested by a Kolmogorov-Smirnov test. Data was analyzed by Graphpad prism (Graphpad Software Inc. V 5.01, La Jolla, CA), Excel (Office, v. 360, Microsoft, Redmond WA) and Statistical Software for social science (SPSS v23, IBM, USA). Test-retest reliability was evaluated by Pearson correlation coefficient R and intraclass correlation coefficient (ICC) assuming two-way random effects, absolute agreement, and a single rater [19]. Internal consistency was evaluated by Cronbach’s alpha.

**Results**

All subjects perceived the peak of the oscillation (highest position of the head) and the beep as synchronous for a range of delays. The mean width of SPI was 590 ± 193.3 ms (n = 30, S1 Table, Fig 3). The point of subjective synchronicity (PSS, Fig 2) defined as the center of this interval was -244 ± 90.2 ms (n = 30). The sound-peak threshold defined as the upper limit of the SPI was evaluated as 50 ± 90.2 ms (n = 30) and the peak-sound threshold defined as the lower limit of the SPI was estimated as -539±163.8 ms (n = 30). The lower limit of SPI, its middle point (PSS) and width had a relatively small dispersion as evaluated by the relative standard deviation (RSD, 30%, 37%, and 33% respectively). However, the upper limit showed significant variation (RSD = 178%).

The mean acceleration threshold was 9.2 ± 4.60 cm/s^2 (n = 30). The dispersion of this measure appeared to be higher than for SPI or PSS (RSD = 87%). There was no correlation between PSS and the acceleration threshold (linear regression test, R = 0.09, p = 0.61).

Parameters concerning the sound-movement delay had a good to excellent reliability in test-retest (same day) and between 2 separate trials (Tables 1 and 2). The acceleration threshold had a lower reliability in the same schedule but still at an acceptable level as judged by Cronbach’s alpha and (Table 1, S1 Table), and the Pearson’s correlation matrix (Table 2). However, ICC was just below the acceptable level for this parameter (Table 1).

Two subjects complained of nausea after the first trial, and nobody complained of any symptom after the second (including those who complained during the first session). One patient expressed stress for the second trial and anticipated nausea.

**Discussion**

In this study, we showed that an oscillatory movement on a swinging bed coupled to a sound signal allows estimating the movement perception delay and acceleration threshold in a non-invasive and reproducible manner in healthy individuals. The estimation of acceleration threshold was in accordance with other reports [1]. The estimation of movement perception delay with a predictable oscillatory movement and a periodic sound stimuli with variable delays led to a synchronous perception of the sound with the peak (maximal head height) in a relatively wide range of delays (535 ± 190 ms). The negative PSS suggested that generally the sound emitted before the peak was considered as synchronous in this setting.

Many studies have reported on the temporal order of sensory perceptions and the synchronous perception of these inputs [12, 13]. Indeed, the timing of these inputs is of paramount
importance in their coherence during action [13]. Previous works have investigated the delays between vestibular, visual, auditory and sensitive entries and have shown that vestibular sensations are perceived later than sound, vision and touch stimuli [14]. In these works, vestibular galvanic stimulation (GVS) or active head movements were employed to provide a precise time point for the stimuli [13, 14]. In these protocols, GVS had to occur approximately 160 ms before other stimuli to be perceived as simultaneous to them and simple reaction times for perceived head movements were significantly longer to touch, light and sound.

Based on these results, we could have expected a positive PSS (an oscillation peak before sound to be perceived as synchronous). However, the major difference between our protocol and the previous reported results is the predictability of the swinging movement by the patient and its constant periodicity. In these conditions, we can hypothesize that the mental preparation for the peak perception and its anticipation plays a major role in reducing the delay of its perception. Capacity to synchronise actions and predict timing is essential for movement stability, interaction with environment and respond to unexpected events [20]. Combining multisensory temporal information (vision, hearing, haptic, tactile, and vestibular) for movement

Fig 2. Relation between sound stimuli and bed oscillation. During the swinging bed-oscillations a beep was generated by the electronic device with an adjustable time lag. The zero was defined as the peak of the oscillation (head at its maximal height). The time lag was modified from -750 ms to +750 ms with 50 ms increments. Subjects were asked to indicate whether the sound and the peak are synchronous. The synchronous perception interval is depicted in gray. The upper and lower borders were measured. The middle of the range was defined as subjective synchronicity delay.

https://doi.org/10.1371/journal.pone.0252914.g002
synchronisation and timing has been largely investigated [20]. This synchronisation involves prediction and anticipation in rhythmic movements such as in music. The movement synchronisation can fit in a linear phase correction model [21] to estimate the temporal corrections.

