Sound localisation under vestibular conditions

Abstract

Sound localisation is important for someone's spatial awareness when there is no visual information from the origin of the sound. The accuracy of localisation can be affected by vestibular stimulation due to multisensory integration. Multisensory integration depends on different streams of sensory information, e.g. sound and visual stimuli presented simultaneously, that are integrated depending on the reliability of these information streams. The interaction of auditory and vestibular information depicts a yet sparsely examined form of multisensory integration. The newly setup of the vestibular chair allows to explore this interaction. The vestibulair chair was used to test whether sound localisation is possible in the vestibular chair. Subsequently, we tested the hypothesis that vestibular stimulation could affect sound source localisation. First the acoustic characteristics of the set-up were determined. Next, 7 participants performed the sound localisation experiment, in which they had to indicate the perceived sound location by pointing their head towards it. The location of 63 speakers emitting 65 decibel, broadband sounds had to be identified by human subjects while moving in a sine, with a vestibular noise pattern and stationary (i.e. the standard localisation experiment) he gain in the standard localisation experiment was below that of other setups, however the chair can still be used with the standard localisation experiment as baseline. The sine and noise movement had none to little effect on the performance of subjects to locate sound sources. In the near future,the chair can be used for further research on multisensory integration.

Introduction

Sound localisation is a vital evolutionary survival feature for detecting opportunities and danger from outside the visual field. In humans, sounds can be localised in 2 dimensions: i.e. in the horizontal (azimuth) and the vertical plane (elevation). While in the natural world a sound typically originates from a single point in space, the brain incorporates different strategies to compute this location. For the azimuth it predominantly depends on 2 complementary mechanisms: i.e. the interaural time difference (ITD) and interaural level difference (ILD) cues, whereas sound elevation is assisted by the spectral features of the head, shoulder and pinna in particular.

The ITD is a temporal cue, based on the time difference it takes a sound to reach both ears. For example, a sound originating from the left of the head at a right angle (i.e. -90° azimuth) will also reach the left ear before it reaches the right with a maximal time difference, whereas sounds originating straight ahead will reach both ears simultaneously with no time differences. These ITD's are thus indicative and utilized for computing the location in the azimuth direction. ITD's allow for meaning full sound localisation for low frequency sounds, as the long waves can bend around the head (Wright and Fitzgerald, 2001).(Fig 1)

For high frequency sounds the brain depends on the ILD cues. The auditory shadow of the head (or head-shadow effect; HSE) effectively blocks and attenuates the intensity of the higher frequencies in one ear. Similar to ITD's, these level dissimilarities between the ears, result in differences in the perceived azimuth location (Wright and Fitzgerald, 2001) (Fig 1).

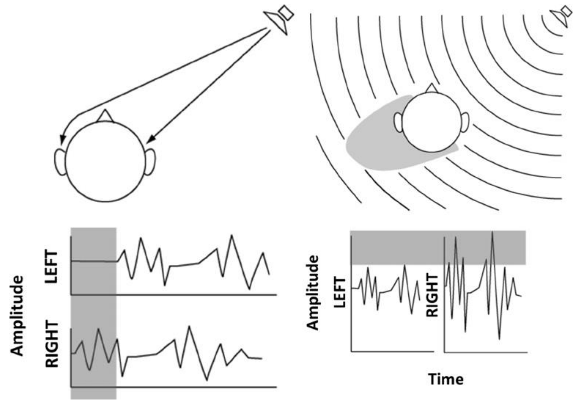


Figure 1 : Left ITD and on the right ILD. In the picture it is clear that when the brain uses ITD the response of the left ear is delayed while the response amplitude is the same. Opposed to ITD, the ILD cue will use the attenuation of the head as response of the HSE as information for sound localisation. (Zhong, X. et al,2015).

As both ears are aligned horizontally, the brain cannot depend on ITD or ILD's for vertical sound localisation. The elevation component is determined by means of the spectral cues of the individual. The shape of the pinna acts as an angle dependent filter. Besides the pinna, the head and surrounding body parts also contribute to elevation percept and together they comprise the head transfer function (HTRF). The HTRF is unique and has to be learned by the brain (Risoud et al, 2018). Low frequencies contribute less to elevation percept due to the small size of the pinna, as the interaction with the outer ear relies on short waves that can be reflected in such a tight space (Risoud et al, 2018).

Finally, the percept of distance of a sound relative to the receiver is thought to be contingent solely on its intensity (Ahveninen et al, 2014). Beside this influence on the sense of depth, it is thought that the sound intensity does not affect localisation behaviour for sounds exceeding the detection threshold. Due the lower energy that is collected from both high and low frequency sounds near this threshold. In elevation, however, the degrading ability for accurate localisation is much harsher due the narrower band of frequencies available (Su and Recanzone, 2001).

Inside the inner ear lay also the vestibular organs, which are responsible for the sense of self motion and spatial orientation. The system consists of three perpendicular semicircular canals, that are filled with a fluid (i.e. endolymph), and two other structures that are called the saccule and utricle. During rotation of the head, the fluid inside the semicircular canals will start to move albeit with some lag due to inertia. This relative movement of the fluid inside the canals, detected by the hair cells, is ultimately converted into a percept of movement. The saccule and utricle provide information about head position in respect of gravity. This is accomplished by the otolith crystals, which displaces when the head tilts and leads to a detection in linear acceleration (Lewald and Karnath, 2002).

Vestibular information is known to influence sound localisation perception, but major interactions are yet to be discovered(Lewald and Karnath, 2002). When the auditory system and vestibular system are stimulated simultaneously they have joint projections to some cortical areas, such as the superior temporal gyrus and the posterior insula (Oh et al, 2018). Moreover auditory processing in these areas are superimposed by vestibular input, which suggest a multisensory nature at these loci. Furthermore these areas are associated with higher order auditory functions, such as sound localisation (Oh et al, 2018).

Multisensory integration is used by the brain to compute senses and makes a signal stronger than the signals of the senses individually added up. The problem with adding different senses to create a uniform perceptis is that every modality created from different mechanisms e.g photoreceptors in the retina and sterecilla in the ear.
Furthermore, the amount the brain depends on one modality changes with different environments or conditions. For example, in a light condition the brain uses visual input to determine the shape of an object in contrast when in darkness touch inputs will prevail over visual inputs. When both inputs are less reliable the brain computes two less reliable cues to achieve a more reliable stimuli (Deneve and Pouget, 2004)(Fig 2). The integration of vestibular and auditory stimuli has a strong presence in the superior colliculus (Meredith and Stein, 1986).

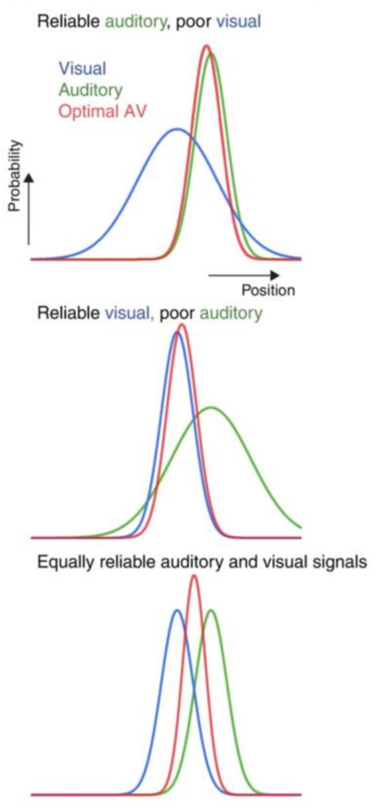


Figure 2: Example how multisensory integration comes to be. Demonstrated with auditory and visual stimuli. (Chandrasekaran. C, 2017)

The basic principle in how the fusion of two senses are integrated is thought to be in concordance to the Bayesian probability theory. This theory gives a mathematical framework in which different cues can be added. There is an uncertainty of how the senses are encoded and how much information the senses can collect. The theory depends on the likelihood, the prior and the posterior. The likelihood is the probability of the data corresponding with the hypotheses. The prior is the knowledge before access to the data. Lastly the posterior which determines the likelihood of the hypotheses in regards to the actual data. These parameters can be written down in a formula(fig..) and can be transformed into a generative model, which can model how known data was shaped by underlying causes. It is thought that the brain computes via this model. The brain has to cope with an enormous data stream and from this has to calculate a best hypothesis. (Olshausen, B. A. 2004).)

