CAVE-BASED VIRTUAL PROTOTYPING OF AN AUDIO RADIOGONIOMETER: ECOLOGICAL VALIDITY ASSESSMENT

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ABSTRACT

This paper is part of a project concerned with the improvement of audio radiogoniometer design ergonomics and sound aesthetic. It introduces a virtual prototyping implementation of a simple radiogoniometer along with a methodology to assess its ecological validity. Said methodology involves a performance comparison between two different radiogoniometer designs, both implemented as virtual prototypes. While suggested assessment achievement supposes a companion study in a real environment (based on a physical prototype), significant results have already been gathered regarding the impact of the virtual environment on the virtual prototype validity.

Abbreviations

CAVE	Cave Augmented Virtual Environment
DF	Direction Finder
DoF	Degree of Freedom
N-N	Nintendo Nunchuk
N-WBB	Nintendo Wii Balance Board
OSC	Open Sound Control
PP	Physical Prototype
RF	Radio Frequency
VE	Virtual Environment
VP	Virtual Prototype
VR	Virtual Reality
VRPN	Virtual Reality Peripheral Network
WIP	Walk In Place

1. INTRODUCTION

Radiogoniometry, i.e. the measurement of the azimuth and elevation of received radio waves, is nearly as old a science as radio transmission itself [1]. Also known as Radio Frequency (RF) direction finding, its applications range from spectrum sensing to civilian rescue operations [2]. Research efforts in this domain have mainly been directed towards antenna geometry and algorithm optimization, particularly since the first application of eigenstructure techniques in the late 1980s [3]. While genuinely efficient designs emerged from these considerations [4], the field still lacks a certain perspective regarding human-machine interfacing. In applications such as avalanche victim location for instance, observed performance issues are generally related to misuse of the radiogoniometer, also called radio Direction Finder (DF), by first responders [5].

Until recently, human-interface assessments involved a lengthy prototyping process. Engineers and researchers usually had to assemble real prototypes to gather some relevant feedback on their design from ergonomists and potential end-users. Recent developments in Virtual Environment (VE) related technologies have given birth to the experimental process known as Virtual Prototyping. It is defined as *"A computer simulation of a physical product that can be [...] tested from concerned product life-cycle aspects [...]"* by Wang in [6]. Its applications range from surgery training (e.g. using head-mounted displays and haptic feedback [7]) to car design evaluations on social network platforms [8]. The process has since considerably improved ergonomic studies, allowing for low-cost and fast design evaluation in a supervised environment [9].

Virtual Prototyping's main issue is its realism, or rather the apprehension of its distance from the Physical Prototype (PP) behavior [10, 11]. Once this apprehension, namely the characterization of its *ecological validity* achieved, the Virtual Prototype (VP) will be used to improve the design aspects it reflects best only. This characterization also focuses on the impact of the VE on task execution and users behavior [12].

A method to assess the validity of a specific implementation is to compare it to an equivalent PP, in terms of performance and ergonomics [13]. As the prototype is modified in both environments (real and virtual), one may observe the correlation of performance evolution, as illustrated in Figure 1.

This paper introduces such a characterization method for the virtual prototyping of a DF, designed for the rescue of individuals based on personal RF emitters. The considered DF is a case study, based on a single RF directional antenna manually steered by an operator. As feedback, the antenna power output is mapped using a Geiger counter sonification metaphor, i.e. a stream of audio pulses played faster as the user steers the antenna towards an RF emitter. More details on the DF design implementation can be found in AppendicesA and B. To reproduce the method exposed in Figure 1, two slightly different designs are under study in both environments. They differ only in the placement of the directional antenna:

Design 1: directional antenna **in** the DF user's **hand**,
Design 2: directional antenna **on** the DF user's **head**.

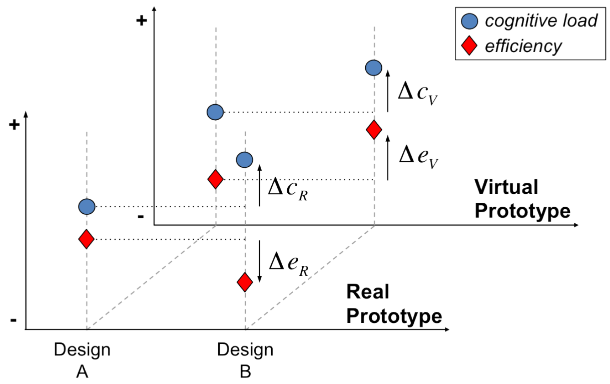

Figure 1: Illustration of suggested characterization method of virtual prototyping implementation. Two different designs (A and B) are implemented and tested both as virtual and physical prototypes. Δe and Δc represent the increase in efficiency and cognitive load respectively between design A and B. Along with a rigorous qualitative assessment, the correlations between Δc_R and Δc_V or Δe_R and Δe_V informs on the ecological validity of the implementation. In this illustration, the core VP implementation appears reliable in terms of cognitive load, while it does not reflect the efficiency decrease observed between PPs A and B.

