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Thèse de Camille Bordeau

**Développement d'un dispositif de substitution sensorielle vision-vers-audition : étude des performances de localisation et comparaison de schémas d'encodage**

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**Discipline** : Psychologie

**Supervision** : Sous la direction de Maxime Ambard et Emmanuel Bigand

**Obtention** : Thèse soutenue publiquement à Dijon le 18 décembre 2023

**Etablissements de rattachement** : Université de Bourgogne, LEAD CNRS UMR5022, Ecole Doctorale Environnement-Santé

**Financeurs** : Région Bourgogne Franche Comté, FEDER, UNADEV.

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**Résumé des travaux de thèse**

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En 2020, on estimait à au moins 337 millions dans le monde le nombre de personnes avec une déficience visuelle moyenne, sévère ou une cécité visuelle<sup>1</sup>, dont **43 millions avaient une atteinte visuelle sévère ou une cécité**. Avec l'accroissement de la population mondiale accompagné de l'augmentation de l'âge moyen, le nombre de personnes avec une déficience visuelle et une cécité est malheureusement en progression. **Les déficiences visuelles ont de graves répercussions sociales, financières, physiques et psychologiques sur le quotidien des personnes concernées**. Par exemple, elles entraînent une augmentation du risque de chutes et de blessures, une diminution de l'accès au monde du travail et aux loisirs, et une diminution de l'autonomie dans les tâches quotidiennes (e.g. faire les courses, la cuisine) et les déplacements<sup>2</sup>. Ces éléments participent à un risque accru d'isolement social et à la diminution de l'autonomie et de la qualité de vie. **Améliorer l'autonomie des personnes non-voyantes lors de leurs déplacements représente un enjeu majeur pour améliorer leur qualité de vie**. Malgré les dispositifs actuels d'aide à la locomotion pour guider et garantir la sécurité dans les déplacements (e.g., la canne blanche, le chien d'aveugle, les GPS sur smartphone), les problèmes persistent. Une autre catégorie de dispositifs d'assistance pour les personnes non-voyantes se révèle prometteuse : les dispositifs de substitution sensorielle.

**Les dispositifs de substitution sensorielle vision-vers-audition sont des outils d'assistance technologique à destination des personnes déficientes visuelles**, qui convertissent des informations visuelles en un paysage sonore. Les informations visuelles

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<sup>1</sup> Steinmetz et al. (2021)

<sup>2</sup> World Health Organization (2019)

prennent la forme d'un flux vidéo acquis par une caméra attachée à la tête de la personne, qui est converti en un ensemble de sons, appelé paysage sonore, qui doit permettre à la personne déficiente visuelle de percevoir son environnement à travers la modalité auditive. Ces dispositifs d'assistance sonore pourraient participer à l'amélioration de l'autonomie des personnes déficientes visuelles en facilitant leurs déplacements pédestres. En revanche, ils ne sont que très peu déployés car ils font face à des contraintes cognitives inhérentes à la nécessité d'apprendre à interpréter de nouveaux sons. Ce nouveau paysage sonore complexe dépend des caractéristiques du son qui sont manipulées (aussi appelés indices acoustiques) dans le schéma de conversion visuel-vers-audition (aussi appelé schéma d'encodage). Maîtriser l'utilisation d'un tel dispositif implique d'apprendre à interpréter de nouvelles informations sensorielles auditives pour percevoir le monde et interagir avec. La mise en correspondance entre les dimensions visuelles et les indices acoustiques modulés dans les schémas d'encodage n'est pas toujours considérée comme intuitive par les utilisateurs déficients visuels. Conséquemment, les entraînements, souvent longs, peuvent être à l'origine d'un découragement freinant l'adoption du dispositif. À terme, il s'agit d'être en capacité d'analyser des scènes auditives complexes, puisqu'il est nécessaire de percevoir les informations auditives provenant à la fois du paysage sonore du dispositif, et de l'environnement réel (e.g., bruit de voitures), sans qu'elles entrent en conflit.

Ce travail de thèse s'est intégré au projet 3DSG (financé par la Région Bourgogne Franche Comté, le FEDER, et l'UNADEV), visant à développer un dispositif de substitution sensorielle en se reposant sur la collaboration de chercheurs et chercheuses en Psychologie et en Informatique.

L'objectif principal des travaux de thèse était de déterminer un schéma d'encodage facilitant la perception spatiale en 3-dimension de l'environnement, et d'évaluer les capacités de localisation d'objets avec le dispositif, le tout en prenant en compte les capacités de perception auditive spatiale pour faciliter l'apprentissage perceptif. Pour déterminer les indices acoustiques du schéma d'encodage du dispositif et pour évaluer les capacités à interpréter ce nouveau paysage sonore, l'objectif de ce travail de thèse était aussi de développer des protocoles de familiarisation et d'évaluation dans des environnements virtuels plus ou moins complexes.

Le premier objectif était de déterminer si la reproduction d'indices acoustiques pour la perception spatiale auditive était plus efficace que l'utilisation d'indices acoustiques alternatifs mais impliqués dans des interactions audio-visuelles. **La première étude** a mis en évidence que la modulation de la hauteur tonale (grave - aigue) dans le schéma d'encodage pour l'élévation (hauteur d'un objet) permettait de compenser en partie les limites des capacités de perception spatiale inhérentes aux indices acoustiques spatiaux. Cette étude est [publiée dans le journal Frontiers in Psychology](#), et a été présentée à la *conférence International Multisensory Research Forum 2023* à Bruxelles (Belgique). **La deuxième étude** a mis en évidence une perception compressée de la distance lorsque le volume (faible – fort) était modulé en fonction de la distance d'un objet, mais qu'une modification de l'enveloppe sonore (modulation du timbre) compensait partiellement ce biais. Cette étude est en cours de préparation et sera bientôt soumise. Les résultats ont été présentés à la *conférence Auditory, Perception, Cognition and Action Meeting 2022* à Boston (Etats-Unis). À l'issue des deux premières études, un schéma d'encodage pour le dispositif a été validé, permettant de maximiser les capacités de localisation, en se reposant sur des indices acoustiques spatiaux (azimut et élévation), de modulation de la hauteur tonale (élévation), et de l'intensité (distance).

Le deuxième objectif de ce travail de thèse était de déterminer dans quelle mesure le schéma d'encodage validé permettait de préserver, ou d'altérer, les capacités de perception spatiale dans un environnement complexe composé de plusieurs objets. Les dispositifs de substitution

sensorielle sont bien souvent évalués dans des contextes minimalistes éloignés de la complexité de l'environnement réel. **La troisième étude** a mis en évidence que les capacités de ségrégation d'une scène visuelle complexe à travers le paysage sonore du dispositif associé dépendaient de la signature spectrale spécifique des objets la composant lorsque la modulation de la hauteur tonale est utilisée comme indice acoustique dans le schéma d'encodage. Cette troisième étude est en cours de révision dans le journal *Attention, Perception, & Psychophysics* et sera prochainement resoumise.

Les travaux de cette thèse ont des **implications pratiques portant sur l'amélioration des dispositifs de substitution**. D'une part, ils montrent la possibilité de compenser les limites de perception spatiale avec l'utilisation d'indices acoustiques non spatiaux dans le schéma d'encodage : la fréquence (grave-aigue) et le timbre. D'une autre part, ils relèvent la nécessité de réduire le flux d'informations auditives issues du dispositif, afin de préserver les capacités de ségrégation du paysage sonore, et ainsi de préserver la perception des sons environnants (par exemple : bruits de voiture, de passants qui discutent). La plateforme expérimentale en environnement virtuel développée durant la thèse a permis de proposer des protocoles de familiarisation et d'évaluation adaptés à la population déficiente visuelle. Ainsi, les travaux de cette thèse soulignent également **le potentiel prometteur et innovant des environnements virtuels dans la recherche**, pour évaluer précisément, et de façon contrôlée, les capacités d'utilisation de dispositifs de substitution dans un contexte sécurisé. Ces travaux de thèse ont également des **implications théoriques** en Psychologie cognitive en appuyant la thèse de l'automatisme de l'association entre hauteur tonale (fréquence : grave – aigue) et hauteur spatiale (bas – haut), et en confirmant un biais de perception compressée de la distance. Enfin, ces travaux ont des **implications sociétales**, en participant à l'amélioration de l'inclusion des personnes déficientes visuelles, en se focalisant sur l'amélioration de l'autonomie et de la sécurité au cours de leurs déplacements.