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

Fig(3) The formula for the bayesian probability theory. Where H = *the hypothesis,* P(D|H) *is the likelihood, P(H)= the prior. P(*H|D*) is the posterior and P(D) is usually an ignorable normalizing constant. (Olshausen, B. A. 2004).)*

In case of two cues from different modalities the variance is lower for the bimodal estimate than for the unimodal estimates, so the combination of two cue makes the perception of an event more reliable. (Angelaki, D. E., Gu, Y., & DeAngelis, G. C. 2009) The bimodal estimate will be between the two unimodal estimates, the unimodal estimates are weighted and if one cue is more reliable it will have a stronger influence on the bimodal estimate (Deneve, S., & Pouget, A. 2004).

Understanding multisensory integration is important for understanding how the brain creates a stable and reliable percept of the world. The interaction between vestibular stimulation and sound localisation has not yet been thoroughly investigated however, it is believed that multisensory integration occurs in these circumstances(Oh et al, 2018). Therefore the goal of the current study is to investigate how vestibular information influences sound localisation. The vestibular chair was used to achieve this goal. First it is paramount to examine if sound localisation in the chair is possible under normal circumstances. Only if the results were sufficient the next question could be examined: Can subjects accurately localise sounds while being moved?

Methods

Vestibular chair

In the centre of the room is the vestibular chair with around it a partial sphere (i.e the hemisphere). The chair can independently rotate around two axis. The black frame rotates around the vertical axis and the blue frame rotates in the horizontal axis. The red frame can be adjusted before the experiment and determines the orientation of within the blue frame. These frames are constructed to have minimal sound interference. The chair itself is positioned in the red frame in the middle of the set up. The position of this chair can be adjusted in the direction up-and-down and back-and-forth. Due adjustment of the setup different body sizes could participate without any differences. Onto the red frame is a wooden frame fixed which holds the acoustic and visual stimuli. Due to the fixed frame the position of the stimuli can never change relative to the subject(Fig 3).

On the wooden frame are 63 speakers (Cambridge Audio MINX MIN12, Cambridge) distributed over the horizontal plane, vertical plane and between these two, with a higher density in the horizontal cardinal direction (every 5°). Each speaker has a green/red led attached to (itBIVAR 5BC-3-CA-F; peak wavelengths respectively 625nm and 568nm) . Each of these speaker-LED-combinations are mounted to have a distance of 1m to the subject's head. Visual, auditory and audiovisual stimuli could be presented via the speakers. It was tested if a speaker was truly on the desired azimuth, elevation and distance. This was done with a distometer. This device emits an infrared laser with which it measures the distance. Together with an angular meter mounted on a tripod, the precise angles were determined. These differences were incorporated by the data acquisition. Fig 4 shows the desired and the actual positions of the speakers and Fig 5 shows there desired and actual distance from the chair.

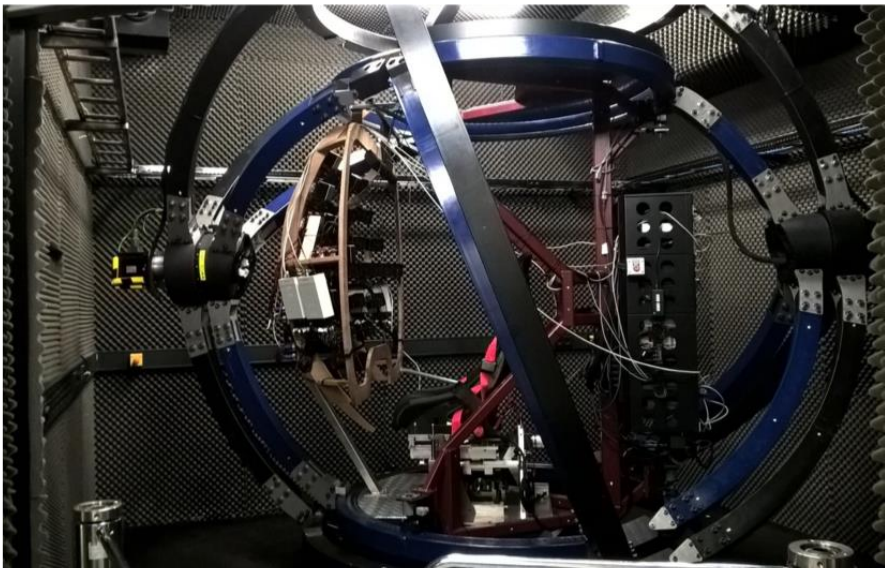


fig 3: the vestibular chair

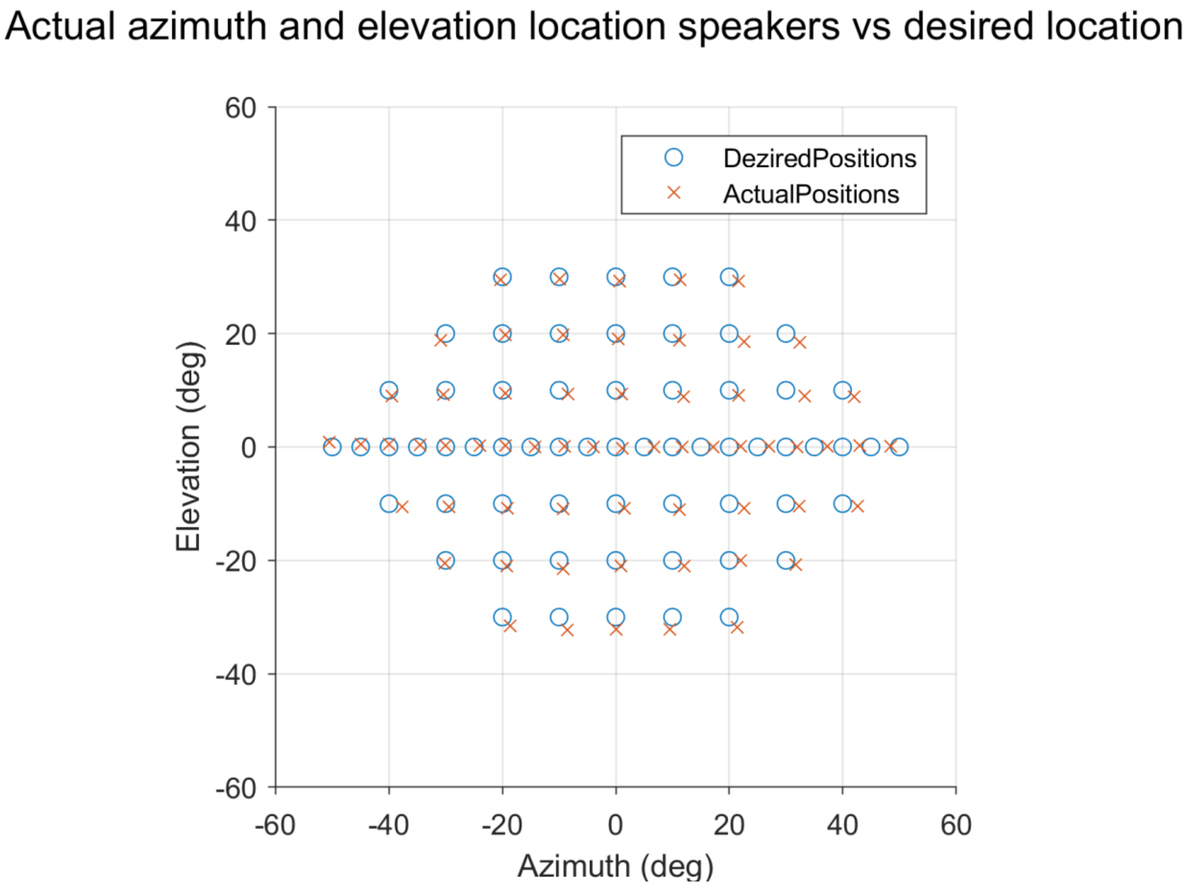


Figure 4: The actual positions of the speakers against the desired positions of the speakers. The actual positions are not too far away from the desired position on average. The accuracy is decreased when the speaker has a greater distance from the speaker in the middle (0, 0)

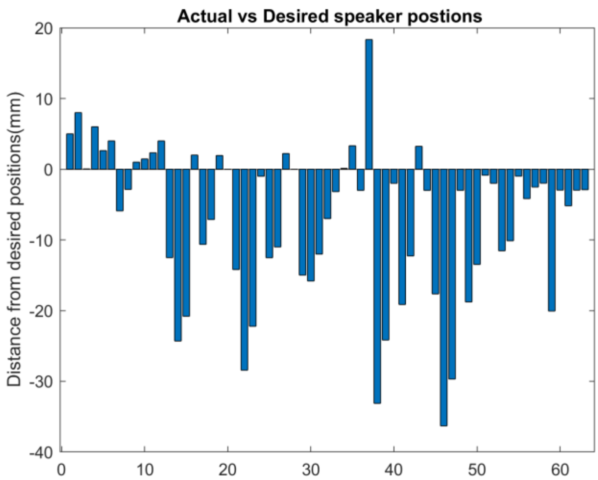


Figure 5: The actual distance from the head to hemisphere compared to the desired distance of one meter. On the x-axis are the different speakers, they are sorted from positive to negative azimuth and the same azimuth are sorted from positive to negative elevation.