Presented results concern the VE aspect of the characterization, focusing on the VP based localization task only.

We chose such a minimal approach (simple core DF design, moderate modification) to limit the amount of independent factors. Comparison of proposed designs merely illustrates a typical step of the ecological validity assessment methodology. In the early stages, understanding the distance between our VE and the reality - for this specific application - is a priority, over any ergonomic or sound aesthetic considerations. Future studies will address a companion experiment in a real environment, before exploiting the PP for DF optimization.

The next sections outline the applied characterization methodology, address results analysis, discussion, and conclusion.

2. METHOD

2.1. Experimental Design

The experiment consisted of a DF assisted target localization task carried out in a CAVE (Cave Augmented VE). It involved virtual targets disseminated in a VE, which participants had to gradually progress towards and localize using one of the two proposed DF designs. Since an equivalent experiment was planned with a PP, the VE has been manufactured to best reproduce features of the foreseen real environment (environment, task conditions, and VP behavior).

A total of 13 volunteers (aged 25 to 40 years) participated in the experiment. This number was reduced to 10 in reported results, as some participants were subject to cybersickness due to the VE (see Section 3.2) and could therefore not complete the task. Participants were introduced to the task after answering a set of questions on their experience relative to the considered experiment (VE practice, use of a DF, etc.). They had a varied range of previous experience in sonification and Virtual Reality (VR), from none to expert, while none had ever used any DF-like apparatus. All participants reported normal vision (or corrected to normal), hearing, and physical condition.

As a training task, participants had to use both DF design to find targets in the VE (two targets per design). Afterwards, participants performed two sessions, one with each design, involving the search of six targets each. The only instruction was to perform the search as fast as possible. Communication between the participant and the experimenter was not allowed during the search. Instead, questions and comments were heartily encouraged during the training session and in the recorded post-experiment interview. The Witmer and Singer presence questionnaire [14], along with open questions during the interview were used to detect VE related issues (cybersickness, VE malfunctions, confusions, etc.). The experiment typically lasted one hour, except when participants required additional pauses between sessions. To limit the influence of learning effects, session and target orders were evenly balanced between the two conditions (DF designs) and six target iterations. The chosen experimental design was therefore a repeated-measures design with two factors: target position and DF design condition (six targets and two DF designs, fixed factors). Associated evaluation metrics concerned with task execution approach and efficiency are presented in Table 1.

2.2. Experimental Setup

The current experiment was conducted in the audio-visual VE designed in EVE [15], using the open source blenderCave software [16, 17] and its associated sound rendering engine. The EVE platform is a CAVE employing active adaptive stereoscopic rendering on four rear-projected screens coupled to a cluster of seven cinema-sized projectors each controlled by an i7 computer, altogether achieving about 36 m^2 of high-definition projection space. Participants explored the VE from a fixed position allowing for an approximate $180°h \times 110°v$ field of view, observed through tracked stereoscopic shutter glasses (c.f. Figure 2). The blenderCave software is an extension of the open source blender 3D game creation software into a complete authoring tool for VR real-time interactive scene rendering. An associated Max/MSP based sound rendering engine was exploited along with an RF wireless headphones module (Sennheiser EK 2000 IEM and HD570 headset) to present audio feedback. To provide some ecological equivalent of walking, navigation in the VE was accomplished using a Nintendo Wii Balance Board (N-WBB) and Nunchuk (N-N: single joystick along with analog buttons) through a hybrid Walk-In-Place (WIP) metaphor as

Independent variables		
participant	10	random variable
DF design	2 (conditions)	DF_{Hand}, DF_{Head}
target	6 (iterations)	$T_1, T_2, \ldots, T_6$

Dependent variables
task execution time, covered distance, average speed
virtual vehicle* orientation (relative to VE or target)
DF antenna orientation (relative to VE or target)

* represents the position & orientation of the CAVE's viewport within the VE.

Table 1: Independent and dependent variables used in the experimental protocol.