# Camille Bordeau

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Marseille, France

## EDUCATION

### PhD in Cognitive Psychology

University of Burgundy – *Thesis successfully defended on December 18<sup>th</sup>, 2023*

Graduated in 2023  
Dijon, France

### M.S. in Cognitive Science, specialty Neuropsychology and Clinical Neuroscience

Université Lumière Lyon 2 – *with honours*

Graduated in 2020  
Lyon, France

### B.S. in Applied Mathematics and IT, specialty Cognitive Science

Université de Bordeaux – *with honours*

Graduated in 2018  
Bordeaux, France

## RESEARCH EXPERIENCES

### Center for Research on Psychology and Neuroscience (CRPN CNRS UMR 7077)

Marseille, France  
Sept 2024 - now

Postdoctoral researcher in the context of DEVISE project “From novel rehabilitation protocols to visual aid systems for low vision people through Virtual Reality”

**Keywords:** assistive technology, visual impairment, eccentric viewing, virtual environments

### Laboratory for Research on Learning and Development (LEAD CNRS UMR 5022)

Dijon, France  
Oct 2020 – Oct 2023

PhD supervised by Maxime Ambard and Emmanuel Bigand “Development of a visual-to-auditory sensory substitution device: study of localization performance and comparison of encoding schemes”.

**Keywords:** assistive technology, sensory substitution, visual impairment, perceptual learning, multisensory perception, cross-modal correspondence, spatial perception, auditory scene analysis, virtual environments.

### Lille Research Center for IT, Signal and Automatic (CRISTAL), team BCI

Lille, France  
Feb 2020 – June 2020

Research internship supervised by François Cabestaing “Power spectral density analysis of steady-state somatosensory

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evoked potentials”

**Keywords:** assistive technology, brain-computer interface, motor impairment, EEG.

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**Lyon Neuroscience Research Center (CRNL), team IMPACT**

Research internship supervised by Claudio Brozzoli

“The effects of object permanence in peripersonal space: facilitation effect of visuo-tactile integration on tactile information processing”

**Keywords:** multisensory perception, peripersonal space, visuo-tactile integration.

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Lyon, France  
Nov 2018 – April 2019

**National Institute for Research in Digital Science and Technology (Inria), team POTTIOC**

College work supervised by Lea Pillette, PhD student

“Brain-Computer Interfaces based on motor imagery for post-stroke motor rehabilitation”

**Keywords:** assistive technology, brain-computer interface, motor imagery, EEG.

Bordeaux, France  
Jan 2018 – May 2018

## PUBLICATIONS AND COMMUNICATIONS

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### Publications

1. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J., & Ambard, M. (2023). Cross-modal correspondence enhances elevation localization in visual-to-auditory sensory substitution. *Frontiers in Psychology*, 14.  
<https://doi.org/10.3389/fpsyg.2023.1079998>
2. Scalvini, F., **Bordeau, C.**, Ambard, M., Migniot, C., Argon, S., & Dubois, J. (2022). Visual-auditory substitution device for indoor navigation based on fast visual marker detection, *16th International Conference on Signal Image Technology and Internet Based Systems*, Dijon, France.
3. Scalvini, F., **Bordeau, C.**, Ambard, M., Migniot, C., & Dubois, J. (2022). Low-Latency Human-Computer Auditory Interface Based on Real-Time Vision Analysis. *ICASSP 2022 - 2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. <https://doi.org/10.1109/icassp43922.2022.9747094>
4. Scalvini, F., **Bordeau, C.**, Ambard, M., Migniot, C., & Dubois, J. (2024). Outdoor Navigation Assistive System Based on Robust and Real-Time Visual–Auditory Substitution Approach. *Sensors* 24(1), 166. <https://doi.org/10.3390/s24010166>
5. Scalvini, F., **Bordeau, C.**, Ambard, M., Migniot, C., Vergnaud, M., & Dubois, J. (2024). uB-VisioGeoloc : An image sequences dataset of pedestrian navigation including geolocalised-inertial information and spatial sound rendering of the urban environment's obstacles. *Data In Brief*, 110088.  
<https://doi.org/10.1016/j.dib.2024.110088>
6. Carlini, A., **Bordeau, C.**, & Ambard, M. (2024). Auditory localization : a comprehensive practical review. *Frontiers In Psychology*, 15.  
<https://doi.org/10.3389/fpsyg.2024.1408073>
7. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J., & Ambard, M. (XXXX). Localization abilities with a visual-to-auditory substitution device are modulated by the spatial arrangement of the scene. (submitted in Attention, Perception & Psychophysics on Nov 29, 2023, under review)

### Communications

8. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J. & Ambard, M. (2023). Visual-to-auditory conversion methods for sensory substitution: soundspatialization only versus cross-modal correspondence, *International Multisensory Research Forum (IMRF 2023)*, Bruxelles, Belgium (Poster)
9. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J. & Ambard, M. (2023). Investigation of the effect of distractors on localization abilities with a visual-to-auditory substitution device, *International Multisensory Research Forum (IMRF 2023)*, Bruxelles, Belgium (Poster)
10. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J. & Ambard, M. (2022). Distance perception of object using visual-to-auditory sensory substitution: comparison of conversion methods based on sound intensity and envelope modulation, *21st Auditory, Perception, Cognition and Action Meeting (APCAM 2022)*, Boston, United States. (Poster)

11. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J. & Ambard, M. (2022). Comparison of visual-to-auditory conversion methods for sensory substitution in a localization task. *Journée des doctorants du Laboratoire d'Etude de l'Apprentissage et du Développement*, Dijon, France (Oral communication)
12. **Bordeau, C.**, Scalvini, F., Migniot, C., Dubois, J. & Ambard, M. (2022). Comparison of auditory encodings for visual-to-auditory sensory substitution in a localization task, *Forum des Jeunes Chercheurs de l'Ecole Doctorale Environnement-Santé*, Dijon, France (Poster)

## Scientific Vulgarisation

13. **Bordeau C.** « Glasses to help blind people to localize obstacles with sounds ». <https://www.experimentarium.fr/les-chercheurs/des-lunettes-pour-aider-les-personnes-aveugles-localiser-des-obstacles-grace-des-sons>. *Experimentarium*. Dijon, France. (Workshops to discuss my PhD research with youngs between 10 and 20 years old)
14. **Bordeau, C.**, Scalvini, F. « Open the ears to better see ». *5<sup>th</sup> day of scientific culture at the Institut Marey, Dijon, France. March, 28 & May, 2, 2023. (Workshops with discussions and demonstrations about my PhD research with high school students)*
15. European Researchers Night 2023 « Our futures » – Objects of the future. <https://marie-sklodowska-curie-actions.ec.europa.eu/event/2023-european-researchers-night>. *Dijon, France. September, 29, 2023. (Workshop with adults and young people to discuss about my PhD research).*

## AWARD

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**Best Poster Award** of the session COGNITION, LEARNING AND MOVEMENT - Congress of Young Researchers of the Doctoral School "Environments – Health"

Dijon, France  
June 16, 2022

## SCIENTIFIC COLLABORATION

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**Laboratory Image and Artificial Vision (ImVia)** in Dijon, France. Collaboration with Florian Scalvini (PhD student in Instrumentation and Computer vision), Cyrille Migniot (Assistant professor in Computer vision), Julien Dubois (Assistant professor in Computer vision), Mathilde Vergnaud (Engineer).

## TECHNICAL TOOLS AND PROGRAMMING SKILLS

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**Guiding technique for blind and visually impaired individuals** with the *Yeux en promenade* and *Voir & Percevoir* associations (2-day course, September 2021).

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### **Python and Psychopy**

- Additive sound synthesis to generate experimental material
  - Auditory signal processing
  - EEG data processing with MNE Python
  - Implementation of behavioural experiments with Psychopy
  - KNN algorithm
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### **Unity**

- Design and implementation of experiments with Unity and C# programming
  - Management of HTC Vive Trackers for motion capture
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### **PTVR : Perception Toolbox for Virtual Reality**

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### **R**

- Statistical analyses of behavioural data with ANOVA, Linear Mixed Models, correlations, linear regression, t-test
- Data visualization with ggplot

Statistical analyses of EEG data

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### **Open Sesame**

- Implementation of behavioural experiments with Open Sesame
- 

### **LaTeX**

- M.S. thesis written with LaTeX
  - Article submitted with LaTeX in *Frontiers in Psychology*
- 

### **Audacity**

- Visualization and basic processing of sound files



## TEACHING

Course	Level	Institution	Year
<b>Cognitive Ergonomy</b>	Third year degree in Psychology	University of Burgundy, France	2021-2022 (10h)
<b>Statistics for Experimental Psychology</b>	Third year degree in Psychology	University of Burgundy, France	2020-2022 (80h)

## VOLUNTEERING

<b>French federation of students and young workers in Cognitive Science (Fresco)</b>		France 2019 – 2020
<ul style="list-style-type: none"> <li>▪ Vice-president in charge of students' associations</li> <li>▪ Project leader for the Colloquium of young researchers in Cognitive Science</li> <li>▪ Project leader for the guide for cognitive science students</li> </ul>		
<b>Lyon student association in Cognitive Science (Estigma)</b>		Lyon, France 2018 – 2019
<ul style="list-style-type: none"> <li>▪ Event team leader</li> <li>▪ Organized 3 conference for popularization of Cognitive Science</li> </ul>		

Laboratoire  
d'Étude  
de l'Apprentissage  
et du Développement

**Maxime AMBARD**  
Maître de conférences  
LEAD CNRS UMR5022  
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Dijon, le 11 février 2025

**OBJET : Lettre de soutien pour l'attribution du prix de thèse de l'IFRATH**

En tant que directeur de thèse de Camille Bordeau, j'ai supervisé son travail durant ses trois années de doctorat. Ses recherches en Psychologie Cognitive visaient à améliorer l'autonomie des personnes déficientes visuelles en développant un dispositif technologique sonore d'aide à la mobilité, appelé dispositif de substitution sensorielle.