The room in which the vestibular chair is located was acoustically shielded (Uxem, Lelystad) and designed to prevent acoustic reflections. There are some safety features, such as a couple of emergency stop buttons and object detection scanners on both sides of the room.The room itself has a surface of 19.0m² and is around 3.6 m high. For further safety measurements, the chair can only be controlled outside of the room.

The experimenter PC

The control of the chair is executed via the custom made software 'vPrime' developed in Matlab on the experimenter PC. Furthermore, the experimenter PC can connect to the Pupil PC and the Optitrack PC. These systems handle the data acquisition from eye and head movements. The experimenter PC also connects with Lab Streaming Layer (LSL) to synchronise all data streams, and The Tucker Davis Technologies, which is used to present the stimuli.

Optitrack

An Optitrack system (V120:Trio) was used for the detection of head movements. This consisted of 3 motion capture cameras above the hemisphere, a headband on which 5 Infrared markers are attached and together forma rigid body. The Optitrack PC was located in the chair and the Motive software was used to track the position and the orientation of the rigid body in 3D. The orientation of the head was converted from quaternion to azimuth and elevation and these orientations were then compared to the actual stimuli\us location.

The Pupil Labs

The Pupil Labs eye tracker was used for detection of eye movements. The eye tracker consists of a frame (without glasses) were two infrared cameras are attached on. One camera on the frame was targeted to the world view of the subject, this was used to calibrate before the experiment. The other camera was targeted on the eye of the subject to estimate the orientation of the eye of the participant. The pupil capture software was executed on a separate PC, which was also located in the chair.

Although the eye tracker was used in both experiments, unfortunately The data from the eye tracker could not be used Due the low coincidence. The pupil could not be tracked in the dark due to its larger diameter. Furthermore the eye tracker was also less stable when the eye moved far away from the center. Lastly the efficiency varied highly between subjects, as some had larger pupils than others. The goal was to transfer ''head in space'' (from optitrack data) and 'eye in head' (from eye tracker data) to ''eye in space'. Due to the missing 'eye in head' data the head roll of the subject couldn't be accounted for, which would give more realistic data. However the data is still reliable as that head movements are more prominent than eye movement when presented with an auditory stimulus (Goossens, H. H., & Van Opstal, A. J, 1997).

The Tucker Davis Technologies (TDT)

The TDT was used for used for data acquisition, stimulus generation and was in charge of stimulus presentation. The TDT has several components the RZ6, stereo amplifiers (2x), Relays (4x) and the RCX-circuits. These components together give rise to the stimulus generation. The sounds are generated real time in the TDT setup and the LED timing is also controlled by the TDT.

Lab Streaming Layer (LSL)

The optitrack, pupil labs and stimulus generation all have different time stamps and different timing in starting from the experimenter computer. The LSL is used to correct the timing to synchronise all data streams. The custom software ‘vPrime’ pulls the Pupil-labs data, the Optitrack data, and the event data of the TDT, which contains information about the onset and offset of the stimuli from the data streams received through the Lab Streaming Layer framework (C. Kothe, "Lab streaming layer (lsl)", 2013).

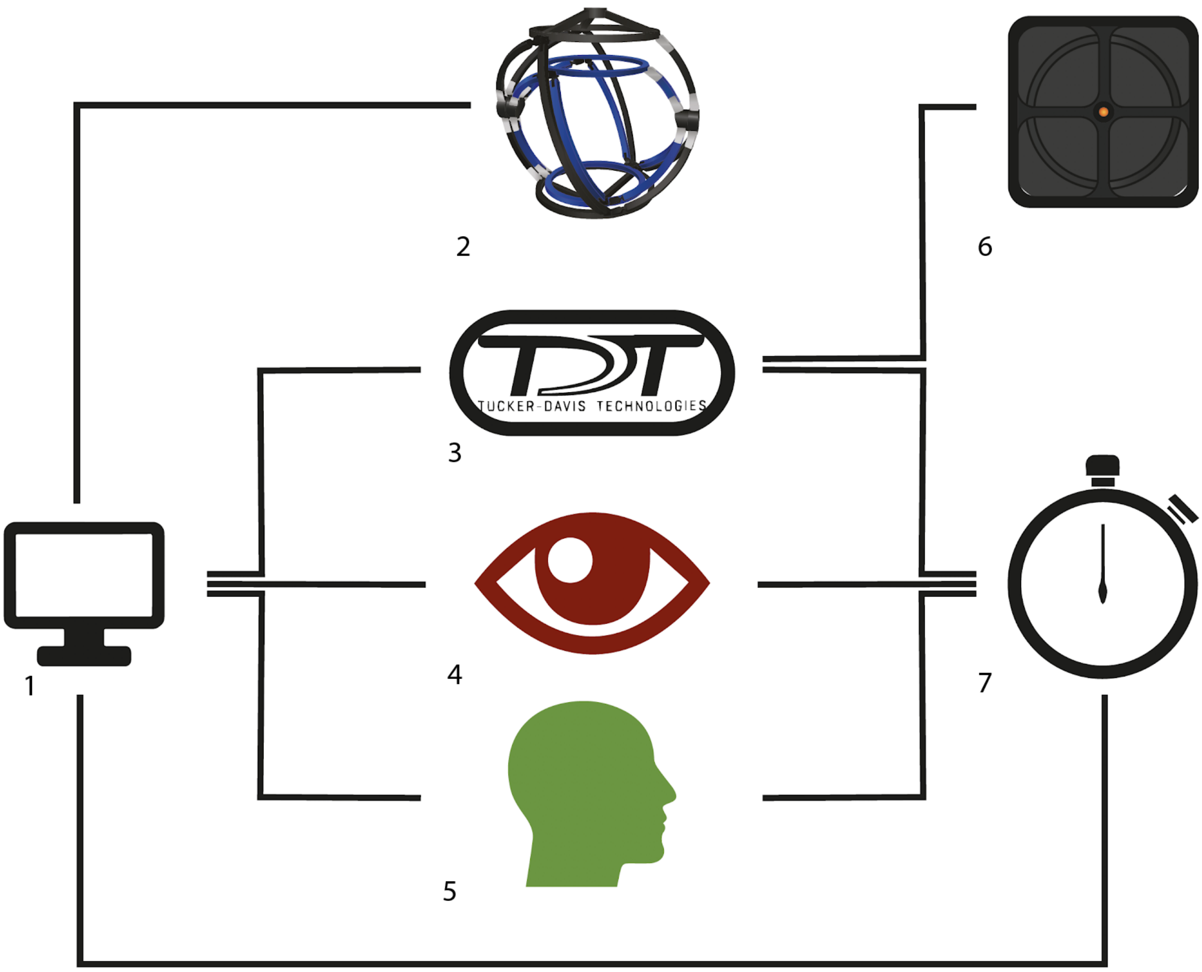


Figure 6 Connections, systems and setup Vestibular Chair. (1)The experimenter PC, (2) the black and blue frames, (3) The TDT, (4) the eye tracker, (5) the optitrack, (6) speaker and (7) the LSL

Acoustic properties of the set-up

To make sure that the data that will be collected is correct there is a need to characterize the set-up. First, the speakers where checked if they all could emulate the correct sound and intensity via projecting sweeps. Due to the number of frames which support the chair there was a need to determine how much these frames reflected sounds which might create a false origin of sound, this was tested with click sounds. The computer that runs the software for the chair is located in the room and makes background noise when powered on. Therefore the background noise had to be determined for the computer, and also in general. The next check was to make sure the setup we used was linear. This was done by measuring pure tones and looking if the gain was the same over a couple of points.