**Fig 3. Dispersion of sound-peak (SP) and peak-sound (PS) thresholds, synchronous perception intervals, point of subjective synchronicity (PSS) and acceleration thresholds.** Open circles represent individual values (n = 30). Each value is the mean of 2 or 4 replicates. Horizontal bars represent mean and the error bars depict standard deviation. For the delays, the zero was defined by the peak of the bed oscillation (head at its maximal height). The point of subjective synchronicity which represents the middle of the synchronous perception interval had a negative value in all cases.

https://doi.org/10.1371/journal.pone.0252914.g003

### Table 1. Tau-equivalent reliability (Cronbach’s alpha) and intraclass correlation coefficient (ICC) for parameters measured on the swinging bed.

| Parameter              | Cronbach’s alpha | Average R | ICC  |
|------------------------|------------------|-----------|------|
| SP Threshold           | 0.92             | 0.74      | 0.76 |
| PS Threshold           | 0.81             | 0.54      | 0.39 |
| SSI                    | 0.89             | 0.68      | 0.68 |
| PPS                    | 0.89             | 0.67      | 0.62 |
| Acceleration Threshold | 0.75             | 0.42      | 0.46 |

Each parameter was measured in 2 test-retest trials (4 measures for each subject, n = 26). A Cronbach’s alpha ≥ 0.7 was considered as acceptable, ≥ 0.8 was considered as a good, and ≥ 0.9 as an excellent internal consistency for the test. R: Correlation coefficient. ICC <0.50 was indicative of poor reliability, and an ICC between 0.5–0.75 indicated moderate reliability. SP: sound-peak, PS: peak-sound, PSS: point of subjective synchronicity, SSI: subjective synchronicity interval.

https://doi.org/10.1371/journal.pone.0252914.t001
made on each movement based on previous asynchrony. Sound appears to have a prominent role among the sensory inputs for movement synchronisation [20].

In our model, subjects faced a multisensorial synchronisation task without a motor response. This task requires vestibular and auditory entries as well as a central time-keeping capacity. Similarly to other synchronization tasks with motor response, we hypothesize that subjects estimate and integrate the temporal correction in their multisensory perception and this correction modifies their perception of synchronicity.

Unfortunately, our experimental design does not allow verifying such a hypothesis. With a continuous back-and-forth sweeping of the time lag around the PSS, we could expect a progressive reduction of the SPI or a PSS approaching zero with the increasing number of sweeps.

Another hypothesis to explain our negative PSS (oscillation peak after the sound perceived as synchronous) is that before reaching the peak, the negative acceleration increases rapidly in its absolute value and this phenomenon may contribute to the inverted temporal relation between sound and movement. It would be interesting to study the effect of the sound emitted at the point of maximum positive acceleration (head at its lowest point) on the PSS.

The reaction delay to movements is crucial for balance. This delay would be the sum of the perception and the response delays. In our study, the protocol was designed in such a way that the subject had ample time (several oscillation periods for each delay) to judge and provide his/her response orally concerning the sound-movement synchronicity. Consequently, the

