

# THREE-DIMENSIONAL SONIFICATION FOR IMAGE-GUIDED SURGERY

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## ABSTRACT

In neuronavigation and image-guided surgery, the clinician's surgical instrument is tracked in relation to the patient's anatomy. This way, they can be guided towards pre-planned target locations, like positions for burr holes, incision points for biopsy needles, or the center of a tumor for thermal ablation. In this paper, I present the initial results of an experiment that simulates a surgical scenario using a skull phantom. After 50 minutes of explanation and training, 24 participants were guided towards target locations by auditory, visual, and audiovisual clues. So far, the results show that all methods successfully guide the participants to the targets. The trajectory lengths, the needed time to find the targets as well as the precision seem to lie in a similar order of magnitude. When guided by sonification, trajectories tend to be longest and axis-by-axis-motions can be observed. Visual guidance seems to suffer from the missing depth of pseudo-3D graphics on a 2D screen. Audiovisual guidance leads to more micro-motions near the targets, compared to purely visual guidance. Further analysis will quantify the effectiveness of sonification as a three-dimensional guidance tool for surgery.

## 1. INTRODUCTION

Image-guided surgery is an umbrella term that includes several procedures and interventions. A topic review is provided in [1]. Here, the term *image* refers to imaging techniques, such as computed tomography (CT) and magnet resonance imaging (MRI). As a first step, an image of the patient's anatomy is produced. This image can be considered a three-dimensional matrix that contains the density per region. In this image, different structures are segmented, i.e., grouped as vessels, bones, healthy tissue, tumor, etc. A segmented image helps to plan an intervention. For example, the best path to insert an ablation needle into a brain tumor is not necessarily the shortest one, but the one that does not penetrate important brain regions or large vessels. During the intervention, the surgical tool of the clinician is tracked in relation to the patient's anatomy. A graphic of the patient's anatomy, the current location of the surgical tool as well as the planned target path or target point help as a guidance tool. The benefit of visual cues in image-guided surgery is obvious. Drawbacks that have been identified are that clinicians look at a screen instead of the patient, which can cause

an unnatural and unhealthy posture [2, 3]. Furthermore, a projection of a three-dimensional anatomy on a two-dimensional screen produces an ambiguous depth dimension [3, 4, 5], and a reference frame conflict [6, 7], i.e., a high cognitive load because clinicians rotate, translate, and scale the graphic mentally to match it with their own visual and haptic perspective [3].

Utilizing sonification as a guidance tool for image-guided surgery has been proposed and conceptualized in [3, 8, 9, 10, 11, 12]. As sonification does not occupy the visual channel, it can contribute to reducing the visual load and thus the cognitive load during surgery, and reduce reliance on computer screens. In some surgical use cases, auditory display is used as a warning system when risk structures are approached [5, 13, 14, 15, 16]. Other works investigated sonification as a continuous, one-dimensional guidance system [4, 17] or as a discrete, two-dimensional guidance system [18] in surgical scenarios. Overviews are given in [19, 20]. The overall conclusion of these approaches is that even though auditory guidance takes longer and produces a higher subjective task load than visual and audiovisual guidance, it is typically similarly precise. Audiovisual guidance tends to be superior and allows clinicians to take their eyes off the screen, and back to the patient.

Motivated by these promising results, we developed a three-dimensional guidance sonification to enable clinicians to reach a target in three-dimensional space as a complement, or even a potential alternative to visual guidance. The use case is bone drilling for a craniotomy: Here, holes have to be drilled at the right positions in order to remove the appropriate part of the bone that allows access to a desired brain region. This paper describes the experimental setup and reports on my visual inspection of the gathered data.

## 2. THREE-DIMENSIONAL SONIFICATION

The three-dimensional guidance sonification is based on our psychoacoustic sonification that has been introduced in [21] and evaluated in [22] for two-dimensional guidance, and conceptually expanded by a third dimension in [23] and evaluated in [24], and implemented in the CURAT sonification game [25]. The sonification has three axes that are independent of one another. The mapping principle is depicted in Fig. 1.