Protocol:

Experiment 1:

Four subjects (three males and one female) without any hearing deficiencies were informed about the goal of the study and participated voluntarily. The subjects were placed and fastened into the chair. Subsequently the chair would be adjusted for the subject to make sure that the eyes of the subject were at the same height as the central speaker. The subject had to perform three different localisation conditions i.e 1: localisation without movement, 2: localisation with horizontal sine movement which had an amplitude of 40 degrees and a frequency of 0,2 Hz and 3: localisation with a horizontal noisy signal with a maximal amplitude of 20 degrees. Each experimental block was repeated 3 times, resulting in a total of 9 blocks. After each condition the subject was asked to report on how the block went and if they were ready for the next block. Each block consisted of 63 trials. Each single trial started with switching on and off the fixation led which was located in the most central speaker. Hereafter, one of the 63 speakers made a noise without repetition of the same speaker in a different trial within the block. The subject had to wear a head tracker on which a rod was attach which had a led light fixed onto the end. The subject was instructed to point the head tracker first to the fixation led at the start of the trial, hereafter the subject had to point the head tracker to the perceived location of the sound.

Experiment 2:

To determine if there were any problems with the optitrack or the actual speakers positions a second experiment was carried out. There were three subjects (two males and one female) without any hearing deficiencies who all performed the same conditions as in experiment 1 and an additional visual condition. This condition was a visual cue without sound. Therefore the subject could accurately point his optitrack to the led light on the speaker. Hereby measuring the difference between input from output would give clearance about any problems regarding the optitrack and the actual speaker positions. Each of the conditions were carried out once per subject. Only the visual condition did not use all of the 63 speakers, but instead used 32 random speakers.

Data analysis

To determine whether the subject correctly localised the sounds, head saccades had to be detected in the Optitrack data. A custom made matlab script (pa_sacdet) was used to detect saccades based on velocity thresholds. The parameters used for the detection of saccades were based on real saccades (Goossens, H. H. L. M., & Van Opstal, A. J., 2006). However the length of the saccade could manually adjusted so that the whole movement from start to end could be detected (Fig 7). Subsequently, various other custom made matlab scripts were used to further analyse the data. Target-response plots were constructed to compare the endpoint of the head saccade with the location of the sound. In addition, regression analyses were performed to test whether the subjects correctly localised the sounds for the different vestibular conditions. . In addition, the mean error (i.e. the difference between target and endpoint head saccade) were computed for the different conditions and a student t-test was used to determine whether the localisation was significantly different between conditions.

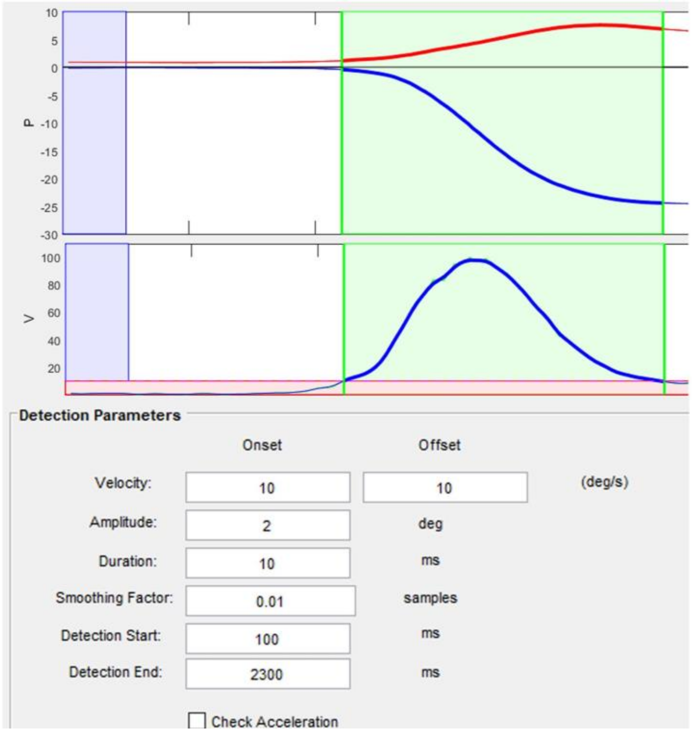
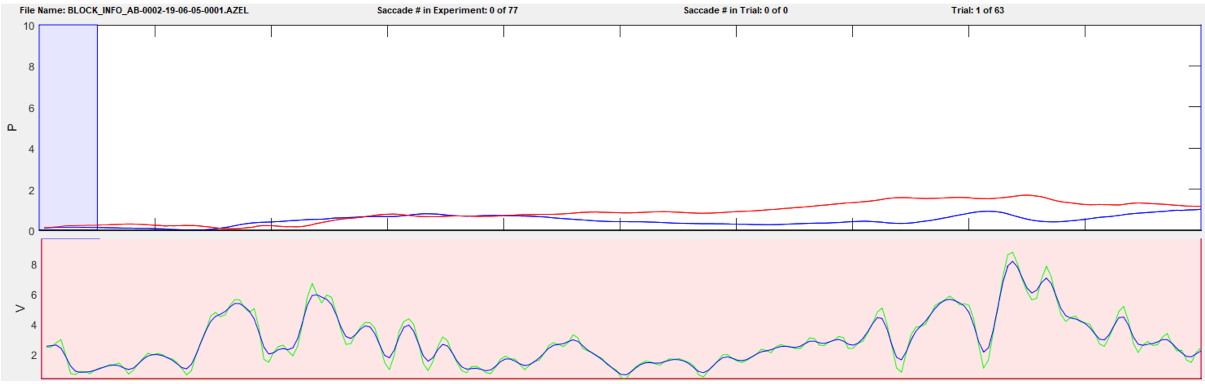


Figure 7: fine tuning saccade program with on the below part detection parameters for saccade detection. The above lines indicate the displacement of the amount of angular degrees. The below line is the velocity of this displacement.

The data that had to be pre-processed by the pa_sacdec program had some irregularities. Occasionally the displaced angular degree line showed a step by step pattern instead of a fluent displacement. Due the detection parameters some trials did not show a saccade. Therefore some data from some speakers a missing per subjects(Fig 8). The reason could be that the subject was unconcentrated or found the stimuli to difficult and responded with a no response.



(Fig 8) a trial in which there was not detectable saccade. The velocity did not reach the threshold and therefore the saccade in this trials remained undetected

irregularities

Due the safe duration of the rotation of the chair the chair stopped after 46 trials by both of the two moving conditions. The subjects proceeded with localisation after the chair stopped till all the 63 trials were completed. Therefore there was data collected from two additional conditions i.e: the stopped sine movement and the stopped noise movement, but these were not significant in any way (appendix). For noise movement There were also some restraints to ensure safety. An amplitude above 20° would often result in an unsafe velocity profile.

Data from subject 5 who participated in the second experiment was unstable, for an unknown reason the optitrack event were less than other subjects. Resulting in uncertainty about the timing of the optitrack in regards to the presented stimulus. Therefore the data from subject 5 was unused for the analysis.

Subject 3 reported after a few blocks to have annoyance form the bright led light attached to the optitrack. Therefore it was decided to cut the experiment short.Instead of performing in all the conditions thrice, he performed the conditions twice.

Results

The raw data could be efficiently translated into input-output data for both the azimuth and elevation angles with relatively low loss of data.

The localisation performance for the different vestibular conditions is presented in Fig. 9. When moving to the perceived position of the speaker, subjects tend to undershoot in both azimuth and elevation angles. Furthermore subjects who did the standard localisation condition in the first experiment had a lower gain than expected(Fig 9), in particular S2 and S3. Next to that there is a positive bias when locating the elevation angles, especially with some subjects (table 1 and 2), which means that subjects tend to perceive the sound at a higher location than it was presented.