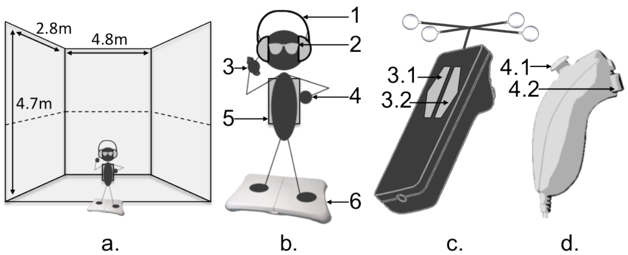

Figure 2: Overview of the experimental hardware setup. **a)** EVE system. Only the lower half (below the dotted line) of the vertical projection screens was used. **b)** User hardware. 1 - Headset and its associated RF receiver. 2 - Tracked stereoscopic shutter glasses. 3 - Virtual DF antenna. 4 - N-N. 5 - 5 kg backpack. 6 - N-WBB. **c)** Detail of virtual DF antenna. Its two analog buttons (3.1 and 3.2) are used for DF sensitivity level selection (c.f. Appendix B). **d)** Detail of N-N. Joystick (4.1) used to control Z axis related rotation of the virtual vehicle (i.e. viewport) during standard WIP navigation, and XY translation when in near-field displacement mode (see Section 2.3) triggered by holding the analog button (4.2).

described in Section 2.3. Finally, DF related interactions exploited a 6 DoF tracker while a 5 kg backpack was worn by every participant to reproduce PP related load.

2.3. Experimental / Audio-Visual Stimuli

The VE was a close reproduction of the 6 ha square field that will be used for the future PP experiment. It was populated with circular fences of variable size to simulate inaccessible areas of the real environment (illustrated in Figure 3), obstructing the user's path and forcing modifications of search patterns. An impassible barrier established the search area limits. Targets were represented by wallet sized boxes ($14\times10\times2\,\text{cm}^3$) placed on the VE ground, yet not inside any inaccessible area. To limit visual clues impacting on the audio aided search task, 20 cm high grass patches were homogeneously distributed in the VE to restrict far field target visual localization (illustrated in Appendix C, Figures 9-11).

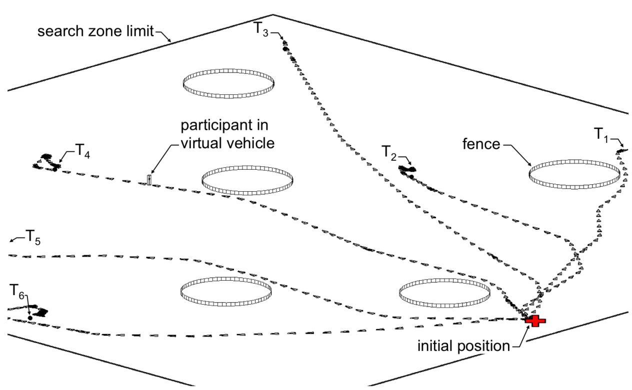

Figure 3: VE and target localization task (one session of six targets) illustration. Dotted lines (succession of triangles, see Figure 6) represent the *virtual vehicle* (CAVE point of view / position in the VE) paths in the VE.

RF propagation was first simulated using the IlmProp 2D ray-tracing model [18]. However, thanks to the selected environment (flat field without any RF obstacles), it was reduced to a simple free space, inverse-square propagation law with no noticeable difference on the VP behavior. The virtual antenna was implemented to match the directional characteristics of the PP antenna (lobe widths and amplitudes, see Appendix A). Its output power was continually fed into the sonification algorithm, from blenderCave to Max/MSP using the Open Sound Control (OSC) protocol. As participants approached the target, the antenna output power increased along with the Geiger counter repetition frequency. They then could select the DF sensitivity level that presented the most meaningful range of repetition frequencies for rhythm appraisal using the analog buttons of the virtual antenna (Figure 2c: 3.1 and 3.2). A more detailed description of the sonification metaphor is provided in Appendix B.

The N-WBB based hybrid WIP implementation was a simplified version of the algorithm introduced in [19], where the N-N joystick controlled Z axis rotations of the virtual vehicle (i.e. viewport) within the VE, as the EVE system is not a full 360°system. To compensate for poor N-WBB based WIP precision for small or lateral movements, a second, less realistic displacement paradigm, called here the *near-field* displacement mode was implemented. Freely triggered by participants, it allowed slow and precise control of the virtual vehicle translation in the VE through the N-N joystick (instead of the WIP metaphor). N-N and WBB streamed data to blenderCave via a VRPN (Virtual Reality Peripheral Network) server, through a bluetooth interface. Participants were asked to remain on the N-WBB (i.e. not to walk in the CAVE) during the search task.

2.4. Experimental Task

Participants started each of the six target localizations (*iteration*) for the two DF designs (*conditions*) at the same position in the VE (initial virtual vehicle position, see Figure 3). Exploring with the DF and navigating via the hybrid WIP, they would progress towards each target. The near-field displacement mode could be used for slower and more meticulous searches. After each target position validation, the virtual vehicle was returned to its initial position and the DF sensitivity level was reset to one (least sensitive, see Appendix B). Once all six targets were located, participants took a short break before proceeding with the second design.