The core of the sonification is a continuous Shepard tone [26]. Guidance along the  $x$ -axis is achieved by chroma change. The deviation along the  $x$ -axis is mapped to the direction rate of chroma change. When the target lies to the right, the chroma moves clockwise, appearing as a rising pitch. The further away, the faster the pitch rises. When you are very far away from the target, the sonification sounds like a siren, as the pitch rises repeatedly and quickly.



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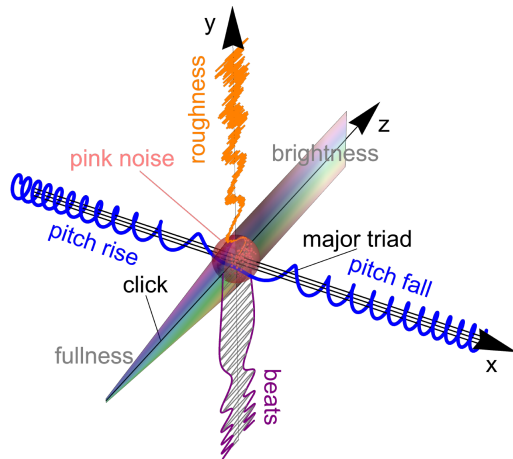


Figure 1: Mapping principle of the three-dimensional guidance sonification. The target is in the center of the coordinate system. The shapes, colors, and terms describe how it sounds depending on your location in the space. From [10].

When the target lies to the left, the chroma moves counterclockwise, appearing as a decreasing pitch. Again, the further away, the faster the pitch decrease. When you are far away from the target, it sounds like a siren, too. Only when you've reached the target  $x$ -coordinate, the pitch is steady. The exact pitch is irrelevant. The steadiness tells you that you have reached the target.

Guidance along the  $y$ -axis is also divided in two. When the target lies above, this is indicated by a loudness fluctuation. The further above, the faster the fluctuation. When you are very far below the target location, the sonification sounds chopped, like an acoustic parking assistant when you approach an obstacle. When the target lies below, the sound becomes rough. The rougher the sound, the further you need to move downwards. When you are far above the target, the sound can be described as harsh or dirty. When you overshoot the target height, a click is triggered as explicit feedback. Only at the target height, the sound has a steady loudness and does not exhibit any roughness. You can listen to the sonification on my YouTube channel on <https://youtu.be/Q9EjdK9qDm4>.

Guidance along the  $z$ -axis is divided in two. The further the target lies to the front, the thinner the sound becomes, i.e., the lower the bandwidth becomes. When you are very far away, the sound is pure-tone-like. You can listen to the fullness-roughness combination on <https://youtu.be/ynxv7pVZCHE>, to the fullness-chroma combination on <https://youtu.be/ZNdZtBx1Ktk> and to the fullness-loudness-fluctuation combination on <https://youtu.be/lyT6RnPU8tI>. The further the target lies to the back, the brighter the sound becomes. When you are very far away, the sound is really shrill. Only near the target, the sound has a high bandwidth and a natural brightness. Every time you overshoot the target along the  $z$ -dimension, a major chord is triggered as explicit feedback. This mapping deviates from the original sound design described in [24].

The sonification has an inherent valence: The nearer the target, the more pleasant the sound. This way, the sonification acts like a gradual warning system. When you move away from the target, the sound becomes more and more obtrusive and alarming, so you

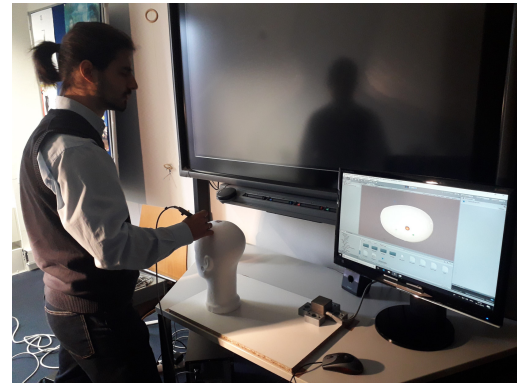


Figure 2: Experimental Setup. From [10].