To check whether the sound localisation of the participants improved over time due to learning effects, or deteriorated due to fatigue or lapses in attention, we compared the sound localisation between different blocks of the same condition (Fig 10 and table 3). There were a couple of small differences in gain, bias and error, but no major differences between the blocks. .

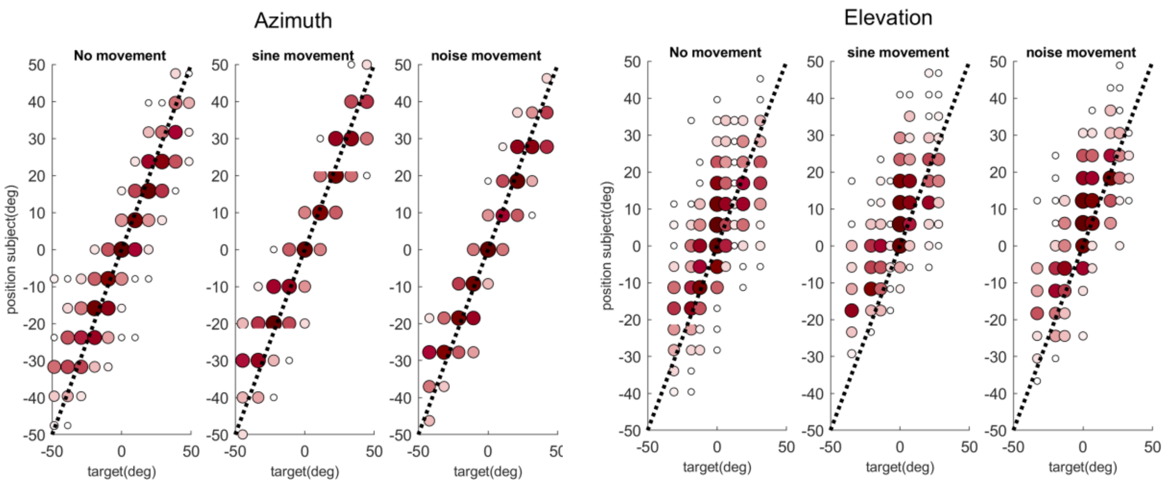


Figure 12: bubble plot azimuth and elevation. The darker the red the higher the agglomeration of trials in that area. The black dotted line is the optimal line as if there were no faults. The azimuth is almost in in the same line as the optimal line, however the line is somewhat skewed towards somewhat more horizontal line. This indicates that that the subject perceived the sounds closer to the middle speaker than the actual source of the sound. This phenomenon also affects elevation localisation were the line is also skewed. The perceived positions here were systematically higher than the actual source of sound.

azimuth	Nom gain	Nom bias	Sm gain	Sm bias	Nm gain	Nm bias	V gain	V bias
S1	0.8139	1.1921	0.7976	1.4075	0.9179	3.3874		
S2	0.6276	-0.7946	0.7628	1.5801	0.7426	-0.7217		
S3	0.6971	1.2669	0.7882	1.2087	0.7608	0.7180		
S4	0.8820	-3.7596	0.9805	-1.2776	0.9130	-3.4096		
S6	0.7566	-0.9724	0.9366	-0.5991	0.7923	-0.1538	0.9475	-1.2352
S7	0.9225	0.8524	0.9675	0.0579	0.9810	-1.0387	0.9446	-1.4365
Mean	0.7832	-0.3692	0.8722	0.3963	0.8513	-0.2031	0.9461	-1.3359

Table1 : Azimuth gain and bias for No movement (No) sine movement (sm) and Noise movement (Nm). The differences between subjects were quite high.

elevation	Nom gain	Nom bias	Sm gain	Sm bias	Nm gain	Nm bias	V gain	V bias
S1	0.6921	9.9686	0.5516	4.4288	0.6295	3.1801		
S2	0.8280	-1.1642	0.7491	10.0953	0.9024	5.532		
S3	0.5024	0.5470	0.29685	2.1664	0.5740	6.3254		
S4	0.5347	0.0604	0.6013	5.8336	0.7110	6.6585		
S6	0.5466	4.7687	0.6857	7.6701	0.5220	2.9077	1.0345	-1.2042
S7	1.0352	13.2874	0.6541	12.0425	0.9705	10.0018	1.1111	0.8740
Mean	0.6898	4.5780	0.5898	7.0395	0.7676	1.0728	0.874	-0.1651

Table2 : Azimuth gain and bias for he mean error of every subject for no movement (No) sine movement (sm) noise movement (Nm) sine stopped movement (Ssm). The differences between subjects were quite high.

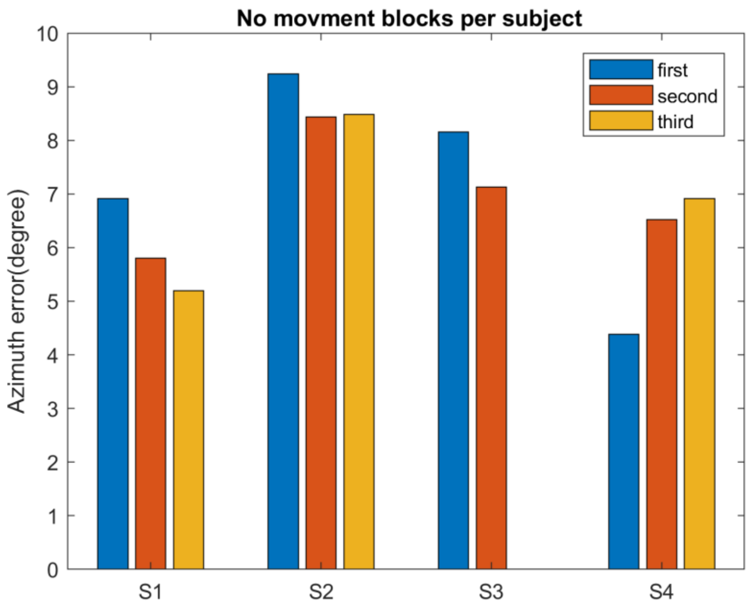
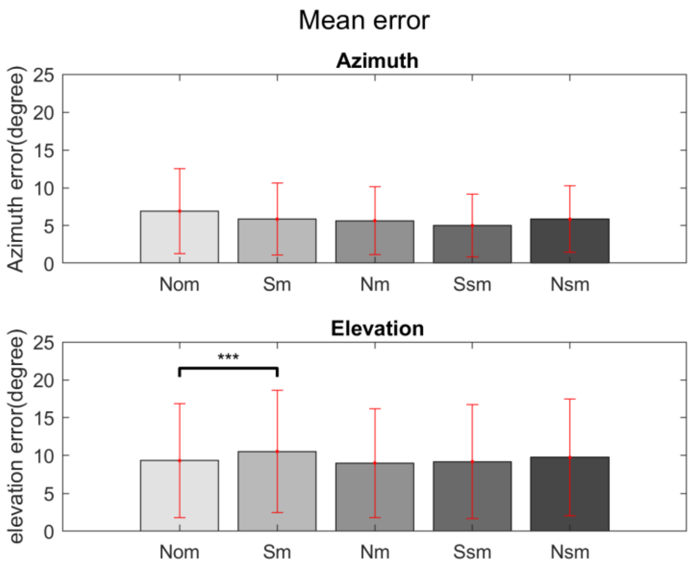


fig 10 the differences in mean azimuth error for the three no movement blocks within the experiment. There was some difference between the blocks, however this was minimal. Also There is not a systematically lower first block or last block, which suggest that the results were random over the three blocks.