To avoid situations where the participant visually searched for a target, often hidden by a patch of grass, participants were instructed to rely on DF sonification only to estimate the targets *rough* position. Hence, they were explicitly asked to memorize the sonification algorithm behavior (adequate sensitivity level, timbre and rhythm) near the target during the training session. To validate the target position, participants where asked to notify the experimenter, preventing any VE interface mishandling from logging false positives. This validation method also appeared to help participants to accept the rough nature of the localization task and focus on the time constraint, since they could verbalize their doubts.

3. RESULTS AND DISCUSSION

This section presents quantitative and qualitative results analysis, concerning performance and ergonomic variations between VP designs. Qualitative observations also serve to understand the impact of the virtual prototype implementation (VE, VP and task execution) in order to avoid misinterpretation of results.

3.1. Quantitative analysis

In the following discussion, the significance of results has been assessed using the non-parametric Kruskal-Wallis one-way analysis of variance with a p-value threshold of 5%, since differences in group variances prevented the use of the more traditional one-way analysis of variance (ANOVA).

The first part of the quantitative analysis concerns DF performance related results. Addressing differences in localization efficiency, Figure 4a shows a comparison of task execution time for each DF design condition. It indicated no significant difference between the time related efficiency of the two DF designs, to the point where the average time values for the subsets were nearly identical (to the nearest second). Comparison of the results between sessions in Figure 4b shows that there is a substantial influence of learning effect, coupled with significant differences in the amount of improvement for each DF design between sessions 1 and 2. The head design appears to be initially harder to use but it shows better results than the hand design in session 2. This means that the DF designs could be different in terms of potential improvement. However, this result is uncertain because of the participant skills repartition with respect to first experimented design. The term *skill* herein defines one's ability to learn and assimilate interactions required by the task at hand (WIP, joystick control, DF usage, etc.). A *skilled* participant will, amongst other things, present a bellow average total task execution time. Regarding task execution time ranking, the top four participants started session one with the same DF design (i.e. holding the antenna in the hand). A cross-observation of boxplots in Figure 4b, comparing [session 1 head - session 2 hand] and [session 1 hand - session 2 head] results points out a similar influence of the learning effect between sessions for both groups, and the uneven skills repartition that may explain the observed difference in potential improvement.

Thorough investigation of participant questionnaires and oral interviews did not provide any differentiating factor between the highlighted groups. Performances seemed to mainly depend on their ability to handle the VE interface and their involvement in the task (see Section 3.2). They did not report any significant preference towards either design. *Quantitative analysis of only session two (removing learning effect) would not be statistically significant, leaving only six targets × five participants per DF design.*

An inter-target performance analysis indicated that participants took significantly less time proportionally to find distant targets than close targets (target localization times normalized by target distance from the initial position in the VE). However, there was no significant difference between inter-target covered distances (again normalized) during the search in the VE. Indeed, participants spent approximately 1/6th of their time exploring within a short distance of the targets (with no significant inter-session, design, nor target fluctuations). This region, defined by a radius of 4 m, was termed the *near-field* search area. Observation of the average speeds of virtual vehicle corroborates the time consuming aspect of the near-field stage of direction finding search in the VE.

The validity of this result is difficult to assess prior to the study of the PP-related task. The VP behavior regarding the free space propagation hypothesis is probably no longer valid at such distances from the RF emitter. The near-field search also forced participants attention on the unrealistic details of the VE implementation (hybrid WIP displacement metaphor, graphics, etc.). Participants would for example report that adding ground bumps in the VE would have considerably helped in the near-field searches (see Appendix C for VE illustrations).

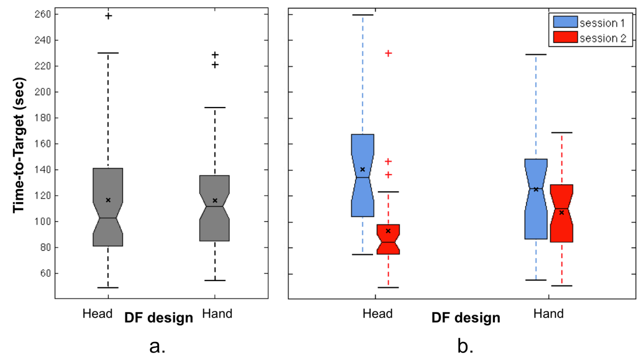

Figure 4: **a)** Distribution of recorded time-to-target for all participants (10×6 targets) as a function of DF design. **b)** Time-to-target results separated by session. "×" and "+" symbols stand as subset means and outliers respectively (with a maximum whisker length of 1.5× inter-quartile range). Notched boxplot middle line indicated the subset median value.

Regarding the accuracy of participants estimations and related navigations, we examined the differences between total covered distances, average DF antenna and virtual vehicle orientations (relative to target) for both DF designs. To remove sudden 180°jumps in orientation related data when participants walked past a target, near-field search area data were not considered. There were no significant variations of either metric between conditions. Inter-target, participants, or design localization accuracy analysis, i.e. distance between virtual vehicle and target when participants validated target position, did not yield any significant result either.