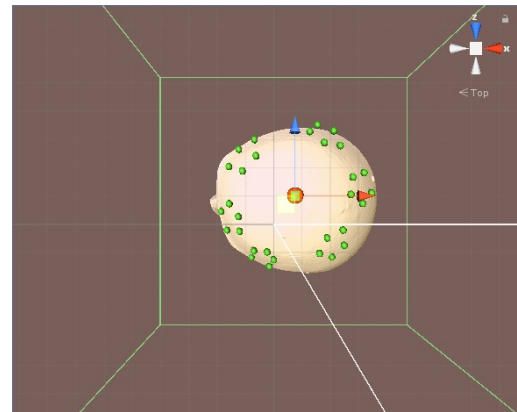


Figure 3: Distribution of targets (green spheres) on the skull.

intuitively understand that you're doing something wrong. The sonification is implemented in Pure Data. The source files can be found in the Sonic Tilt repository [27], the open-source version of Tiltification [28], our spirit-level sonification app.

### 3. SETUP

The experimental setup can be seen in Fig. 2. A styrofoam skull was glued on a board near an electromagnetic transmitter. The board was placed on a table right next to a computer screen and a computer speaker. Participants used a wired stylus whose position and orientation were tracked via an electromagnetic tracking system. We have generated a computer model of the skull so that the position of the stylus tip relative to the skull was recorded during the experiment.

We distributed 30 targets on the skull as illustrated in Fig. 3. The distribution consisted of 5 circularly arranged points at 6 different locations on the skull.

We defined a path from target 1 to target 30. The path was pseudo-random such that one or more points from one circle had to be reached and then one or more points from another circle and so on. Targets 1 to 10 had to be reached, guided by method 1, targets 11 to 20 by method 2 and targets 21 to 30 by method 3. The guidance methods were auditory (A), visual (V), and audiovisual (AV). We divided the 24 participants into 6 groups

1. A–V–AV
2. A–AV–V
3. AV–A–V
4. AV–V–A
5. V–A–AV
6. V–AV–A

à 4 participants to counterbalance the effect of the order of the guidance methods.

#### 4. METHOD

We explained to the participants that their task would be to approach 30 targets in a row with a stylus. We told them to approach the targets as quickly and precisely as possible. This instruction is common in experiments regarding image-guided tool movement [29]. We also informed them about the three guidance methods and showed them the setup and the visualization with an exemplary target.

We verbally explained each dimension of the sonification to the participants. This includes me vocally imitating the sounds to be expected. Then, we played some audible examples, let them guess their meaning, and talked about what we heard. Next, we let the participants interact with the sonification using the stylus and a visible sticker on the skull. We started with the  $x$ -axis only, continued with the  $y$ -axis, then the  $z$ -axis, and, finally, all three dimensions combined. We suggested the participants to close their eyes during the interaction, to get a feeling for the sound aspects that they need to concentrate on, the clues that the sonification gives, and the meaning of the sound parameters and their magnitudes. Of course, closing their eyes should also help them get used to relying on what they hear, which many people rarely do in their lives. The explanation of the task, the introduction to the system, and the exploration of the sonification took about 50 minutes.

The target finding took roughly 15 minutes. After the experiment, the participants filled out a questionnaire for 5 minutes or so, which is out of the scope of this paper. So the complete experiment took a bit longer than one hour.

#### 5. RESULTS AND DISCUSSION

First, I carried out a visual inspection of the trajectories. We have done the same in earlier studies [30], and it helped identify typical strategies that participants used as well as exceptional observations.

In all guidance modes, many participants stuck to the skull and moved the stylus tip on or near the phantom surface, as illustrated in Fig. 4. Most participants approached all the targets with high precision, none ended up on the wrong side of the skull. When guided by sonification, many participants moved axis-by-axis instead of approaching the target directly, as illustrated in Fig. 5. We have observed this strategy before [30]. A likely explanation is that following a single dimension of the sonification is easier than interpreting all three dimensions and deriving the resulting target location, which takes time and cognitive resources because you consciously switch attention from one aspect of the sound to another. Participant 19 started with great confusion and moved far away from the skull, as illustrated in Fig. 6.