	S2Az gain	S2Az bias	S3Az gain	S3Az bias
Trial 1	0.5960	-0.6144	0.7096	3.3690
Trial 2	0.6555	-0.7231	0.6860	-0.8669
Trial 3	0.6315	-1.0664	-	-

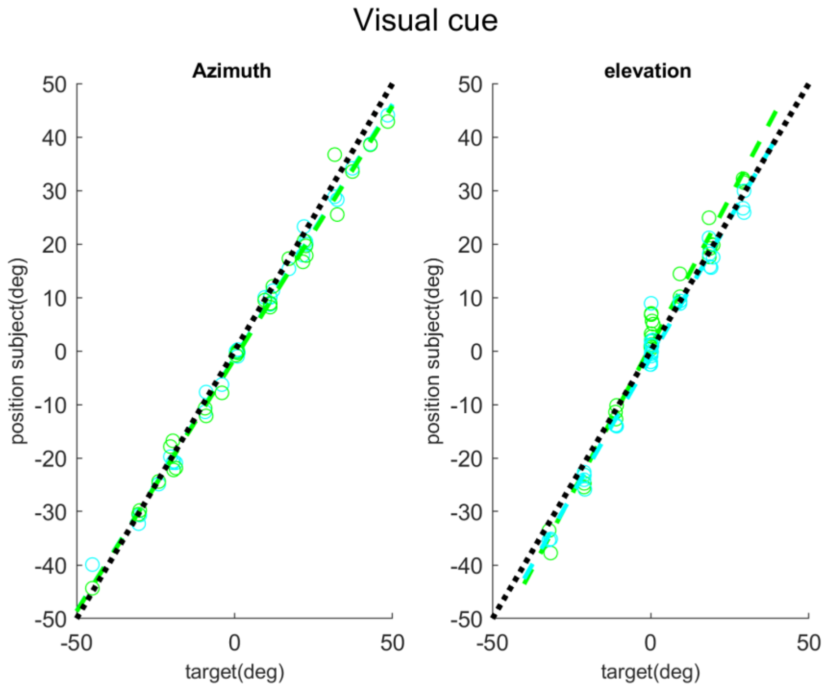
Table3: The difference of azimuth gain and bias for the three no movement blocks within the experiment.

Furthermore the vestibular signal is investigated. There was minimal difference of error in azimuth localisation between the sine and noise condition. Remarkably, both conditions appear to have a lower error than the standard localisation condition, however these differences were not significant. In contrast, subjects have a higher error when locating a speaker in elevation when the subject is moved in a sine pattern. The noise condition had a comparable mean error in regards to the standard localisation condition (Fig 11).



Figure(11) The mean error of every subject for no movement (No) sine movement (sm) noise movement (Nm) sine stopped movement (Ssm) and noise stopped movement (Nsm). The difference between conditions is minimal. The elevation is less accurate, which is in concordance to the literature (Risoud, M. et al, 2018).

To check whether the low gains for the sound localisation in the first experiment were a result of issues with the Optitrack system, or the speaker positions, the second experiment was performed. The participants had to locate visual stimuli and were expected to perform close to perfect in this task. Fig 12 shows that the achieved regression line is almost identical to the optimal line without any errors, so the Optitrack appears to work without any problems. Remarkably S7 did much better on average than the subjects in the first experiment, but also had a greater bias .



Figure(12) The sanity check. The subjects were presented with a visual stimulus which they accurately could localise. The black dashed line is the optimal line. The trails almost follows perfectly the dashed line. Which suggest that subjects could accurately point there optitrack at the correct speaker when the led light up. Therefore the optitrack could

Discussion

The results indicate that the sound localisation of subjects in the vestibular chair seems less accurate than expected. Some possibilities of problems were eliminated due the results from experiment 2. The optitrack showed to be reliable in a visual localisation experiment. Therefore, we concluded that the optitrack and the positions of the speakers were not the issue with the not optimal standard sound localisation experiment. The suboptimal standard localisation in the chair could be due reflections from the setup or even reflections from the body. Especially the sound of the lower speakers could be reflected, as they almost directly project their sound onto the wooden frame. Reflections can influence the cues voor IID and therefore is a factor in azimuth localisation (Rakerd, B., & Hartmann, W. M, 1985). The vestibular chair setup is a complex structure with many objects that can possibly influences sound localisation due to the reflected sounds. Due to these difficulties, the analysis of reflections in the setup could not be completed. There is also the possibility that the subjects were too close to the speaker. Further investigation on the setup of the chair is warranted to examine these issues. Although the sound localisation in the chair is suboptimal, the standard localisation experiment can still be used as a baseline for other conditions. This allows to compare how vestibular stimulation influences the accuracy and precision of sound localisation in comparison to no vestibular stimulation i.e. the standard localisation experiment.

That standard localisation is somewhat worse than that in the sine and sm conditions is an unexpected result. The explanation for this phenomenon could be that subjects had to habituate to the experiment. The first block was always a standard localization experiment and therefore approximately one third of the standard localisation could be less reliable due to the fact that the subject had to habituate to the experiment. However when comparing the first block against the two later in the experiment there were no major differences. Furthermore some subjects did the first block better than the later ones. The subject themselves indicated that the experiment was long and that they became bored in the blocks at the end. However this can't be explained with the data. Concluding that underperforming in the first block is unlikely to be the cause for observed high error in the standard localisation experiment

When asked, the subjects indicated that they had difficulties with locating the source of the sound in the sine movement condition. However the data shows that this is only significant when the subject had to locate the elevation source of sound. Albeit it has to be stated that there was only a mean error difference of somewhat more than 1°. In contrast the sine movement in azimuth localisation did not reach the significance threshold of λ=0,05 even though it was close to this number. With more subjects it could be clearer if the sine was really insignificant or it was really more difficult to localise such as the subjects reported themselves. The vestibular signal itself may have been insignificant, due the relative few movements the subject experienced.

In the future the chair can execute standard localisation sufficient and can be used for further experiments. However the ideal setup is still to be discovered, this could be achieved with some minor troubleshooting for reflections and distance between the subject and the speakers. Also reducing background noise from the computer attached to the chair may yield improvements in sound localisation. Thus the goal off the main experiment to determine the viability of the standard sound localisation in the vestibular chair is achieved.The follow up experiment was to determine the effects of vestibular information on sound localisation. However in contrary to the hypothesis that vestibular stimuli will interfere with sound localisation, it seems to have minor to none effect on the performance of the subjects. Future experiments with more subjects and a stronger vestibular stimulus could give definitive answer.