As a measures of *how much* participants steered the antenna for each design during the localization task, the following metric is proposed. The accumulated sum of the angular position derivative calculated for the DF antenna motion relative to the virtual vehicle, ignoring the near-field phase, is defined in the following equation:

$$\sum_{n=1}^{N_{tot}-N_{\textit{far-field}}} abs(\theta_{\text{antenna2vehicle}}[n] - \theta_{\text{antenna2vehicle}}[n-1])$$

where n stands for sample number, N_{tot} and $N_{\textit{far-field}}$ are respectively the total number of recorded samples and the sample number that correspond to the start of the near-field part of the search (both potentially different for each participant, session, and target). $\theta_{\text{antenna2vehicle}}[n]$ is the antenna orientation relative to the CAVE reference frame (i.e. virtual vehicle) at sample n. The proposed metric quantifies the antenna steering dynamic during the search, identical for two similar antenna motions of different speeds, and null for a static antenna.

Figure 5 shows results of this metric regarding DF designs and sessions (to within the multiplicative sample time constant of 0.1 sec). Figure 5a presents a significant difference which indicates that participants scanned their surroundings more thoroughly in the hand design condition. Separation of this analysis by session (Figure 5b) supports this observation, furthermore suggesting that

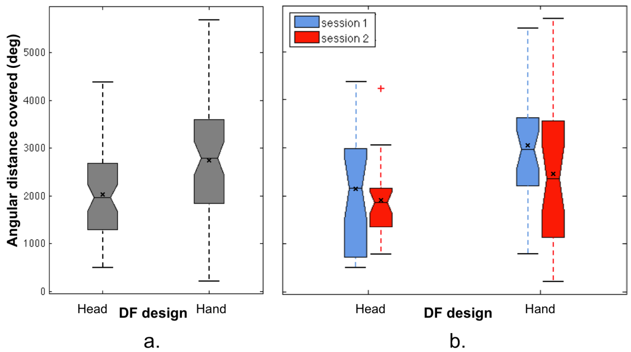

Figure 5: **a)** Distribution of summed angular distance covered by the DF antenna during target search (10×6 targets) as a function of DF design. **b)** Summed angular distances separated by session.

skilled users (i.e. the [session 1 hand - session 2 head] group, introduced earlier in this section) needed significantly less antenna movements to find the targets in the second session.

Regarding this issue, the VE implementation was believed to induce non-realistic behaviors, and a potential bias on inter-design and participants comparison. With the head design, participants did not scan (i.e. look) beyond the field of view of the projection screens. Also, The WIP allowed for a natural dissociation between the walking direction and the head orientation for participants comfortable with the VE interface, while others had to stop walking to scan their surroundings when the directional antenna was positioned on their head (see Figures 6b-c).

3.2. Qualitative analysis

Qualitative analysis is concerned with discussion of DF uses and observed target search strategies, along with non-realistic behaviors induced by the virtual prototyping implementation.

In the experiment, search strategies seemed to primarily depend on participant skills and their control of the VE interface rather than the specific features of each DF design. The strategies applied in session 1 (for a given DF design) were often reused and refined in session 2.

Maximum Power search strategy: involves steering the DF antenna until an angular maximum of signal power is found (i.e. the antenna orientation producing the shortest audio sample repetition period for a given sensitivity level). Every participant started the experiment using this strategy while only 50% of them exclusively used it until the very end. This strategy was optimal for those able to quickly assess rhythmic fluctuations while advancing through the VE. An informal study based on the PP suggests that this strategy is mainly hindered by the increasing complexity of received RF data as obstacles appear (building, cars, etc.), since they induce multi-path propagation pulling the user towards fake temporary maximums.

Minimum Power search strategy: involves the reverse process; steering the DF antenna until an angular minimum of signal power is found. It exploits the directional antenna main null (opposite to its main lobe and often particularly narrow, c.f. Figure 7b). This strategy was instinctively adopted by three participants, proving to be more time consuming because of the unnatural antenna orientation (opposed to the walking direction) and the slow dynamic of rhythmic feedback in the low power regions (having to compare between *slow* and *very slow* pulsations). It eventually resulted in more confident estimations for those who were uncomfortable with detection of subtle rhythmic fluctuations. The informal study based on the PP suggests that the minimum search strategy is more robust with regard to multi-path propagation. This method was easier to operate with the handheld antenna, because of the antenna orientation often opposed to the walking direction.