| Table 2. Pearson correlation matrix for test-retest in the 2 trials. |
|-----------------|-----------------|-----------------|
|                 | Retest 1         | Test 2          | Retest 2         |
| PSS             |                 |                 |                 |
| Test 1          | 0.64 [0.36–0.81] *** | 0.51 [0.16–0.75] ** | 0.41 [0.02–0.68] * |
| Retest 1        | 0.66 [0.37–0.84] *** | 0.70 [0.43–0.85] **** |                 |
| Test 2          |                 | 0.85 [0.68–0.92] **** |                 |
| SSI             |                 |                 |                 |
| Test 1          | 0.80 [0.63–0.90] **** | 0.56 [0.22–0.78] ** | 0.51 [0.15–0.75] ** |
| Retest 1        | 0.69 [0.42–0.85] **** | 0.71 [0.44–0.86] **** |                 |
| Test 2          |                 | 0.81 [0.61–0.91] **** |                 |
| PS threshold    |                 |                 |                 |
| Test 1          | 0.61 [0.32–0.79] *** | 0.12 [-0.28–0.48] | 0.13 [-0.27–0.49] |
| Retest 1        |                 | 0.38 [0.0–0.67] | 0.43 [0.03–0.70] * |
| Test 2          |                 | 0.78 [0.56–0.90] **** |                 |
| SP threshold    |                 |                 |                 |
| Test 1          | 0.78 [0.59–0.88] **** | 0.75 [0.51–0.88] **** | 0.61 [0.30–0.81] **** |
| Retest 1        | 0.79 [0.59–0.90] **** | 0.80 [0.60–0.91] **** |                 |
| Test 2          |                 | 0.84 [0.66–0.92] **** |                 |
| Acceleration threshold |                 |                 |                 |
| Test 1          | 0.46 [0.10–0.71] * | 0.67 [0.35–0.85] ** | 0.41 [0.01–0.70] * |
| Retest 1        | 0.51 [0.12–0.77] * | 0.12 [-0.30–0.50] |                 |
| Test 2          |                 | 0.50 [0.12–0.76] * |                 |

Values represent Pearson correlation coefficient R [confidence interval] and level of significance:

* p<0.05

** p<0.01

*** p<0.001, and

**** p<0.0001. Tests and retests 1 and 2 indicate results from the first and the second trials 2 to 15 days apart. PSS: Point of subjective synchronicity, SSI: subjective synchronicity interval, PS: peak-sound, SP: sound-peak.

https://doi.org/10.1371/journal.pone.0252914.t002

made on each movement based on previous asynchrony. Sound appears to have a prominent role among the sensory inputs for movement synchronisation [20].

In our model, subjects faced a multisensorial synchronisation task without a motor response. This task requires vestibular and auditory entries as well as a central time-keeping capacity. Similarly to other synchronization tasks with motor response, we hypothesize that subjects estimate and integrate the temporal correction in their multisensory perception and this correction modifies their perception of synchronicity.

Unfortunately, our experimental design does not allow verifying such a hypothesis. With a continuous back-and-forth sweeping of the time lag around the PSS, we could expect a progressive reduction of the SPI or a PSS approaching zero with the increasing number of sweeps.

Another hypothesis to explain our negative PSS (oscillation peak after the sound perceived as synchronous) is that before reaching the peak, the negative acceleration increases rapidly in its absolute value and this phenomenon may contribute to the inverted temporal relation between sound and movement. It would be interesting to study the effect of the sound emitted at the point of maximum positive acceleration (head at its lowest point) on the PSS.

The reaction delay to movements is crucial for balance. This delay would be the sum of the perception and the response delays. In our study, the protocol was designed in such a way that the subject had ample time (several oscillation periods for each delay) to judge and provide his/her response orally concerning the sound-movement synchronicity. Consequently, the
measured delays do not estimate the reaction time but rather the tolerance of the central integration system for the judgement of synchronicity, and indirectly the movement perception delay.

The precision of the upper and lower limits of the subjective synchronicity interval (SSI), and consequently its center (PSS) depends on the increments. It should be underlined that PSS is not directly signaled by the patient but calculated from the measured upper and lower borders of the SSI which are the sound-peak and the peak-sound thresholds. These thresholds are probably prone to some variations related to the experimental conditions (e.g., bed acceleration, patient’s concentration) and this may explain the dispersion of the values. Moreover, while the 50-ms increments allowed us to sweep a large range of delays in a reasonable time, they could limit the precision of the measurements. This could be suspected especially for the upper threshold which has a significant dispersion. Future studies, with smaller time lag increments focusing on the determination of these borders with various paradigms (ascending, descending, and random lags) will be helpful for the standardization of the test.

The vestibular function deteriorates with age [22]. After the age of 60, a reduction in the number of vestibular sensory hair cells, neurons in the scarpaganglion, and those in the vestibular nuclei is observed [22, 23]. The reduction of otoconia both in number and volume together with alterations of the their composition are associated to a more frequent detachment of these structures from the otolithic membrane and to changes in the organ function [22–24]. These deteriorations are associated the reduction of vestibulo-ocular reflex gains [22, 23], cervical and ocular vestibular evoked myogenic potentials [25, 26]. This gradual decline potentially participates in a poorer detection of body movements.