Bien que novice dans la thématique de recherche de la substitution sensorielle, en psychoacoustique et dans l'outil méthodologique de réalité de virtuelle, Camille a fait preuve d'une grande détermination pour s'appropriier ces domaines. Ses travaux ont permis d'identifier des caractéristiques sonores pertinentes (fréquence, volume, timbre...) pour le dispositif de substitution sensorielle, et d'évaluer les capacités de perception spatiale qu'il offre. Rapidement, elle a manifesté un intérêt pour la compréhension des problématiques rencontrées par les personnes déficientes visuelles, en entrant en contact avec une association de personnes déficientes visuelles et en suivant une formation de technique de guide.

Durant sa thèse, Camille a mené à bien 3 études, dont une est publiée dans *Frontiers in Psychology*, une seconde est en cours de révision dans *Attention Perception & Psychophysics*, et la dernière est en cours de préparation. Son profil interdisciplinaire, sa motivation et son esprit critique lui ont permis de développer des protocoles expérimentaux rigoureux, d'implémenter une plateforme expérimentale en réalité virtuelle, d'analyser les données et de diffuser ses travaux de recherche dans des congrès internationaux et des revues scientifiques. En parallèle, elle a su échanger et collaborer avec des chercheurs d'autres disciplines en contribuant à 4 publications, dont une revue.

Camille a démontré son envie de promouvoir la recherche sur les technologies d'assistance à destination des personnes déficientes visuelles en s'impliquant de sa propre initiative dans des événements Grand et Jeune public. Elle a pris part à plusieurs reprises au dispositif Experimentarium qui vise à créer un dialogue entre des chercheurs et chercheuses et le Jeune public au cours d'ateliers. Elle a ensuite participé à La nuit Européenne des chercheurs en 2023 pour échanger avec le Grand Public sur ses travaux et le sensibiliser aux problématiques des personnes déficientes visuelles.

Les travaux de thèse de Camille Bordeau ont significativement contribué à la recherche sur le handicap visuel et ouvrent la voie à une amélioration sensible de l'autonomie des personnes déficientes visuelles. La qualité de ses travaux interdisciplinaires alliant la psychologie et la technologie pour la remédiation du handicap me semblent correspondre totalement à l'approche que l'IFRATH promeut et c'est pourquoi je pense que l'attribution de ce prix de thèse serait tout-à-fait justifié.



Maxime Ambard

Rapport de la thèse de

**Camille Bordeaux**  
École doctorale Environnements - Santé (ES)  
Université de Bourgogne  
par  
**Christian Graff**  
Laboratoire de Psychologie et de Neuro-Cognition  
Université Grenoble-Alpes

Camille Bordeaux soumet sa thèse de Doctorat d'Université de de l'École doctorale *Environnements - Santé* (ES) de l'Université de Bourgogne, menée sous la direction de Maxime Ambard et Emmanuel Bigand au Laboratoire d'Étude de l'Apprentissage et du Développement - CNRS UMR5022, intitulée « Développement d'un dispositif de substitution sensorielle vision-vers-audition : étude des performances de localisation et comparaison de schémas d'encodage ».

Une introduction et une discussion générales mettent en perspective trois séries expérimentales destinées à paramétrer un prototype qui restitue l'environnement sous forme de paysage sonore à l'usage des non-voyants. Les deux premières séries font l'objet d'articles publiés, la troisième d'un manuscrit formaté, présentés en annexe. Elles évaluent le pointage de sources sonores dans un espace virtuel 3-D en absence de vision.

## INTRODUCTION

L'introduction donne un état de l'art clair et actualisé des principes de substitution de la vision vers l'audition, avec un chapitre particulièrement didactique sur les paramètres de signaux acoustiques qui constituent la sortie du dispositif, et dont les avantages et les inconvénients font l'objet de la thèse. Les paramètres spatiaux qui constituent les entrées du dispositif ne font pas l'objet de paragraphe dédié.

Le dispositif de substitution visuelle (DSS) au cœur du travail traduit une image vidéo en « paysage sonore ». Des variations temporelles contrastées dans une région de l'image (en niveaux de gris) initient la sonification du groupe de pixels concernés. Pour cela l'objet focal à détecter (obstacle, cible, ou distracteur) durant les essais bouge en rotation sur lui-même.

La démarche de validation est graduelle, le milieu est parfaitement contrôlé en employant la réalité virtuelle, qui réduit au minimum les variables indépendantes des entrées (métriques spatiales) et des sorties (métriques acoustiques) du dispositif, ainsi que les variables dépendantes de l'utilisateur (métriques spatiales), permettant de sérier les problèmes et les solutions. Les tests sont effectués sur des formes synthétiques sans valeur sémantique. L'usager, les yeux bandés, porte sur la tête la caméra virtuelle à l'origine de l'image vidéo dont il entend les pixels actifs comme autant de sources sonores. Le son varie selon la position (et le nombre) des pixels actifs. Les études se focalisent sur la perception de la position d'un petit groupe de pixels symbolisant un objet, traduit par un groupe compact de sources sonores. Dans la première série expérimentale, cet objet focal est seul et à distance fixe devant et autour de la tête du participant (variations en azimut et en élévation uniquement) ; dans la seconde série, il est posé sur le sol à distance variable, en un ou deux exemplaires ; dans la troisième, il est placé à distance fixe en un seul exemplaire parmi deux ou quatre objets d'une autre forme en arrière-plan (variations en azimut et en élévation). Dans plusieurs protocoles, il est demandé aux participants de ne pas bouger la tête.

## ETUDE 1

Les participants sont plongés dans un VAS (Virtual AudioSpace) ou paysage sonore virtuel, comportant une sphère de 1 m de rayon dont le centre est le sommet de la tête du participant. Sur l'avant de cette sphère apparaît, par une convolution HRTF (Head-Related Transfer Filter, son spatialisé), une source sonore en 25 positions possibles combinant symétriquement cinq positions en azimut et cinq en élévation. À l'aide d'un objet pointeur (pistolet), les participants indiquent la position de la source. Selon les essais, la base sonore employée est un bruit blanc (condition contrôle commune), ou bien soit une sinusoïde pure (pour un groupe de participants), soit une combinaison de trois sinusoïdes harmoniques combinées (autre groupe de participants). L'élévation est encodée par les paramètres HRTF dans les deux conditions, auxquels se rajoute la fréquence des sinusoïdes, les sons plus hauts indiquant des positions plus en hauteur. Les essais se déroulent sans explication en une première phase où les participants se fient à un ressenti spontané. Une deuxième phase d'essais est conduite après une séance d'entraînement accompagné d'explications sur les liens entre les sons entendus et la position de leurs sources. Cet entraînement consiste à faire entendre la position pointée librement par l'utilisateur.

Dans l'ensemble, les participants restituent les positions, au moins qualitativement (haut, très haut, bas, très bas, à gauche très à gauche ou à droite, et au milieu). Les erreurs angulaires, de plus de quinze degrés en général, avoisinent celles reportées pour la localisation de sons spatialisés synthétiques dans la littérature. Les performances sont nettement meilleures dans la deuxième phase, en particulier pour les sons sinusoïdaux, avec un léger avantage pour la sinusoïde pure. Les erreurs sont particulièrement dues (en élévation) à une sous-estimation de la hauteur des sources, et (en azimut) à une exagération de la latéralité, avec un décalage mineur vers la gauche.