Triangulation search strategy: involves moving the virtual vehicle in the VE without steering the antenna, until a rhythmic fluctuation is perceived due to the distance variation between the RF emitter and the DF antenna. The directional characteristics of the antenna were not exploited: the user moves in the VE to gather information on target direction. While not optimal in the overall experiment, this strategy proved extremely efficient for near-field searches, i.e. for precise target localization where small movements of the virtual vehicle produced important shifts in the received signal power (due to the RF propagation model, despite the bin-wise pseudo linearization evoked in Appendix B). For far field search, participants always coupled it with one of the strategies described above.

Interval search strategy: (*unexpected at first, this strategy is related to the sonification clipping paradigm evoked in Appendix B*) involves steering the DF antenna using a hypersensitive level (i.e. subject to *clipping*). The clipping related sound is then added to the sonification, only for received signal powers above the clipping threshold. Considering the antenna directivity, this threshold can be illustrated as a cone drawn from the virtual vehicle to the target. The clipping sound is then heard only when the antenna aim is inside this cone, with an angle depending on the target distance and current sensitivity level. Identifying right and left clipping limits allowed to precisely estimate the target direction. Three participants adopted this strategy, which resulted in slow yet confident estimations. This strategy particularly hindered user movements, as the clipping limits were more relevant if measured by pair (right and left) at a given distance from the target. An informal study based on the PP suggests that this strategy has no validity in a real environment, since it relies on the deterministic nature of the implemented RF propagation model.

While reasonable performances where obtained using one of these strategies, the 2 best performing participants (in terms of task execution time) were able to seamlessly use all four of them during the experiment. As the amount of information increased, they roamed the VE more confidently, adding motion dynamics to the audio feedback (the faster you move towards an RF target, the greater the Geiger counter rhythmic fluctuations). The programer involved in the sonification design reported exploiting the sound timbre (different for each sensitivity level, see Appendix B) for rough yet steady target distance assessments. When asked, participants reported that they probably would have needed a more intensive training session to exploit this feature.

Mishandling of sensitivity levels proved to be one of the main performance issues. Participants underestimating the required sensitivity level (for a given target distance) would, for instance, have to differentiate between a slow and a very slow pulsation (e.g. 1 and 0.5 bps) to find their way towards the next target, where an

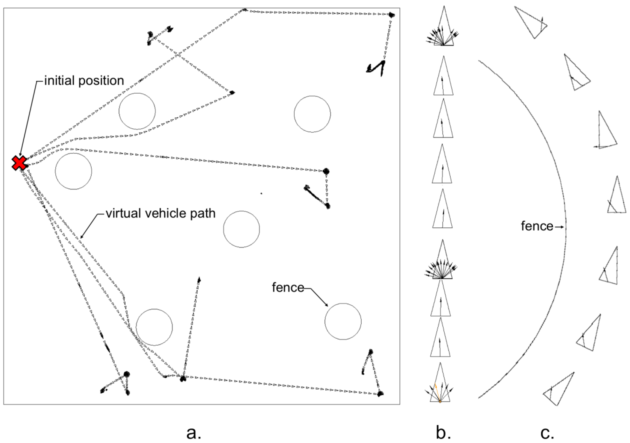

Figure 6: **a)** Full search path illustration of the first session of one of the slowest participants (regarding task execution time). Triangles and arrows represent respectively recorded virtual vehicle positions and antenna orientations. Path straightness and static rotations of the virtual vehicle (instead of the directional antenna) suggest a non-optimal use of the WIP metaphor (compared to Figure 3). **b)** (Zoom in of a)) dissociated walk and DF estimation: the user stopped walking every few seconds to scan with the DF. **c)** (Zoom in of Figure 3) Alternate participant using both DF and WIP simultaneously.

appropriate sensitivity level would have resulted in a comparison between 40 and 1 bps for the same raw data . All 3 removed participants experienced such a situation, reporting afterward that their irritation and lack of trust in the DF measurements affected their attention in the experimental task. It may be related to their experiencing *cybersickness*, a form of motion sickness that results from interaction with virtual environments [20].

The sonification metaphor was kept as simple as possible, except for the interaction induced by sensitivity level selection, required to address inverse square law dynamic issues (see Appendix B). However, the time required to confidently work with the levels was underestimated. We would suggest a pre-training session, scaled to the participants needs to reach a good understanding of the task-related interactions, to reduce this learning effect related bias.

The main VE related performance issues came from difficulties in using DF and WIP simultaneously. Participants able to use the WIP in the VE as they would use their legs in a real environment could focus on the DF behavior. Figure 6 illustrates differences in VE exploration efficiency between 2 typical participants. Suggested improvement would be to thoroughly evaluate participants skills regarding VE related interaction mechanisms (longer training sessions) to strictly limit the virtual prototyping analysis to VP design related fluctuations.

Ultimately, participants lacked the urgency related to typical DF aided searches, as in victim rescue operations. This issue is related to the experimental context rather than the VE. While this is an issue regarding ecological validity, it does not necessarily affect the VP external validity [12], i.e. the bias induced thereby does not necessarily invalidate VP issued result generalizations.