Moreover, the multisensorial integration appears to deteriorate in senior subjects [10, 20]. While the ability of detecting errors in a rhythmic sound sequence remains intact with age [27], the multisensory synchronisation of sound and touch [28] or sound and vision [29] become less performant in senior. The effect of aging on sensory synchronisation is not exclusively due to central processing, since the alteration of one of the inputs may also disturb the perceptual synchronisation [20]. In our protocol, it is impossible to distinguish a peripheral deficit from a processing abnormality, but in combination with more peripheral tests, the swinging bed evaluation will potentially provide interesting indications on the mechanisms of dizziness and the risk of falls.

Perceptual acceleration threshold for linear displacements has been already reported in several publications [1, 30–32]. Although authors stated that the movement detection was mainly insured by the otolithic function, experimental setups could not totally suppress the tactile and somatosensory cues. The reported acceleration thresholds appeared to be influenced by the stimulation repetition frequency ranging from 1.8 to 8.5 cm/s$^2$ in healthy subjects which is in accordance with our findings. Acceleration threshold measurements had an acceptable test-retest reproducibility, making this parameter a candidate for routine clinical investigation [1]. Interestingly, age also appears to be positively correlated to the anteroposterior acceleration threshold [1], and this observation is in line with the decreased ability of detecting movements in elderly [11].

Our procedure had several limitations. By delivering a pendular movement in a supine position, we stimulated several vestibular captors. The participation of superior and posterior semicircular canals, and both utricular and saccular maculae in the detection of the pendular movement is probable since the acceleration has horizontal, vertical and rotatory components in the vertical plane of the oscillation. Moreover, even if all sensory inputs in exception of auditory and vestibular entries were minimized, the presence of other cues such as somatosensory information could not be excluded at supraliminary stimulation levels. The presence of uncontrolled sensory cues would increase the intraindividual and inter individual variabilities of the
parameters, but our measures appeared reproducible and coherent indicating the stability of the sensory cues during the trials. Further studies will probably elucidate the participation of different inputs and central processing in this test. Another issue is the detection of the sound source movement relative to the head position by monaural (spectral changes, doppler effect) [33] or binaural functions (interaural time and intensity differences) [34]. These effects are sensitive to signal duration [35]. Considering the shortness of the sound stimuli (5 ms, 0.16% of the oscillation period), this effect can be considered as negligible.

The advantages of this system in comparison to what is presented in the literature to estimate the movement perception is that the swinging bed remains easy to install and calibrate and appears non-invasive. It is applicable to fragile, handicapped, senior subjects and children. Instructions are easy to understand and the test procedure is relatively short.

**Conclusion**

Our swinging bed coupled to a sound source provided reproducible and coherent perceptual acceleration threshold and movement perception delay in healthy human subjects. This non-invasive and simple device potentially allows exploring otoneurological diseases and fallers.

**Supporting information**

S1 Table. Individual data concerning swinging bed measurements and test tolerance. Acceleration thresholds are expressed as swinging bed deviations in cm. This deviation was converted to maximal tangential acceleration (a, cm/s$^2$) by the following formula: $a = 9.81 \times \left(\frac{d}{240}\right) \times 100$.

S1 Appendix. Individual data concerning swinging bed measurements and test tolerance. Acceleration thresholds are expressed as swinging bed deviations in cm. This deviation was converted to maximal tangential acceleration (a, cm/s$^2$) by the following formula: $a = 9.81 \times \left(\frac{d}{240}\right) \times 100$.

**Author Contributions**

**Conceptualization:** Michel Toupet, Alexis Bozorg Grayeli.

**Data curation:** Maxime Guyon, Cyrielle Chea, Davy Laroche.

**Formal analysis:** Maxime Guyon, Davy Laroche, Alexis Bozorg Grayeli.

**Investigation:** Cyrielle Chea, Audrey Baudet, Michel Toupet, Alexis Bozorg Grayeli.

**Methodology:** Davy Laroche, Isabelle Fournel, Audrey Baudet, Michel Toupet, Alexis Bozorg Grayeli.

**Project administration:** Alexis Bozorg Grayeli.

**Software:** Audrey Baudet.

**Supervision:** Isabelle Fournel.

**Validation:** Alexis Bozorg Grayeli.

**Writing – original draft:** Maxime Guyon, Davy Laroche, Michel Toupet, Alexis Bozorg Grayeli.

**Writing – review & editing:** Alexis Bozorg Grayeli.
References

1. Kingma H. Thresholds for perception of direction of linear acceleration as a possible evaluation of the otolith function. BMC Ear Nose Throat Disord 2005; 5: 5. https://doi.org/10.1186/1472-6815-5-5 PMID: 15972096