## ETUDE 2

Une seconde série expérimentale rajoute une troisième dimension pour l'usage du dispositif, à savoir la distance à une « cible » au sol, à partir d'impulsions sonores (durée et taux de répétition fixés). Celles-ci la traduisent non par l'ensemble composite des paramètres de la convolution HRTF (les paramètres secondaires sont maintenus constants), mais par une baisse d'intensité inversement proportionnelle au carré ; pour la modalité la plus simple, l'enveloppe de l'impulsion est plate ; pour une modalité contrastée, cet encodage est rehaussé par une forme gaussienne de l'enveloppe (qui multiplie l'amplitude de crête), l'intensité moyenne restant la même dans les deux modalités. La position perçue est pointée au sol par la direction d'un pistolet dans la main de l'usager. Deux tâches sont proposées. Dans la première, les sources sonores sont présentées successivement, et l'on mesure sur une échelle continue la coordonnée sur l'axe sagittal de la position pointée sur le sol (0,8 - 3 m) ; dans la seconde, deux sources sonores (de même forme) d'intensités différentes sont présentées simultanément, une à droite et une à gauche de l'axe, et l'on relève le côté de la position pointée par le participant sur le sol – à gauche ou à droite – de la source la plus proche (son plus intense), dans un protocole d'évaluation psychophysique d'ajustement.

Les résultats indiquent une correspondance entre l'intensité sonore et la distance pointée. La divergence entre la régression observée et la loi de puissance psychophysique théorique montre une sous-estimation des distances surtout les plus grandes, pour les deux formes d'impulsions sonores.

Ces résultats confirment l'usage possible de ces indices sonores pour traduire la distance relative d'objets mouvants par rapport à la caméra. Les biais observés sont mis en lien avec les données de la littérature indiquant une compression dans l'évaluation des distances c'est-à-dire une sous-estimation des longues distances et une surestimation des plus petites. Cependant cette surestimation des petites n'est pas exprimée en pratique dans les conditions des expériences.

### ETUDE 3

La dernière série de travaux rend plus complexe la localisation d'une source virtuelle ; elle compare la situation où la source est isolée comme précédemment (placée à 1 m de la caméra centrée sur la tête), à une situation où elle est placée parmi deux ou quatre autres sources plus distantes (à 2 m de la caméra sur la tête) et différentes d'elle. La position de la source focale et celles des distracteurs est traduite par la convolution HRTF marquant en particulier la distance par l'intensité du son et l'azimut par la stéréo, mais aussi en renforçant les indices de l'élévation par modulation de la fréquence sonore. La source virtuelle peut être placée au milieu ou à l'un des quatre angles d'un rectangle projeté, de  $-25^{\circ}$  à  $+25^{\circ}$  en élévation et de  $-20^{\circ}$  à  $+20^{\circ}$  en azimut ; à chaque essai elle se superpose aux distracteurs apparaissant avant elle ; l'utilisateur pointe sa position à l'aide du pistolet.

Les directions de pointages sont bien corrélées à celles des sources.

Les directions pointées marquent les mêmes biais, avec ou sans distracteurs : le pointeur vise systématiquement trop bas et trop loin de côté ; ainsi, en moyenne, les sources hautes (situées à  $+20^{\circ}$  en élévation) sont pointées à mi-hauteur (moins de  $3^{\circ}$ ), et les points à gauche ( $-20^{\circ}$  en azimut) apparaissent très à gauche (en-deçà de  $-35^{\circ}$ ). Comme ces données sont en accord avec celles de la littérature, la discussion porte sur une exception : lorsque la source cible est placée sur la même ligne horizontale que les quatre autres (distracteurs) c'est-à-dire lorsque cinq sources sonores émettent à la même fréquence, les biais sont fortement réduits.

### DISCUSSION.

La discussion rappelle l'intérêt potentiel des SSD, du montage (virtuel) et des protocoles de test. Elle insiste sur l'importance des boucles perception action, et met en valeur les protocoles de familiarisation avec le dispositif testé sur des personnes voyantes aux yeux bandés, adaptable aux personnes non voyantes. Elle évoque les applications finales potentielles des résultats des études, en particulier pour l'assistance aux déplacements pédestres en milieu encombré, pour lesquels la détection d'obstacles proches est prioritaire. Elle relève les problèmes de biais et d'excentricité de pointage par rapport à la source en rappelant que ces résultats sont en accord avec les données de la littérature. Elle montre aussi les apports théoriques offerts par ce type d'étude pour la compréhension des mécanismes de perception multisensorielle. Elle propose d'améliorer la sélection des paramètres spatiaux traduits en sons par le dispositif afin de réduire la charge cognitive, et bien sûr d'impliquer des personnes non voyantes dans la poursuite des tests.

### COMMENTAIRES

Le document est très clairement rédigé, avec de nombreux paragraphes de synthèse et des figures parlantes qui favoriseront la discussion. Les expériences effectuées sont de grande qualité méthodologique. Les différentes modalités des variables indépendantes et dépendantes sont pertinentes et choisies avec soin, et les autres variables sont parfaitement contrôlées. La significativité des résultats est très élevée. La progression est méthodique. Le travail montre les compétences matures de la chercheuse en sciences cognitives en méthodologie expérimentale et traitement de données, ainsi que sur les principes fondamentaux de l'acoustique de toute sonorisation. Je tiens à souligner ces grandes qualités qui mériteraient une place plus importante dans mon rapport par rapport aux réserves plus longues à développer.

Il s'agit pour moi d'un travail particulièrement fiable et parfaitement reproductible.

Les limites de cette recherche sont celles de la science actuelle hyper-spécialisée : elle ne peut raisonnablement adresser et répondre qu'à un nombre limité de questions, employant des technologies

complexes qui ne peuvent être maîtrisées sous tous leurs aspects (ex : architecture du système informatique de réalité virtuelle, détail de l'HRTF employé, ...) et dans toutes leurs applications (acceptabilité, sociologie du handicap...). Ces limites sont particulièrement pénalisantes dans les approches interdisciplinaires, et je salue la prise de risque de la chercheuse et ses collaborateurs.

Le travail montre (ou confirme) les limites de l'HRTF (au moins pour le système non personnalisé employé, mais en accord avec la littérature) pour la localisation d'une source sonore. Il suggère et justifie d'améliorer substitution sensorielle, en rehaussant les contrastes acoustiques par des variables supplémentaires, en particulier la hauteur de son (signalant l'élévation) qui est intuitive et très précise. En ceci le travail propose l'emploi de tels paramètres redondants pour assister à la discrimination, contribuant ainsi à l'amélioration de futurs SSD. L'intérêt de l'HRTF par rapport à une simple stéréophonie n'est pas évoquée, elle peut être testée avec les mêmes moyens.

Le travail montre (ou confirme) une excentricité presque systématique du pointage par rapport à la source sonore virtuelle. Les biais d'écarts ou « erreurs » peuvent être attribuées au système perceptif des participants, à l'algorithmique de l'HRTF ou aux paramètres spatiaux du système de pointage directionnel. Cette dernière hypothèse est assez peu explorée. La maîtrise du dispositif expérimental permettrait de trancher, en combinant la situation virtuelle avec des sources sonores réelles (haut-parleurs).

Le travail montre (ou confirme) en particulier une compression des distances ; celle-ci ne mérite pas nécessairement d'être corrigée, de telles distorsions peuvent être adaptatives comme cela est suggéré en conditions écologiques : un obstacle apparaissant plus près qu'il n'est sera évité plus volontiers. Le passage du virtuel au réel permettrait de trancher en employant des obstacles matériels.

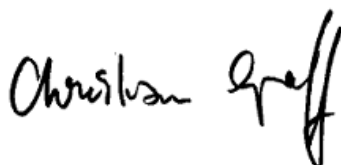
Formellement, les expériences ne confrontent pas la position perçue par un utilisateur d'une source sonore avec la position exacte de cette source matérielle ; elles confrontent la position imaginée d'une source virtuelle avec une position pointée virtuellement. Il s'agit donc essentiellement d'une confrontation de paramètres sonores à des paramètres posturaux de participants. Un deuxième mode d'évaluation de la position ressentie pourrait lever l'ambiguïté.

L'expérience 2 montre un écart entre la courbe psychophysique (assimilable à une loi de Stevens) et la loi de puissance observée. Un examen plus approfondi des données et un test éventuel permettraient de savoir en quoi les paramètres de cette loi de puissance sont en lien avec l'exposant (-2) employé pour traduire la distance, et l'énergie totale dégagée par les signaux d'enveloppe simples ou gaussienne.

Dans l'expérience 3, la configuration cible-distracteurs donnant des réponses se détachant des cinq autres configurations aligne cinq sources sonores émettant toutes simultanément à la même fréquence ; les déphasages qui émergent pourraient générer des interférences dans l'HRTF employé expliquant cette exception.

En conclusion, les apports de ce travail - et de sa poursuite éventuelle employant le même dispositif de test - consolident des principes fondamentaux de la perception multimodale et des liens perception-action. Ceux-ci sont indispensables au développement de la substitution sensorielle à l'usage de non-voyants ; ils sont essentiels au développement de la réalité virtuelle 3-D dont les extensions sont de plus en plus larges. Comme souligné en conclusion, les applications à l'usage des personnes privées de vision nécessiteront une collaboration avec elles mais aussi leurs accompagnants, pour une confrontation à la réalité du handicap.