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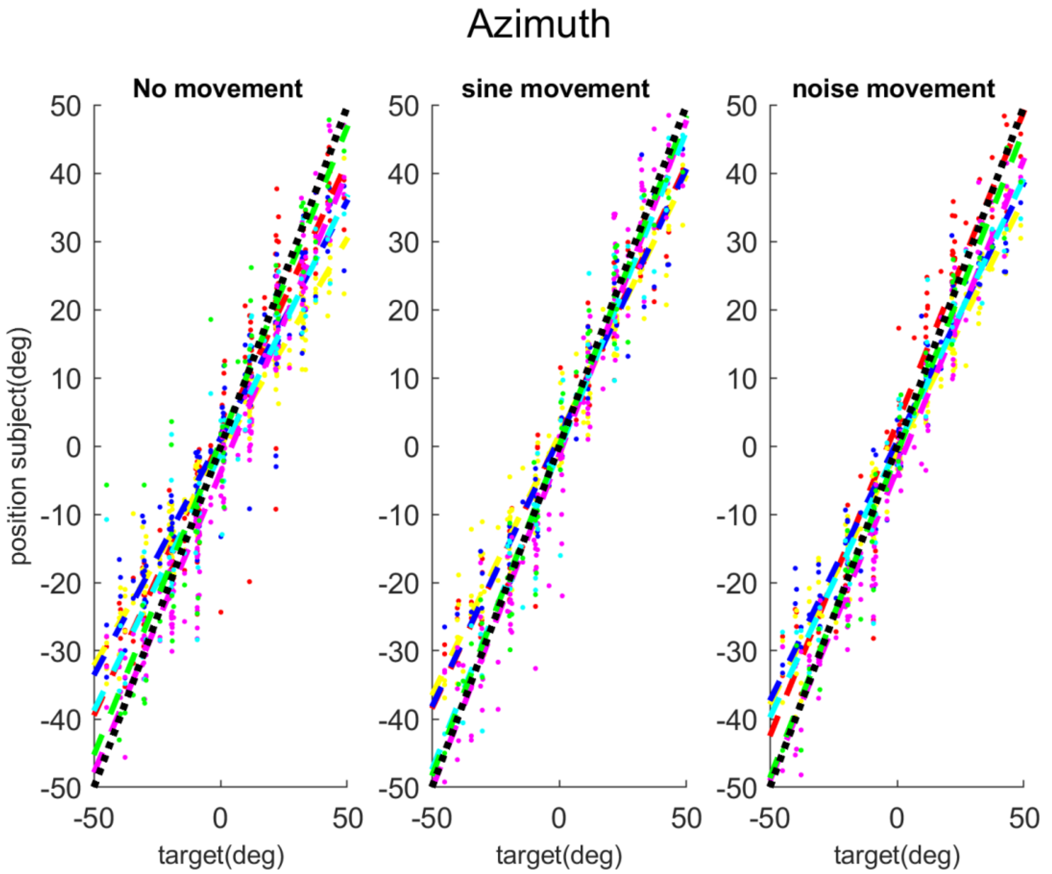
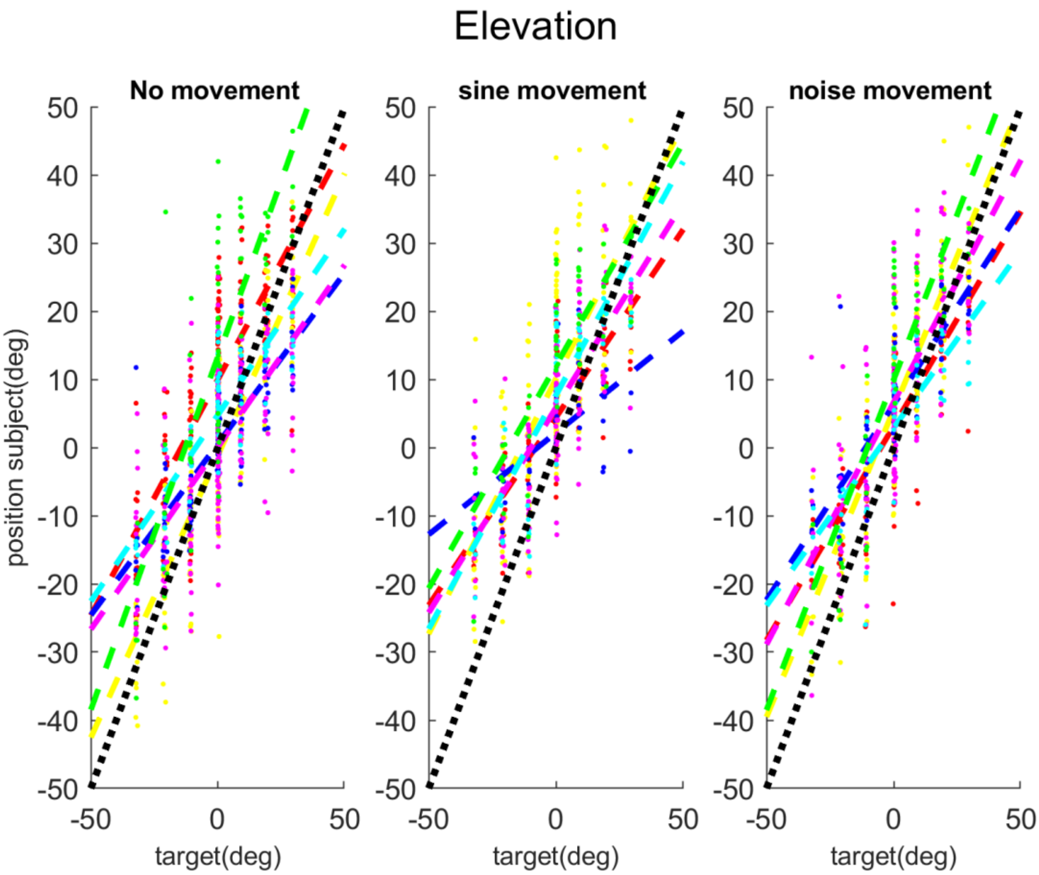
Appendix

Subjects	colour
S1	Red
S2	Yellow
S3	Blue
S4	Magenta
S5	No data
S6	Cyan
S7	Green

the colours corresponding to the trials of the subject.

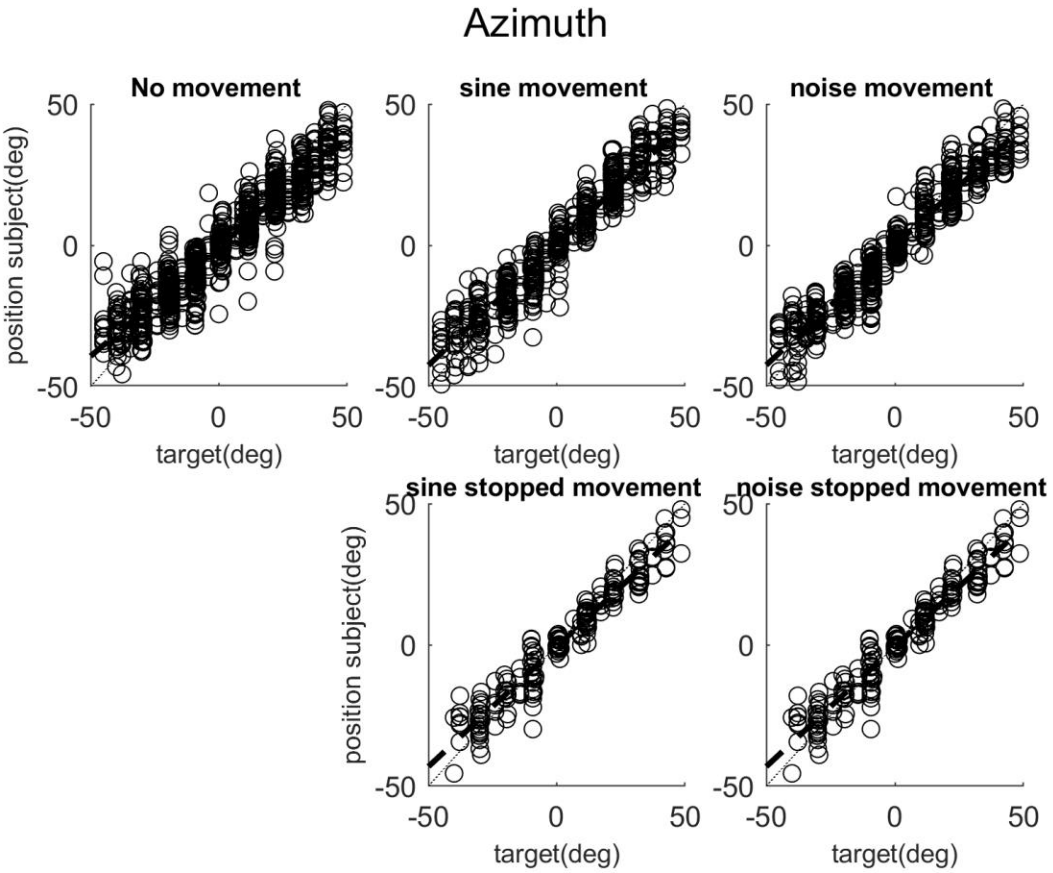


All the subjects azimuth regression plots.