2. Nooij SAE, Nesti A, Büllhoff HH, Pretto P. Perception of rotation, path, and heading in circular trajectories. Exp Brain Res 2016; 234: 2323–2337. https://doi.org/10.1007/s00221-016-4638-0 PMID: 27056085

3. Nesti A, Barnett-Cowan M, Macneilage PR, Büllhoff HH. Human sensitivity to vertical self-motion. Exp Brain Res 2014; 232: 303–314. https://doi.org/10.1007/s00221-013-3741-8 PMID: 25567421

4. Lewis RF, Priesol AJ, Nicoucair K, Lima K, Merfeld DM. Dynamic tilt thresholds are reduced in vestibular migraine. J Vestib Res 2011; 21: 323–330. https://doi.org/10.3233/VES-2011-0422 PMID: 22349397

5. Peel NM. Epidemiology of falls in older age. Can J Aging. 2011; 30: 7–19. https://doi.org/10.1017/S071498081000070X PMID: 21401978

6. Feder G, Cryer C, Donovan S, Carter Y. Guidelines for the prevention of falls in people over 65. The Guidelines’ Development Group. BMJ 2000; 321: 1007–1011. https://doi.org/10.1136/bmj.321.7267.1007 PMID: 11039974

7. Iwasaki S, Yamasoba T. Dizziness and Imbalance in the Elderly: Age-related Decline in the Vestibular System. Aging Dis 2015; 6: 38–47. https://doi.org/10.14336/AD.2014.0128 eCollection 2015 Feb. PMID: 25657851

8. Cyran CA, Boegle R, Stephan T, Dieterich M, Glasauer S. Age-related decline in functional connectivity of the vestibular cortical network. Brain Struct Funct 2016; 221: 1443–1463. https://doi.org/10.1007/s00429-014-0983-6 PMID: 25567421

9. Pauelsen M, Vikman I, Johansson Strandvikst V, Larsson A, Röijezon U. Decline in sensorimotor systems explains reduced falls self-efficacy. J Electromyogr Kinesiol 2018; 42: 104–110. https://doi.org/10.1016/j.jelekin.2018.07.001 PMID: 30015133

10. Setti A, Burke KE, Kenny RA, Newell FN. Is inefficient multisensory processing associated with falls in older people? Exp Brain Res 2011; 209: 375–384. https://doi.org/10.1007/s00221-011-2660-z PMID: 21293851

11. Wright ML, Adamo DE, Brown SH. Age-related declines in the detection of passive wrist movement. Neurosci Lett 2011; 500: 108–112. https://doi.org/10.1016/j.neulet.2011.04.007 PMID: 21704124

12. Lupo J, Barnett-Cowan M. Impaired perceived timing of falls in the elderly. Gait Posture 2018; 59: 40–45. https://doi.org/10.1016/j.gaitpost.2017.09.037 PMID: 28987765

13. Barnett-Cowan M, Harris LR. Perceived timing of vestibular stimulation relative to touch, light and sound. Exp Brain Res 2009; 198: 221–231. https://doi.org/10.1007/s00221-009-1779-4 PMID: 19352639

14. Barnett-Cowan M. Vestibular perception is slow: a review. Multisens Res 2013; 26: 387–403. https://doi.org/10.1163/22134808-00002421 PMID: 24319930

15. Mahoney JR, Cotton K, Vergheze J. Multisensory Integration Predicts Balance and Falls in Older Adults. J Gerontol A Biol Sci Med Sci 2019 Aug 16; 74(9): 1429–1435. https://doi.org/10.1093/gerona/gly245 PMID: 30357320

16. Versino M, Mandalà M, Colnaghi S, Ricci G, Faralli M, Ramat S. The integration of multisensory motion stimuli is impaired in vestibular migraine patients. J Neurol 2020; 267: 2842–2850. https://doi.org/10.1007/s00412-020-09305-6 PMID: 32448951