A Grenoble, le 22 novembre 2023





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**Rapport sur le mémoire de Thèse de Doctorat de Camille Bordeau :**  
**« Développement d'un dispositif de substitution sensorielle vision-vers-audition : étude des performances de localisation et comparaison de schémas d'encodage »**

The doctoral work of Camille Bordeau focused on visual-to-auditory sensory substitution devices (SSDs). Such devices map image features to sound, often in the perspective of assistive devices for blind people. The idea has been actively explored for at least half a century, but to date SSDs have not yet seen a significant uptake. They are also at the core of an intriguing fundamental debate about the phenomenal experience that emerges after prolonged use of an SSD. In her thesis, Camille Bordeau presents three new experimental studies, comparing different visual-to-auditory encoding schemes and testing whether such schemes are robust to the presence of more than one visual object.

The thesis opens with a general introduction, which first addresses the central and intriguing issue of the nature of perception with an SSD: do SSD users “experience” vision when images are mapped to sound, or are the benefits due to a deliberate translation of auditory cues to an amodal spatial representation? Then, a brief review of auditory dimensions is provided, followed by a systematic description of the image-to-sound mappings used in past and current SSDs. The introduction is well-written and the systematic review of SSDs is useful and relevant to the rest of the work. All of the issues tackled in the subsequent parts of the work are described, making for a clear motivation of the experimental project.

The experimental part of the thesis takes the form of three different manuscripts. In the first study, the question was about optimizing the spatial localization performance of a single acoustic source in a virtual reality setting. Blindfolded participants had to point to a visual target, which they could not see but which was sonified. Auditory cues were provided to allow localization in terms of azimuth and elevation. The cues always included the interaural and monaural cues derived from head-related transfer functions, which were not individualized as is often the case for SSDs. Such cues were complemented with “pitch” cues in some conditions, using the established association between frequency and spatial elevation: high frequencies tend to be associated to high spatial locations. Such a mapping is already implemented in several SSDs, but a systematic investigation of its benefits was still lacking. Also, the study aimed to evaluate the benefit of a short familiarization phase where the image-to-sound mapping was demonstrated to participants. Overall, results showed that the addition of frequency cues was beneficial to localization performance. Moreover, familiarization helped, but some benefit was also observed right from the start, suggesting an intuitive use of the frequency cue mapping. In terms of methodological contributions, a complete SSD setup was implemented in a virtual reality setting, so the study provided the groundwork needed for future extensions.

In the second study, the ability to estimate distance through sonification cues was explored. Conveying the distance of obstacles is an obviously important goal of SSDs if they are to be used by blind people. However, previous studies have shown different biases in distance estimation through sound, including offsets and compressive biases. The present study tested whether the default intensity cue to distance could be complemented by an amplitude envelope-modulation cue. The practical advantage of such a mapping is that it could be implemented in a real-time sonification scheme without compromising other cues, such as the frequency cues tested in the first study. Overall, the results suggested a benefit of adding the envelope



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cue to the intensity cue. In terms of methodology, participants reported subjective distance by pointing to the floor, with free head movements, which represents a clever way to adapt such experiments to future increasingly complex environments.

In the last study, distractors were added to the visual scene in addition to the target to be localized. The whole scene was then sonified with one of the mapping schemes tested in the first study. Five different positions differing in azimuth or elevation were tested for targets, which had to be localized in isolation or alongside two or four distractor objects. Results showed surprisingly little effect of the distractors on localization error. This was interpreted as a robustness of the localization processes using an SSD. As acknowledged, it now remains to be tested whether participants segregated the target from the background to maintain their localization performance, or instead used more holistic cues specific to the experimental design. Again, the study presents a methodological advance, progressing toward the ultimate aim to translate laboratory setups to fully realistic natural or virtual-reality scenes.

Overall, the thesis brings encouraging and useful data for future SSDs and, importantly, establishes new experimental paradigms that should be well-suited to blind participants in follow-up studies. The amount of novel data is significant: in all experiments, sighted but blindfolded participants (about 80 in total) used a virtual-reality setup to perform spatial localization tasks. The logical progression between experiments is clear and the questions addressed have both practical and fundamental interest. The experiments required the design and implementation of novel methodological tools, embedding the generation of stimuli and the efficient collection of localization and distance judgments into virtual reality setups. The publication output of the work is satisfactory. One of the studies (the first one) is already published in an international peer-reviewed journal (*Frontiers in Psychology*). The other two are presented as manuscripts that are close to submission quality. It is also important to note that the thesis was part of a broader research project, which includes more technical and translational questions. As a result, Camille Bordeau has been involved in technical collaborations, which resulted in peer-reviewed conference proceedings and an open dataset submitted for publication. This effort to make the output of her work readily available to both the research and development communities involved in SSDs should be commended. More generally, Camille Bordeau has demonstrated her ability to bridge the gap between fundamental questions and practical applications, making her an important contributor to the ambitious project she has been a part of.

Based on this evaluation, I thus recommend that the thesis should be defended.

Le 20/11/2023

Daniel Pressnitzer  
Directeur de recherche, CNRS  
Professeur attaché à l'École normale supérieure





**PROCES VERBAL DE SOUTENANCE du 18 décembre 2023 à 12h30**

**Année universitaire 2022-2023**

Doctorante : Madame Camille BORDEAU  
 Née le 11 décembre 1994  
 Diplôme : Doctorat de Psychologie  
 Titre des travaux : Développement d'un dispositif de substitution sensorielle vision-vers-audition : étude des performances de localisation et comparaison de schémas d'encodage  
 Ecole doctorale : Environnements Santé  
 Unité de recherche : UMR 5022 - Laboratoire d'Etude de l'apprentissage et du développement  
 Directeur de thèse : Emmanuel BIGAND  
 Codirecteur de thèse : Maxime AMBARD ☐ HDR ☒ NON HDR  
 Lieu de soutenance : Amphithéâtre - Université de Bourgogne - Maison des sciences de l'Homme - 6 Esplanade Erasme - 21000 Dijon  
 Soutenance : ☒ Publique ☐ A huis clos  
 Résultat : ☒ Admission ☐ Ajournement  
 Confidentialité : ☐ Oui ☒ Non  
 Corrections mineures demandées par le jury<sup>1</sup> : ☐ Oui ☒ Non  
 Corrections majeures demandées par le jury<sup>1</sup> : ☐ Oui ☒ Non  
 La doctorante a prêté serment à l'issue de la soutenance : ☒ Oui ☐ Non

**Membres du jury<sup>2</sup>:**

Nom	Qualité	Etablissement	Rôle	Signature
Mme Malika AUVRAY	Directrice de recherche	Sorbonne Université - Institut des Systèmes Intelligents et de Robotique	Examineur	
M. Cyrille MIGNIOT	Maître de conférences	Université de Bourgogne Franche-Comté (Dijon) - Laboratoire ImVIA	Examineur	
M. Daniel PRESSNITZER	Directrice de recherche	ENS - Laboratoire des Systèmes Perceptifs	Rapporteur	
M. Christian GRAFF	Maître de conférences	Université Grenoble Alpes - Laboratoire de Psychologie et Neurocognition - CNRS UMR 5105	Rapporteur	

Nom et Signature du président du jury : DANIEL PRESSNITZER

1. L'intéressé(e) dispose d'un délai de trois mois à compter de cette date pour déposer la version électronique corrigée de son manuscrit sur ADUM. Ce délai expiré, la thèse sera transmise à la Bibliothèque Universitaire, EN L'ÉTAT, et ne sera pas reproduite, ni diffusée, mais uniquement archivée.  
 2. Conformément à l'arrêté du 25 mai 2016, le directeur de thèse (et les codirecteurs le cas échéant) n'est pas autorisé à signer le PV de soutenance.