When guided by visualization, trajectories went pretty straight from one target to the next, as illustrated in Fig. 7. Often, the

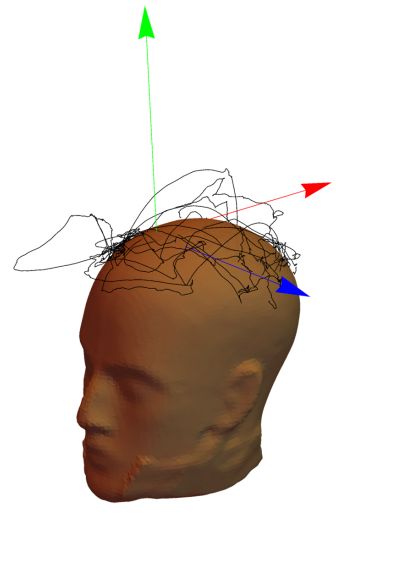


Figure 4: All 30 trajectories of a single participant.

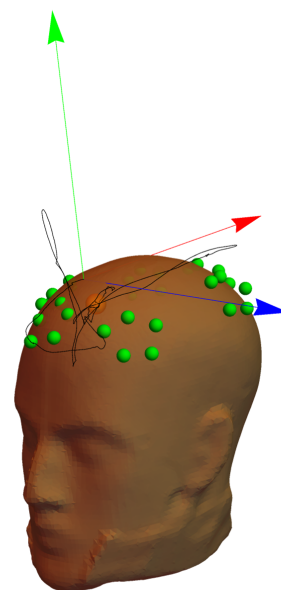


Figure 5: Typical trajectory for the auditory guidance method. A quick deflection back and forth along a single dimension is carried out. This may serve as a reminder of the mapping principle. Furthermore, this is one of the largest misses, i.e., the stylus was around three centimeters away from the actual target.

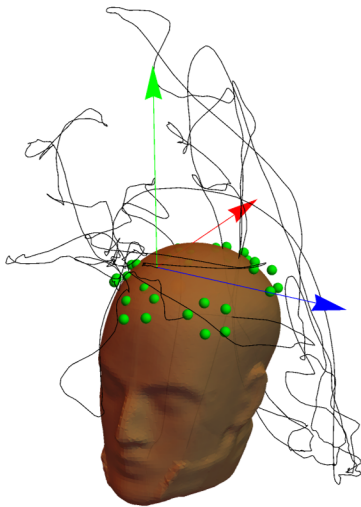


Figure 6: Participant 19 started with great confusion and moved quite far away from the phantom.

target was reached precisely. However, sometimes the target was missed by quite a lot along the  $z$ -dimension. This becomes evident when switching from the top view (left) to side view (right). This is probably because the screen showed a top view, the only perspective from which all targets can be seen. As a consequence, it is difficult to derive the  $z$ -dimension from the graphic. The most prominent clue is the overlay of the green target sphere and the semi-transparent orange sphere that represents the stylus tip.

When guided by combined visualization and sonification, the trajectories looked largely like the trajectories from the visual guidance, as illustrated in Fig. 8. Occasionally, one could observe micro-adjustments near the target. It is likely that participants relied on visual guidance. Only when the sound was not right, they scanned the nearer region for a better-sounding place to click. However, this search seems more random than the trajectories during the purely auditory guidance.

Next, I inspected some statistics of each participant. Figure 9 shows how long it took each participant to reach target 1 to 10, 11 to 20, and 21 to 30. The distribution looks quite homogeneous, except for one outlier: Participant 19, who started with total confusion in the auditory mode, took much longer to reach targets 1 to 10, guided by sonification.

Figure 10 shows cumulated path lengths for individual patients. As for the duration, the distribution looks fairly homogeneous. Again, participant 19 is an obvious outlier. The person moved by far the longest trajectory in the auditory mode, but the shortest of all paths in the visual mode (which is a bit difficult to see in the plot). Participants 4 also moved a much longer path than the others. Again, it was the auditory mode. Participant 17 moved an exceptionally long path in both the audiovisual and the auditory