17. Bujang MA, Omar ED, & Baharum NA. A Review on Sample Size Determination for Cronbach’s Alpha Test: A Simple Guide for Researchers. Malays J Med Sci, 2018; 25: 85–99. https://doi.org/10.21315/mjms2018.25.6.9 PMID: 30914882

18. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005; 19: 231–240. https://doi.org/10.1519/15184.1 PMID: 15705040

19. Wing AM, Doumas M, Welchman AE. Combining multisensory temporal information for movement synchronisation. Exp Brain Res 2010; 200: 277–282. https://doi.org/10.1007/s00221-009-2134-5 PMID: 20039025

20. Schulze HH, Vorberg D. Linear Phase Correction Model for Synchronization: Parameter Identification and Estimation of Parameters. Brain and Cognition 2002; 48: 80–97. https://doi.org/10.1006/brcg.2001.1305 PMID: 11812034
Agrawal Y, Van de Berg R, Wuyts F, Walther L, Magnusson M, Oh E, et al. Presbyvestibulopathy: Diagnostic criteria Consensus document of the classification committee of the Bárány Society. J Vestib Res 2019; 29: 161–170. https://doi.org/10.3233/VES-190672 PMID: 31306146

Ji L, Zhai S. Aging and the peripheral vestibular system. J Otol 2018; 13: 138–140.https://doi.org/10.1016/j.joto.2018.11.006 PMID: 30671091

Igarashi M, Saito R, Mizukoshi K, Alford BR. Otoconia in young and elderly persons: a temporal bone study. Acta Otolaryngol Suppl. 1993; 504: 26–29. https://doi.org/10.3109/00016489309128117 PMID: 8470528

Tseng CL, Chou CH, Young YH. Aging effect on the oculovestibular-evoked myogenic potentials. Otol Neurotol 2010; 3: 959–963. https://doi.org/10.1097/MAO.0b013e3181e8f1a PMID: 20601917

Li C, Layman AJ, Carey JP, Agrawal Y. Epidemiology of vestibular evoked myogenic potentials: Data from the Baltimore Longitudinal Study of Aging. Clin Neurophysiol 2015; 126: 2207–2215. https://doi.org/10.1016/j.clinph.2015.01.008 PMID: 25703943

Turgeon M, Wing AM, Taylor LW. Timing and aging: slowing of fastest regular tapping rate with preserved timing error detection and correction. Psychol Aging 2011; 26: 150–161. https://doi.org/10.1037/a0020606 PMID: 20973598

Elliott MT, Wing AM, Welchman AE. The effect of ageing on multisensory integration for the control of movement timing. Exp Brain Res 2011; 213: 291–298. https://doi.org/10.1007/s00221-011-2740-x PMID: 21688143

Bedard G, Barnett-Cowan M. Impaired timing of audiovisual events in the elderly. Exp Brain Res 2016; 234: 331–340. https://doi.org/10.1007/s00221-015-4466-7 PMID: 26474576

Gundry AJ. Thresholds of perception for periodic linear motion. Aviat Space Environ Med 1978; 49: 679–686. PMID: 306819

Benson AJ, Hutt EC, Brown SF. Thresholds for the perception of whole-body angular movement about a vertical axis. Aviat Space Environ Med 1989; 60: 205-213. PMID: 2712798

Benson AJ, Spencer MB, Stott JR. Thresholds for the detection of the direction of whole-body linear movement in the horizontal plane. Aviat Space Environ Med 1986; 57: 1089–1096. PMID: 3790028

Grothe B, Pecka M, McAlpine D. Mechanisms of sound localization in mammals. Physiol Rev. 2010; 90: 983–1012. https://doi.org/10.1152/physrev.00026.2009 PMID: 20664077

Baumann C, Rogers C, Massen F. Dynamic binaural sound localization based on variations of interaural time delays and system rotations. J Acoust Soc Am. 2015; 138: 635–650. https://doi.org/10.1121/1.4923448 PMID: 26328682

St George BV, Cone B. Perceptual and Electrophysiological Correlates of Fixed Versus Moving Sound Source Lateralization. J Speech Lang Hear Res. 2020; 63: 3176–3194. https://doi.org/10.1044/2020_JSLHR-19-00289 PMID: 32812839