## RAPPORT DE SOUTENANCE DE DOCTORAT DE Psychologie







Nom et prénom du candidat : Camille BORDEAU

Date et lieu de naissance : 11 décembre 1994 à ALBI - Tarn France

Lieu, Date et heure de soutenance : Amphithéâtre - Université de Bourgogne - Maison des sciences de l'Homme - 6 Esplanade Erasme - 21000 Dijon , le 18 décembre 2023 à 12h30

*voir pièce jointe*Fait à *Dijon* le *18/12/2023*  
Nom, prénom et signature du président du jury

## Membres du jury :

Nom, prénom	Signature	Nom	Signature
Emmanuel BIGAND		Maxime AMBARD	
Malika AUVRAY		Cyrille MIGNIOT	
Daniel PRESSNITZER		Christian GRAFF	



**DELEGATION DE SIGNATURE - MEMBRE DU JURY EN VISIOCONFERENCE**

NOM et Prénom du candidat : Camille Bordeaux

Date de soutenance : 18 / 12 / 2023      Heure de soutenance : 12h30

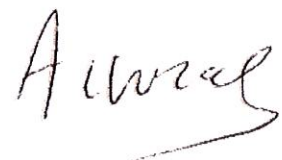
Lieu de soutenance : Dijon

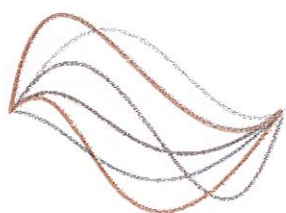
Je soussigné(e), AUVRAY Malika (*NOM et Prénom du membre du jury en visioconférence*), déclare avoir pris connaissance des conditions de soutenance en visioconférence et donne délégation de signature au président du jury pour signer en mon nom les documents suivants afférents à la soutenance, à savoir :

- le procès-verbal de soutenance ;
- le rapport de soutenance.

Fait à Paris, le 09 /12/2023

Signature



**UBFC**UNIVERSITÉ  
BOURGOGNE FRANCHE-COMTÉ**DELEGATION DE SIGNATURE - MEMBRE DU JURY EN VISIOCONFERENCE****HDR / DOCTORAT**

Article 19 de l'arrêté du 25 mai 2016 fixant le cadre national de la formation et les modalités conduisant à la délivrance du diplôme national de doctorat :

*« A titre exceptionnel, le président ou le directeur de l'établissement, après avis du directeur de l'école doctorale, sur proposition du directeur de thèse, peut autoriser le doctorant et les membres du jury, en totalité ou partiellement, à participer à la soutenance de thèse par tout moyen de télécommunication permettant leur identification et garantissant leur participation effective continue et simultanée aux débats ainsi que la confidentialité des délibérations du jury.*

NOM et Prénom du candidat : Camille BORDEAU

Date de soutenance : 18 décembre 2023 Heure de soutenance : 12h30

Lieu de soutenance : Amphithéâtre - Université de Bourgogne - Maison des sciences de l'Homme - 6 Esplanade Erasme - 21000 Dijon

Je soussigné, Christian GRAFF, déclare avoir pris connaissance des conditions de soutenance en visioconférence et donne délégation de signature au président du jury pour signer en mon nom les documents suivants afférents à la soutenance, à savoir :

- le procès-verbal de soutenance ;
- le rapport de soutenance.

Fait à ..... Grenoble campus ..... , le ...24... / ...11... / 2023...



Signature



**Christian Graff**, rapporteur, entame la discussion en soulignant la grande qualité de la présentation orale, en continuité avec celle du document écrit, et les illustrations très claires à l'appui. Il souligne l'intérêt de l'exposé des paramètres sonores dans le chapitre d'introduction qu'il pourra employer pour de nouveaux chercheurs en substitution vision-vers audition.

Il pose d'entrée la question des applications envisagées des découvertes, puisque les utilisations effectives de la substitution sensorielles sont restées jusqu'ici limitées à des tâches pratiques très circonscrites ; en particulier concernant le pointage d'une position 3-D, est-on dans une logique de cible ou d'obstacle, ces deux notions pourtant antinomiques étant plus ou moins confondues dans les présentations. Camille Bordeau reconnaît volontiers la nécessité de définir des tâches précises d'assistance à la non-voyance, plutôt qu'un remplacement de la modalité sensorielle. Pour un point unique, il lui semble que les tests de pointage employés dans ses études préparent plutôt à l'atteinte de cible.

Christian Graff souligne ensuite que chacune des études consiste à mettre en correspondance la position 3-D d'une source virtuelle sonore avec une position 3-D pointée virtuellement ; les travaux sont en ceci détachés de la réalité matérielle. Les résultats attestent avec méthode d'une très forte corrélation entre les coordonnées de ces deux points, et dans tous les cas d'un biais tout aussi significatif, dans chacune des trois dimensions. Mais la discussion ne propose aucune explication à ces biais, ni de moyen de les corriger. Camille propose pour le biais en azimut un problème lié à la confusion avant arrière de l'HRTF, mais ne sait pas expliquer pourquoi ce biais se ferait vers la gauche. Pour l'élévation, elle invoque une confusion du référentiel puisque la caméra se trouve sur le sommet de la tête, alors que les oreilles et le pointeur chacun à une hauteur différente plus bas ; de plus, lors de certains essais, la direction de la caméra variait, ce qui changeait la position en hauteur de la source sonore dans le « paysage sonore » ; pour la profondeur, le biais serait de même origine. Christian Graff reprend la thématique en proposant un effet du mode de pointage ; il regrette que l'objet matériel ne soit pas visible. Il mentionne que l'une des tâches principales en ergonomie appliquée aux non-voyants est d'apprendre la tenue de la canne blanche en référence au plan sagittal. Camille Bordeau reconnaît que le mode de pointage est un problème en soi.

Il approfondit ensuite le problème de la « compression des distances », en tentant de préciser les retombées applicatives. Après un échange sur les résultats montrant cet effet, ils conviennent que la surestimation des courtes distances résulterait plutôt en un évitement exagéré des obstacles qu'en un risque accru de collision. De semblables distorsions existent par ailleurs hors de la substitution sensorielle, par exemple une hyper-sensibilité pour l'altitude selon qu'on est en haut et non en bas d'une falaise.

Dans l'ensemble, Camille Bordeau comprend bien et répond directement aux questions posées dans la mesure de ses connaissances, et ne se hasarde pas vers des implications applicatives et des enjeux théoriques des résultats obtenus au-delà de sa parfaite maîtrise du paradigme expérimental décliné dans son travail de doctorat.

**Daniel Pressnitzer**, second rapporteur de la thèse, commence par rappeler brièvement les grandes lignes de son évaluation du mémoire. Il souligne l'intérêt du travail, à l'interface entre recherche fondamentale et appliquée. Il note aussi une grande logique dans la progression et l'enchaînement des études. Tout ceci reflète une activité intense, avec le développement d'un environnement expérimental en lien avec la réalité virtuelle permettant des innovations méthodologiques, un recueil de données conséquent, et la valorisation du travail par des publications et des actions grand

public. Par nature, le projet a dû se confronter aux inévitables compromis entre rigueur d'une approche fondamentale et besoin de généralisation pour une application pratique. La plupart des questions portent donc sur ce type de compromis. Une première série de questions porte sur la première étude expérimentale, et notamment sur des détails techniques comme la composition spectrale des sons choisis, ou le format et la durée de la phase de familiarisation. Camille Bordeau répond à ces questions de façon précise, démontrant sa maîtrise parfaite des caractéristiques et limites éventuelles du protocole développé. Ensuite, des questions portant sur l'interprétation des données de la deuxième étude expérimentale sont abordées, notamment concernant les effets de plafond et les stratégies utilisées par les participants. Là encore, Camille Bordeau démontre une parfaite connaissance de l'utilisation d'analyses statistiques dans un contexte expérimental. Enfin, une critique possible du dessin expérimental de la dernière étude est abordée : est-ce que la position d'objets dits « distracteurs » ne pourrait pas apporter de l'information sur l'objet dit « cible » ? Camille Bordeau s'engage dans la discussion de façon réfléchie, démontrant un recul et une maturité très appréciable. Daniel Pressnitzer conclut en félicitant la candidate tant pour son travail que pour les qualités pédagogiques de sa présentation. Son goût évident pour les collaborations et le caractère interdisciplinaire de ses travaux sont prometteurs pour la suite de sa carrière.

**Malika Auvray**, examinatrice de la thèse, prend ensuite la parole. Elle se joint aux autres membres du jury pour souligner la qualité générale du manuscrit, très clair, bien écrit et illustré ainsi que les qualités pédagogiques de la présentation, qui rend manifeste l'important travail conceptuel, méthodologique et technique qui a été effectué et les implications nombreuses du travail expérimental mené.