4. CONCLUSION

This paper introduced the virtual prototyping implementation of a radio Direction Finder (DF), along with a suggested method to assess its realism regarding an equivalent physical prototype. Said method relies on the parallel observation of both physical and virtual prototypes during a target localization task. When the design paradigm is modified, performances change for both prototypes. The correlation between these variations is assumed to represent an indicator of the implementation ecological validity, i.e. *how much* it reflects reality. The current experiment and associated results were concerned with the virtual task implementation only.

Two different DF designs were implemented and tested in a CAVE, where participants had to use each design to localize several targets in a minimum amount of time. The core DF design was based on a single directional antenna steered by an operator along with a Geiger counter sonification metaphor of the antenna output power. Implemented designs differed only in the position of said antenna: in the hand or on the head of the DF user.

Raw performances (e.g. task execution time) were identical for both designs. They induced a difference in antenna steering dynamic. The individual search strategy that was adopted was selected on the basis of listening skills and participant familiarity with the VR interface rather than on DF design specifications.

The virtual prototyping implementation itself produced a bias between participants, according to their abilities to learn and assimilate non-realistic interactions like Walk In Place (WIP) or joystick control. The implementation may also have induced an inter-design bias, the WIP allowing participants to easily move and look in different directions for a large amount of time (while one of the DF design involved head movements to steer the antenna). As it is, regarding the virtual environment, the proposed methodology requires thorough learning sessions, along with a careful examination of eventual benefits from the implementation on specific prototyped designs.

Informal tests with a physical DF prototype in a flat field environment suggested that the simple RF model (free field propagation) induced DF behaviors that reflected the reality. The virtual prototyping of more complex environments will however definitively require a more advanced raytracing model. Furthermore, as the complexity of the considered design increases, so will the risk of result misinterpretation and biased behaviors.

Ultimately, the virtual prototyping of human interfaces would be advised for long term design studies only, since its validity assessment can prove to be time consuming, especially for complex paradigms evaluations. Once characterized though, it can become a potent testbed for ergonomics assessment.

5. FUTURE WORK

Future works will focus on the DF aided target localization task in the real environment, to achieve the proposed virtual prototyping characterization method. Accordingly, the VP is to be afterwards exploited for time saving, economical and reproducible DF ergonomics evaluations, mainly focused on the sonification paradigm and sound aesthetics for the task at hand.

6. ACKNOWLEDGMENTS

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Appendix

The sonification metaphor and DF design are reported here since they should not be considered as the main focus of the current study. Implementation choices are thus not discussed here but merely summarized to ensure the paper's integrity.

A. Direction Finder Design

DF designs are based on a single directional antenna steered by an operator, illustrated Figure 7. The two designs differ only in the positioning of said antenna: in the user's hand or on its head. *In the head design, the antenna orientation is computed from participants' head position, logged in through the tracked stereoscopic glasses (introduced in Section 2.2).*

Of questionable relevance regarding current state of the art direction finding considerations [1], the proposed core design offers a solid case study for the considered ecological validity assessment. It is recognized as a textbook case of low implementation and human-machine interaction complexity.

B. Geiger Counter Sonification Metaphor

The sonification metaphor involves a mapping of the DF output signal power to the repetition tempo of a given noise, hence the *Geiger counter* reference. Said output signal power depends on the antenna orientation and its distance with respect to the RF emitter. Due to the free field RF propagation model implemented (i.e.

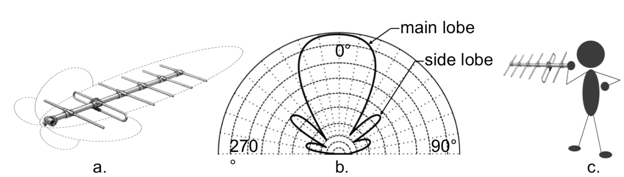

Figure 7: **a)** Illustration of a *yagi* like directional antenna, and likely associated azimuth plane pattern (dotted lines). **b)** Example of a directional antenna azimuth plane beam pattern plot in polar coordinates. **c)** Illustration of the hand held design operation. The antenna dimensions (e.g. length) determine its resonant frequency that must be tuned to the RF emitter of interest for direction finding applications. A maximum output power is reached when the antenna is aimed straight at the RF emitter.