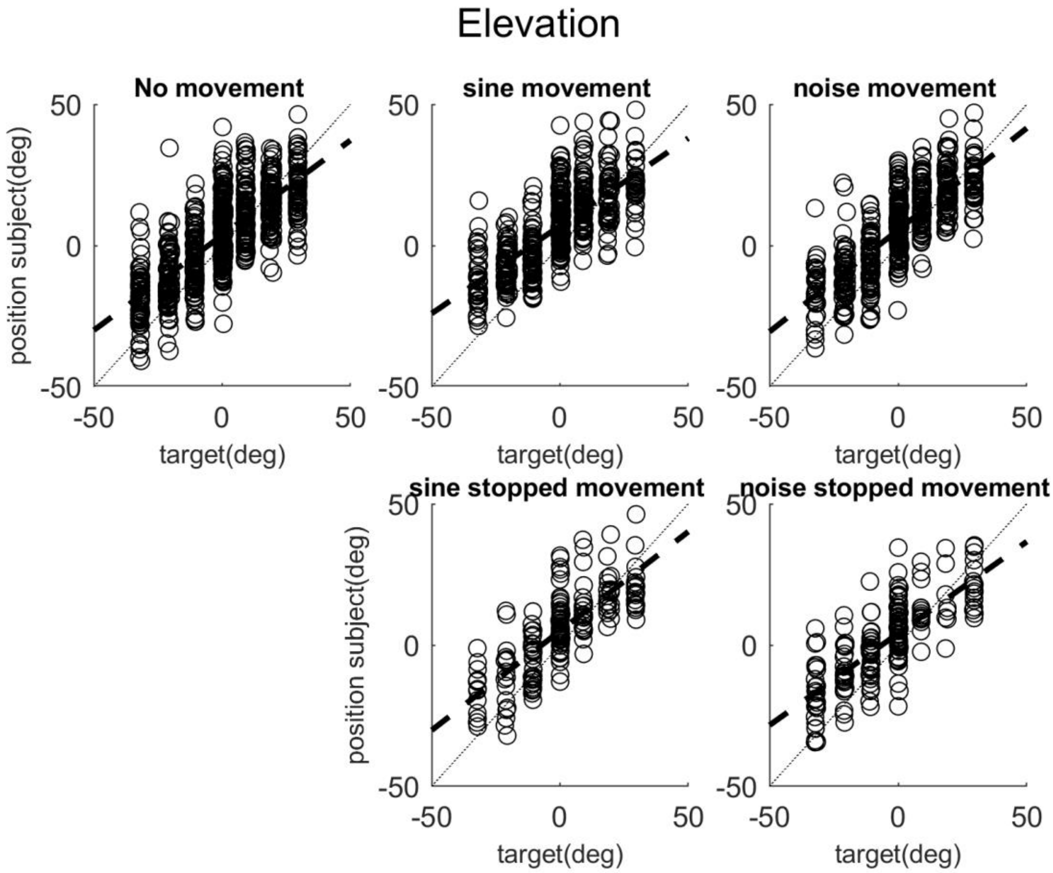
Every subject regression of the position of head versus the position of the speaker. There is a high variance between the subjects.

appendix



The azimuth angle for all subject for the 3 conditions plus the 2 accidental conditions

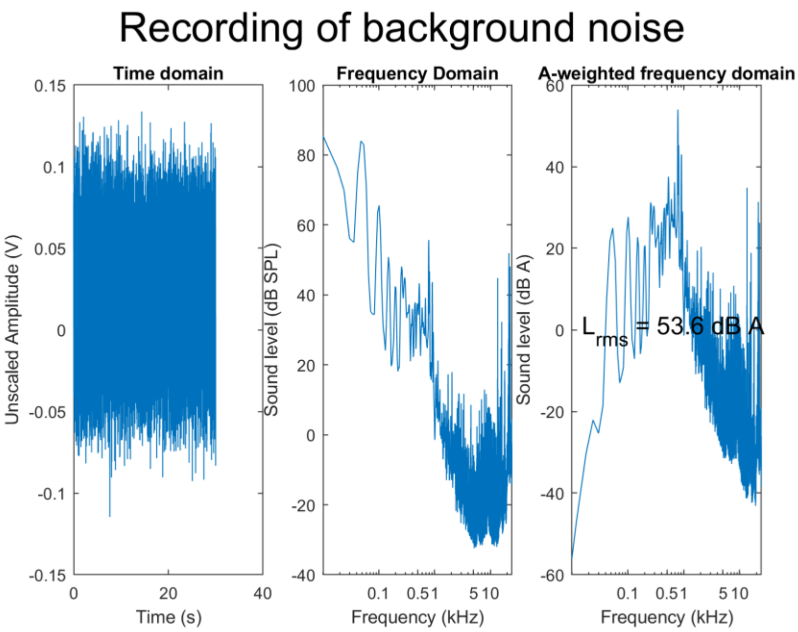
appendix



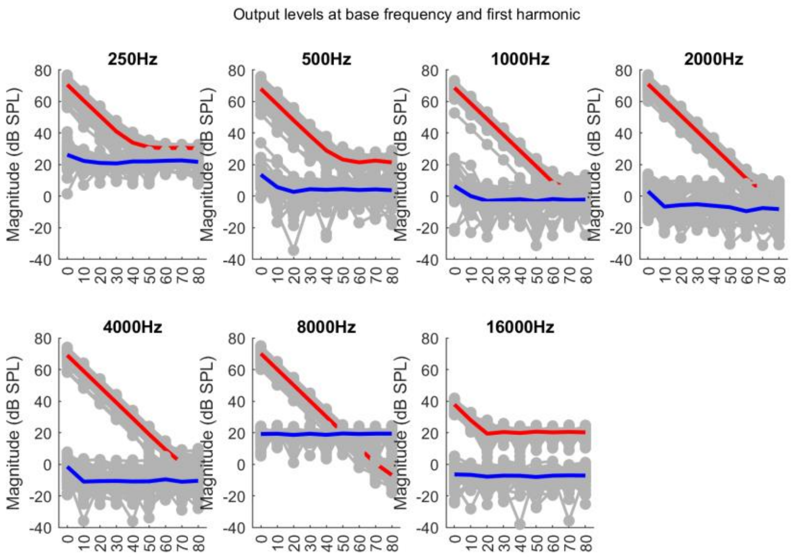
The elevation angle for all subject for the 3 conditions plus the 2 accidental conditions

Acoustics of the set-up

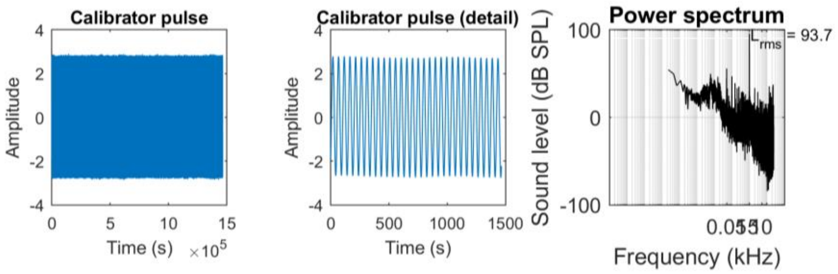
The calibration showed that the background noise was rather high in some frequencies and therefore that linairities could not be achieved with these frequencies. An A-weighted filter was used to get the best model for the human ear(Fig 7 and 8) (Rimell, A. N. et al 2014). The actual positions of the speakers were often nearly the same as the desired positions of the speakers (Fig 4 and 9). The microphone and the speakers sounds mimicked the expectations that there were no problems with the equipment.(Fig 10 and 11).



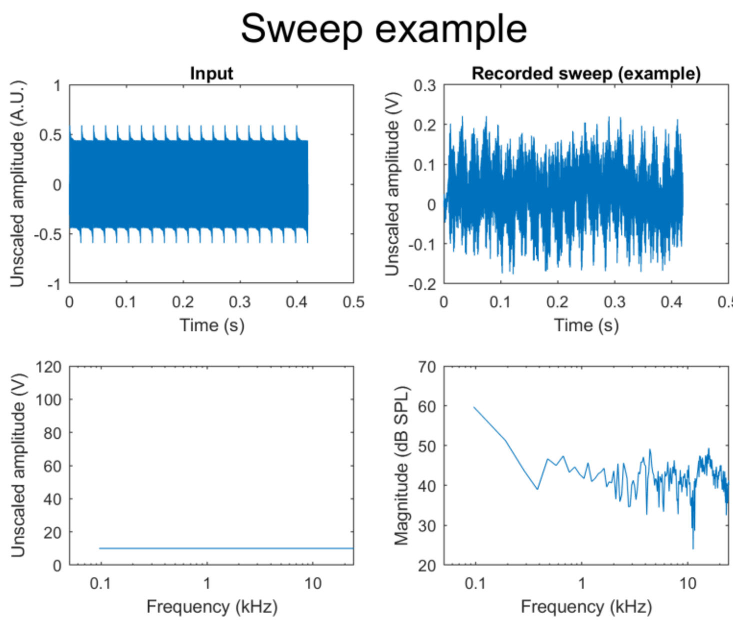
Background noise. In the time domain frequency with and without A-weighted filter. There is a lot of background noise around 800 to 1000 Hz.



linearity of the speakers. Red line is base frequency, the blue line is the 1ste harmonic and the grey lines are all the different speakers. Background noise could explain some of the non-linearities. On the x-axis are the different db attenuations.



A: Calibrations of the microphone



Recorded sweep: input in time and frequency domain of the speakers.