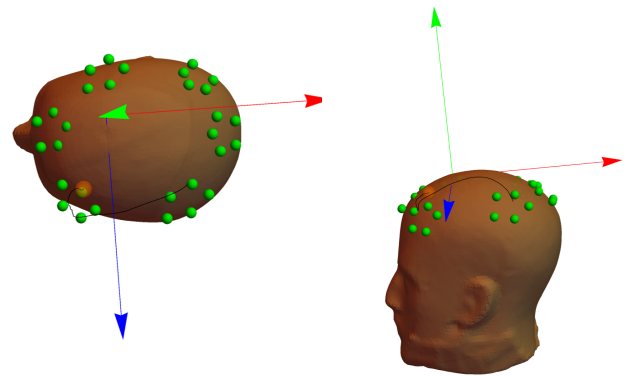


Figure 7: Typical trajectory for the visual guidance method. The path is short and from the top view (left) the precision seems high. But from another viewpoint, you see that the starting point is below the last target and the endpoint lies above the target.

guidance mode. Participant 3 also seemed to have trouble with the sonification.

I refer to the Euclidean distance between the center of the target and the stylus tip when clicked as the precision. The precision is plotted in Fig. 11. Often, the participants achieved a precision of less than one centimeter in all guidance modes. Four participants exhibited a much lower precision than the others, namely participants 1, 4, 17, and 19. Interestingly, their low precision was almost independent of the guidance mode.

In summary, one can say that all guidance methods were successful. Depending on the considered measure, between 20 and 23 out of the 24 participants performed similarly well. However, some individuals seemed to have difficulties with auditory guidance. In [31] we already suggested including sonification not only in surgical interventions but already during surgical training, as a multimodal offer to account for diverse types of learners. The presented experiment seems to underline that sonification can successfully guide people toward an invisible target. But sonification is more helpful for some people than for others. A closer look at the three plots as well as statistical analyses of the results will provide quantitative and more reliable results concerning the effectiveness of sonification as a guidance method for clinicians in image-guided interventions.

## 6. CONCLUSION

In this paper, I presented an experiment in which participants navigate their stylus through a three-dimensional space guided by sonification, a pseudo-3D graphic, and an audiovisual combination. The setting simulates a surgical use case to investigate the usefulness of sonification as a guidance tool in image-guided surgery and neuronavigation. A visual inspection of the trajectories reveals that participants find targets with all three guidance methods. When guided by sonification, participants tend to move axis-by-axis. Some trajectories are quite diffuse and move away from the skull. When guided by a pseudo-3D graphic, participants tend to take the direct path, but sometimes miss the target along the  $y$  axis. The audiovisual trajectories look like the visual trajec-

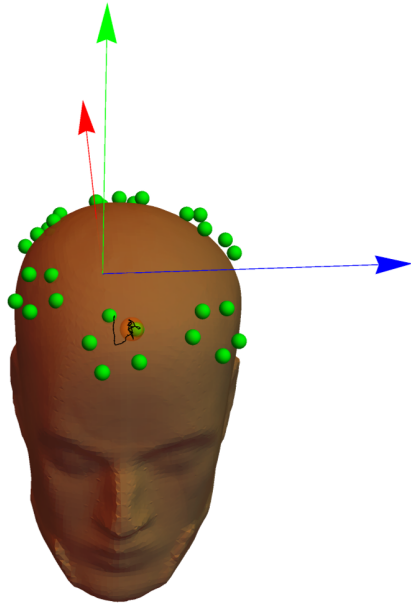


Figure 8: Typical trajectory for the audiovisual guidance. The trajectory is quite short and direct. But many little adjustments are carried out near the target.

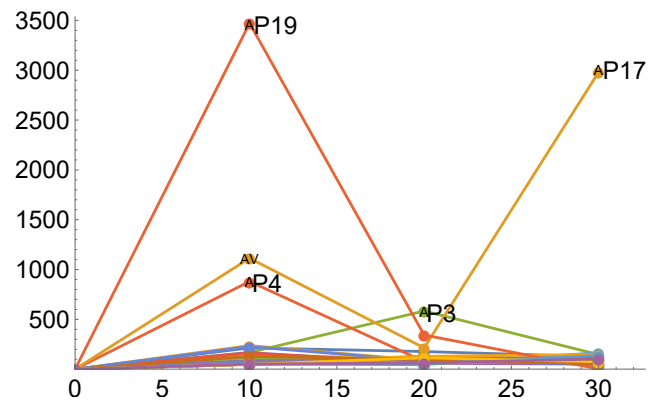


Figure 10: Cumulated length (in centimeters) of the trajectories from the beginning to target 10, from target 10 to target 20, and from target 20 to target 30.