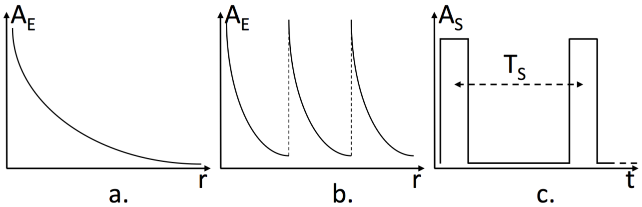

Figure 8: **a)** Inverse square law illustrating the DF received signal power dynamic A_E relative to the distance r between the DF antenna and the RF emitter. **b)** Piecewise linearization of a), into DF user controlled sensitivity levels. **c)** Geiger sonification metaphor illustration, depicting audio bursts repeated every T_s. The decrease of T_s as the DF output power increases give the natural sensation that the RF emitter gets closer.

inverse square law, see Section 2.3), the DF output signal power follows the dynamic illustrated in Figure 8a from right to left (r decreasing) as the DF user draws nearer to the RF emitter. To provide the DF user with a roughly linear dynamic, i.e. for him to perceive a more constant rhythmic evolution as he progresses towards the RF emitter, the function of Figure 8a has been divided into the piecewise relatively linear function of Figure 8b. An informal preliminary study on DF assisted localization tasks, exploiting the raw RF dynamic, indeed resulted in participants not being able to distinguish rhythmic variations when moving towards or opposite to the RF emitter from afar.

Shifting between *sensitivity levels*, allows the DF user to select a dynamic range appropriated to the current distance to the RF emitter. This shift is achieved using the 6 DoF tracker analog buttons of Figure 2c (3.1 and 3.2 to obtain more and less sensitive levels respectively). The corresponding rhythmic fluctuations can thus be scaled to fit user's preferences. The size of the environment, i.e. the maximum distance between DF and RF emitter, suggested the creation of six different sensitivity levels: a tradeoff between DF usability (ensure there is a *relevant* sensitivity level, regarding rhythmic variations, for every potential DF/Target distance) and complexity (not too many levels to deal with). To give the user some feedback on the distance to the RF emitter, i.e. to be able to differentiate between sensitivity levels, the impulse sonification sound (440 Hz marimba note) is filtered according to the current sensitivity level to sound increasingly more *metallic*.

To prevent situations where the more sensitive levels would be triggered near the target and untrained participants would attempt to establish a distinction between 8000 and say 8600 bps, the tempo is limited to a maximum of one sample per 40 ms. Once this maximum is reached (for a given sensitivity level and received RF signal strength) a short *click* notification sound is added to the Geiger sonification every 0.9 s. This notifies the user that the level reached its limit for the current distance and antenna orientation. This state is referred to as *clipped*. Initially designed to minimize potential misuses of the sensitivity levels paradigm, this implementation incited an unexpected search strategy in some participants who used this clipping to determine quite precisely the target direction (c.f. Section 3.2).

C. Virtual Environment

The VE has been implemented with blenderCave [16], an extension of blender for VR real-time and interactive scene rendering. The scene was constructed to best reproduce features of the foreseen RE, a 6 ha square grass field. Visual references have been added to the VE (trees, mountain range, etc.) to enhance motion perception and path integration [21], along with fences to simulate inaccessible areas of the real environment, obstructing the DF user path and momentarily modifying his search pattern. The main purpose of the grass is to hide the visual RF targets (see Figure 11), previously visible from far away, inducing an obvious bias in the audio-based search task.

Figure 9: VE screen shot, aerial view.

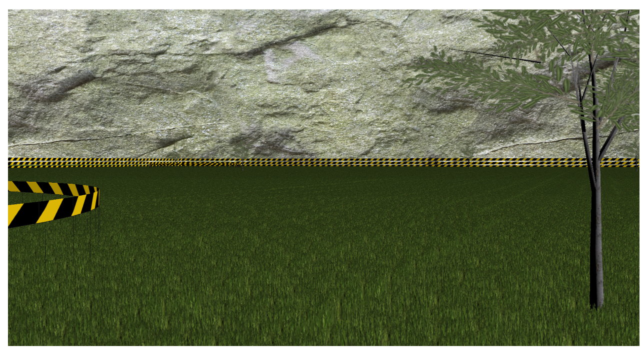

Figure 10: VE screen shot, virtual vehicle point of view (CAVE front screen).

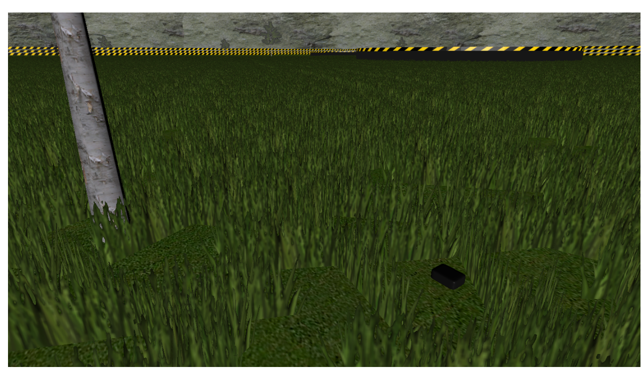

Figure 11: VE screen shot, Target illustration.