La première question porte sur l'utilisation de la correspondance intermodale entre fréquence auditive et élévation visuelle pour le dispositif testé. En particulier les résultats contrastés sur leur existence dans la population non-voyante obtenus par Deroy et al. (2016) et Hamilton-Fletcher et al. (2016) pourraient s'expliquer par le fait que la correspondance intermodale est sensorielle dans la première étude et métaphorique dans la seconde. Ainsi, il devient plus questionnable d'utiliser cette correspondance sensorielle si elle n'est pas présente dans la population cible du dispositif de conversion vision-vers-audition. Malika Auvray demande aussi des précisions sur la possibilité d'utiliser des correspondances intermodales alternatives et sur leur caractère relatif versus absolu qui pose question dans certaines études. Les réponses de la candidate ont fait preuve d'une importante maturité scientifique en abordant les diverses correspondances intermodales relatives à l'élévation visuelle à mettre en regard des codages possibles du dispositif et en interrogeant les conditions de possibilité d'un transfert d'une correspondance intermodale métaphorique à une correspondance intermodale sensorielle. Un second ensemble de questions s'attarde sur certains choix méthodologiques des expériences menées, en particulier la durée de la phase de familiarisation avec le dispositif, en dessous de ce qui pourrait compter comme apprentissage, le nombre d'essais et le nombre de cibles. Les réponses de la candidate ont démontré sa maîtrise des protocoles expérimentaux et des outils statistiques, et plus globalement, des méthodologies propres à la psychologie cognitive. Une troisième question a porté sur les différences individuelles susceptibles d'émerger lors de l'utilisation de dispositifs de substitution sensorielle. La candidate a abordé les différentes possibilités, telles que l'âge et le genre, montrant sa maîtrise en profondeur de la littérature liée au sujet de thèse. Malika Auvray s'est déclarée satisfaite des réponses de la candidate et lui a réitéré ses félicitations pour le travail accompli.

**Cyrille Migniot**, encadrant de la seconde thèse réalisée sur le projet 3DSG sur le côté informatique-vision, a souligné lors de son intervention la façon dont la candidate a su profiter de cette structure à deux thèses pour enrichir sa réflexion par une ouverture sur un autre domaine et a fait l'effort de comprendre les contraintes et les aboutissants du travail en informatique pour proposer des solutions adéquates pour les deux thématiques. Il a également insisté sur ses qualités de transmission, que ce soit lors des passages des participants de ses expérimentations à travers ses présentations claires ainsi que ses protocoles rigoureux, mais aussi à travers plusieurs événements de vulgarisation scientifique.

Lors de la délibération, il a relevé la pertinence et le recul des réponses de la candidate face à des questions sur des aspects vision qui ne sont pas directement liés à sa spécialité, ce qui démontre une évidente polyvalence et une grande maturité scientifique.

**Emmanuel Bigand** prend ensuite la parole en précisant qu'il est ravi d'avoir contribué à la réalisation de ce travail de thèse durant lequel Maxime Ambard a entièrement mené la direction effective. Le travail a de très nombreuses qualités, et E. Bigand a été particulièrement impressionné par l'intelligence didactique du document. La candidate écrit avec le souci constant de rendre son texte facile à lire et à intégrer par le lecteur. C'est une qualité rare et très précieuse pour une future enseignante chercheuse. Dans le même ordre d'idée, E. Bigand a particulièrement apprécié la maturité scientifique de la candidate, qui se manifeste par son écoute des questions et la nature de ses réponses. Sa thématique de recherche est innovante mais soulève naturellement des interrogations (comment le sujet peut-il différencier les scènes sonores de l'environnement réel de celles venant du dispositif mis en place ?) mais la candidate ne se laisse jamais désarçonner par ces difficultés. Elle trouve sa confiance dans la volonté de comprendre en profondeur son domaine d'étude, ce qui témoigne d'une belle maturité scientifique, pas si fréquente à ce niveau académique. Il est donc convaincu qu'elle apportera une grande contribution à l'enseignement et à la recherche en France, et il la félicite pour tout cela.

**Maxime Ambard**, Maître de conférences en informatique au laboratoire LEAD, co-encadrant de la thèse de Camille Bordeau et responsable scientifique du projet 3DSG au sein duquel s'est déroulée cette thèse a finalement pris la parole. Il a tout d'abord résumé les grandes étapes des 3 ans de la thèse. La première année a consisté à acquérir l'état de l'art dans les domaines de la localisation de sources sonores et des systèmes de substitution sensorielle. Camille a ensuite rédigé le dossier pour le Comité d'Ethique de la Recherche, préalable indispensable à la conduite des futures expérimentations. Elle s'est ensuite familiarisée avec la plateforme Unity et les systèmes de réalité virtuelle. La passation d'une première expérience sur les performances de localisation d'obstacles en azimut et en élévation a ensuite été conduite lors de la seconde année et un article a été rédigé et rapidement publié dans un journal de rang Q1. Une seconde expérimentation sur l'estimation des distances sur la base d'indices acoustiques a ensuite été conçue. Enfin, lors de la troisième année, la seconde expérience a été finalisée et un article rédigé. Une troisième expérimentation a été conduite et un article rédigé. Ces 3 articles ont servi de socle pour la rédaction du manuscrit de thèse.

Maxime Ambard a ensuite décrit les difficultés particulières liées au sujet et au contexte dans lequel s'est déroulée cette thèse. L'analyse de scènes auditives était un domaine de recherche nouveau pour la candidate et les protocoles expérimentaux (réalité virtuelle - programmation Unity) nécessitaient une forte compétence technique. De plus, ces travaux étant intégrés dans un projet visant la constitution d'un système de substitution sensorielle opérationnel, il y avait de

fortes attentes des autres acteurs du projet pour des résultats expérimentaux directement exploitables. Il a alors mentionné le profil de compétences très riche de Camille, intégrant à la fois une solide connaissance en psychologie expérimentale, mais également des compétences en Mathématiques et en programmation informatique, un niveau d'anglais très satisfaisant et des fortes compétences en statistiques, discipline qu'elle a d'ailleurs particulièrement enseignée lors de sa thèse. Les difficultés rencontrées ont pu être surmontées grâce à sa pugnacité et une maturité remarquable qui lui a permis de prendre les bonnes décisions au bon moment quant au déroulement de ses travaux. Il a également souligné la forte capacité d'écoute et de dialogue lui ayant permis de s'intégrer sans difficultés au sein du projet inter-disciplinaire 3DSG.

Il a conclu en résumant les apports considérables de Camille Bordeau au projet 3DSG avec notamment la pose de jalons importants du projet 3DSG dans les recherches sur les systèmes de substitution sensorielle, la réation de protocoles expérimentaux originaux pour l'estimation des performances de localisation d'obstacles par systèmes de substitution sensorielle, la caractérisation précise des performances de localisation, et la constitution d'une solide base de données de travaux scientifiques sur l'apprentissage perceptif, la localisation de sources sonores, et les systèmes de substitution sensorielle.





## OPEN ACCESS

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## SPECIALTY SECTION

This article was submitted to  
Perception Science,  
a section of the journal  
Frontiers in Psychology

RECEIVED 25 October 2022

ACCEPTED 06 January 2023

PUBLISHED 26 January 2023

## CITATION

Bordeau C, Scalvini F, Migniot C, Dubois J and  
Ambard M (2023) Cross-modal  
correspondence enhances elevation  
localization in visual-to-auditory sensory  
substitution. *Front. Psychol.* 14:1079998.  
doi: 10.3389/fpsyg.2023.1079998

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# Cross-modal correspondence enhances elevation localization in visual-to-auditory sensory substitution

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**Introduction:** Visual-to-auditory sensory substitution devices are assistive devices for the blind that convert visual images into auditory images (or soundscapes) by mapping visual features with acoustic cues. To convey spatial information with sounds, several sensory substitution devices use a Virtual Acoustic Space (VAS) using Head Related Transfer Functions (HRTFs) to synthesize natural acoustic cues used for sound localization. However, the perception of the elevation is known to be inaccurate with generic spatialization since it is based on notches in the audio spectrum that are specific to each individual. Another method used to convey elevation information is based on the audiovisual cross-modal correspondence between pitch and visual elevation. The main drawback of this second method is caused by the limitation of the ability to perceive elevation through HRTFs due to the spectral narrowband of the sounds.

**Method:** In this study we compared the early ability to localize objects with a visual-to-auditory sensory substitution device where elevation is either conveyed using a spatialization-based only method (Noise encoding) or using pitch-based methods with different spectral complexities (Monotonic and Harmonic encodings). Thirty eight blindfolded participants had to localize a virtual target using soundscapes before and after having been familiarized with the visual-to-auditory encodings.

**Results:** Participants were more accurate to localize elevation with pitch-based encodings than with the spatialization-based only method. Only slight differences in azimuth localization performance were found between the encodings.

**Discussion:** This study suggests the intuitiveness of a pitch-based encoding with a facilitation effect of the cross-modal correspondence when a non-individualized sound spatialization is used.

## KEYWORDS

Virtual Acoustic Space, spatial hearing, sound spatialization, image-to-sound conversion, cross-modal correspondence, assistive technology, visual impairment, sound source localization

## 1. Introduction

Visual-to-auditory Sensory substitution devices (SSDs) are assistive tools for blind people. They convert visual information into auditory information in order to convey spatial information about the surrounding environment when vision is impaired. The visual-to-auditory conversion relies on the mapping of selected visual features with specific auditory cues. Visual information is usually acquired using a camera capturing the visual scene in front of the person. Then the scene converted into auditory information is transmitted to the user through soundscapes (or auditory images) delivered with headphones.