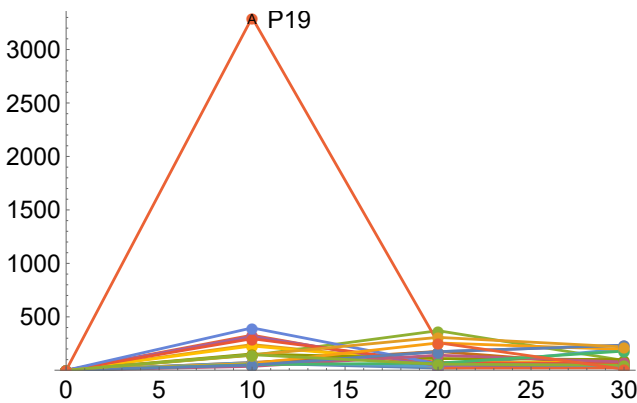


Figure 9: Cumulated time (in seconds) it took each participant (individual colors) to reach targets 1 to 10 (dots above the 10), 11 to 20 (dots above the 20), and 21 to 30 (dots above the 30). One outlier had troubles with the auditory guidance (A).

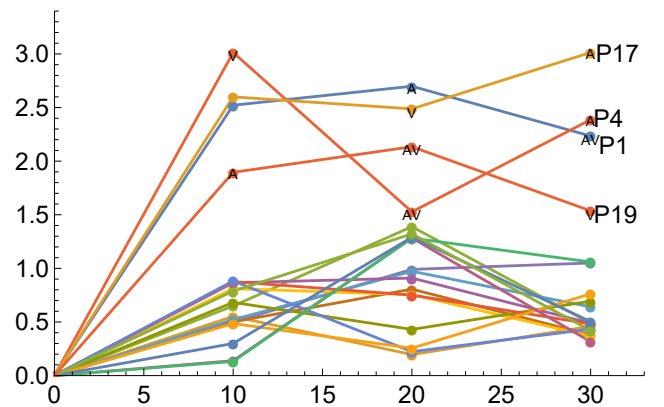


Figure 11: Average (not cumulated) precision (in centimeters) for targets 1 to 10, 11 to 20, and 21 to 30. Participants 1, 4, 17, and 19 achieved a much worse precision in all three modes compared to all other participants.

tories, but sometimes subtle corrections are carried out near the target. Despite some outliers, the participants' performances were quite similar, indicating that a 50-minute training before the experiment is an adequate preparation to evaluate sonifications. But for some people, sonification does not seem to be a suitable guidance tool. Statistical analyses will quantify the effectiveness of sonification as an alternative and a complementary guidance method for image-guided surgery. Comparing navigation results with passive sonification evaluation methods, like PAMPAS [32] and [33], will shed light on the question of how interaction affects judgment and interpretation of sonification.

## 7. ACKNOWLEDGMENTS

Many people have been involved in preparing the presented experiment, which took many years from planning over preparing to conducting and analyzing. I thank Ron Kikinis who had the idea of a craniotomy as a use case for sonification-guided surgery. I thank Matthias Günther who granted me access to the MRI scanner and Simon Konstandin who helped me glue and tape the styrofoam skull in a water-filled box, test multiple sequences, and finally invert the MRI scan to produce a precise skull model. I thank my colleague Holger Schultheis who was involved in conceptualizing the experiment. I thank David Black for the interesting exchange of ideas, my intern Nuttawut Nuchprayoon and my student assistants Kashish Sharma, Kilian Krüger, and Saleem Ahmad for their assistance. I thank Peter Haddawy for inviting me to the Intelligent Virtual Environments for Surgical Training workshop, Thomas Hermann and Roberto Bresin for allowing me to organize the Interactive Sonification Workshop (ISon2022), and the Hanse Wissenschaftskolleg financing and hosting it.

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