Various visual-to-auditory encodings are used by the existing visual-to-auditory SSDs to convey spatial information. Some of them use encoding schemes based on a Virtual Acoustic Space (VAS). A VAS consists in the simulation of a binaural acoustic signature of a virtual sound source located in a 3D space. In the context of visual-to-auditory SSDs, this is mainly used to simulate sound sources at the location of the obstacles. This simulation is achieved by spatializing the sound through the incorporation of spatial auditory cues in the original monophonic sound. Then a synthesized stereophonic signal simulating the distortions occurring while receiving the audio signal by the two ears is obtained. Among the SSDs used in localization experiments, the Synaesthetre (Hamilton-Fletcher et al., 2016a; Richardson et al., 2019), the Vibe (Hanneton et al., 2010) and the one presented by Mhaish et al. (2016) spatialize azimuth (lateral position) and elevation (vertical position). Other SSDs only spatialize the azimuth: the See differently device (Rouat et al., 2014), the one studied in Ambard et al. (2015), and the recent one presented in Scalvini et al. (2022).

The generation of a VAS is based on the reproduction of binaural acoustic cues related to the relative sound source location such as timing, intensity and spectral features (for an in-depth explanation of the auditory localization mechanisms see Blauert, 1996). Those features arise from audio signal distortions mainly caused by the reflection and absorption of the head, pinna and torso and are partly reproducible using Head-Related Transfer Functions (HRTFs). HRTFs are transfer functions characterizing these signal distortions as a function of the position of the sound source relatively to the two ears. They are usually obtained by conducting multiple binaural recordings with a sound source carefully placed in various positions while repeatedly producing the same sound.

Due to the technical difficulty in acquiring these recordings in good conditions, non-individualized HRTFs acquired in controlled conditions with another listener or a manikin are frequently used. However, these HRTFs failed to simulate the variability of individual-specific spectrum distortions that are related to individual morphologies (head, torso and pinna). Consequently, the localization of simulated sound sources using non-individualized HRTFs is often inaccurate with front-back and up-down confusions that are less resolvable (Wenzel et al., 1993), and a less perceptible externalization (Best et al., 2020). Nonetheless, due to the robustness of the binaural cues, azimuth localization accuracy is well preserved compared to the perception of elevation since azimuth perception relies less on the individual-specific spectrum distortions (Makous and Middlebrooks, 1990; Wenzel et al., 1993; Middlebrooks, 1999). Therefore, visual-to-auditory encodings only based on the creation of a VAS have the advantage to rely on acoustic cues that mimic natural acoustic features for sound source localization, nevertheless in practice the elevation perception can be impaired.

To compensate for this difficulty some visual-to-auditory SSDs use additional acoustic cues to convey spatial information. For instance, pitch modulation is often used to convey elevation location (Meijer, 1992; Abboud et al., 2014; Ambard et al., 2015). This mapping between elevation location and auditory pitch is based on the audiovisual cross-modal correspondence between pitch and elevation (see Spence, 2011 for a review on audiovisual cross-modal correspondences). Humans show a tendency to associate high pitch with high spatial locations and low pitch with low spatial locations.

For example, they tend to exhibit faster response times in an audio-visual Go/No-Go task when the visual and auditory stimuli are congruent, i.e., higher pitch with higher visual location, and lower pitch with lower visual location (Miller, 1991). They also tend to discriminate more accurately and quickly the location of a visual stimulus (high vs. low location) when the pitch of a presented sound is congruent with the visual elevation (Evans and Treisman, 2011). Also, humans tend to respond to high pitch sounds with a high-located response button instead of a lower-located response button (Rusconi et al., 2006). The pitch-based encoding used in the vOICE SSD (Meijer, 1992) has been suggested somewhat intuitive in a recognition task (Stiles and Shimojo, 2015). Nevertheless, the main drawback of a pitch-based encoding is caused by the limitation of the abilities to perceive elevation through HRTFs due to the audio spectral narrowband (Algazi et al., 2001b). Although some acoustic cues for elevation perception are present in low frequencies below 3,500 Hz (Gardner, 1973; Asano et al., 1990), localization abilities are higher when the spectral content contains high frequencies above 4,000 Hz (Hebrank and Wright, 1974; Middlebrooks and Green, 1990). Since the ability to perceive the elevation through HRTFs is higher with broadband sounds containing high frequencies, the spectral content of the sound used in the visual-to-auditory encoding might modulate the perception of elevation through HRTFs. No study has directly compared encodings only based on HRTFs with encodings adding a pitch modulation and it remains unclear if the simulation of natural acoustic cues is less efficient for object localization than a more artificial sonification method using the cross-modal correspondence between pitch and elevation.

Many studies investigating static object localization abilities have already been conducted with blindfolded sighted persons using visual-to-auditory SSDs. Various types of tasks have already been used, for example discrimination tasks with forced choice (Proulx et al., 2008; Levy-Tzedek et al., 2012; Ambard et al., 2015; Mhaish et al., 2016; Richardson et al., 2019), grasping tasks (Proulx et al., 2008), index or tool pointing tasks (Auvray et al., 2007; Hanneton et al., 2010; Brown et al., 2011; Pourghaemi et al., 2018; Commère et al., 2020), or head-pointing tasks (Scalvini et al., 2022). Those studies showed the high potential of SSDs to localize an object and interact with it. However, long trainings were often conducted before the localization tasks to learn the visual-to-auditory encoding schemes: from 5 min in Pourghaemi et al. (2018) to 3 h in Auvray et al. (2007). On the contrary, in the study of Scalvini et al. (2022) the experimenter only explained verbally the encoding schemes to the participants.

Virtual environments are more and more used to investigate the abilities to perceive the environment with a visual-to-auditory SSD (Maidenbaum et al., 2014; Kristjánsson et al., 2016) since they allow a complete control of the experimental environment (e.g., number of objects, object locations...) (Maidenbaum and Amedi, 2019) and a more accurate assessment of localization abilities with precise pointing methods. They have been used in standardization tests to compare the abilities to interpret information provided by SSDs in navigation or localization tasks (Caraiman et al., 2017; Richardson et al., 2019; Jicol et al., 2020; Real and Araujo, 2021).

The current study aimed at investigating the intuitiveness of different types of visual-to-auditory encodings for the elevation in the context of object localization with a SSD. Therefore, we conducted a localization task in a virtual environment with blindfolded

participants testing a spatialization-based encoding and a pitch-based encoding. This study also aimed at assessing whether a higher spectral complexity of the sound used in a pitch-based encoding could improve the localization performance. Therefore, 2 types of pitch-based encodings were investigated: one monotonic and one harmonic with 3 octaves. We measured the localization performance for the azimuth and for the elevation. For each of these measures, we studied the effect of the visual-to-auditory encoding before and after an audio-motor familiarization of short duration.

Since the audio spatialization method was not based on individualized HRTFs, and since the pitch-based encodings were not explained to the participants, localization performance for the elevation was expected to be impaired. However, a facilitation effect of the pitch-based encodings for the elevation localization accuracy was hypothesized. Among the two pitch-based encodings, a higher elevation localization accuracy was predicted with the harmonic encoding since the sound has a higher spectral complexity. Also, the intuitiveness of the azimuth perception for all the encodings was hypothesized since it is based on less individual-specific acoustic spatial cues than elevation perception.

## 2. Method

### 2.1. Participants

Thirty eight participants were divided into two groups: the Monotonic group (19, age:  $M = 25.5$ ,  $SD = 3.04$ , 6 female, 19 right-handed) and the Harmonic group (19, age:  $M = 24.4$ ,  $SD = 3.27$ , 10 female, 18 right-handed). No participant reported impairments of hearing or any history of psychiatric illness or neurological disorder. The experimental protocol was approved by the local ethical committee Comité d'Éthique pour la Recherche de Université Bourgogne Franche-Comté (CERUBFC-2021-12-21-050) and followed the ethical guidelines of the Declaration of Helsinki. Written informed consent was obtained from all the participants before the experiment. No monetary compensation was given to the participants.

### 2.2. Visual-to-auditory conversion in the virtual environment

The visual-to-auditory SSD used took place in a virtual environment created in UNITY3D and including the target to localize, a virtual camera, and a tracked pointing tool. Four HTC VIVE base stations were used to track the participants' head and the pointing tool on which HTC VIVE Trackers 2.0 were attached. Participants did not carry a headset and therefore could not explore visually the virtual environment. The pointing task can be separated in several steps that are explained in detail below: the virtual target placement, the video acquisition from a virtual camera, the video processing, the visual-to-auditory conversion and the participants' response collection using the pointing tool.

#### 2.2.1. Virtual target

The virtual target that participants had to localize was a 3D propeller shape of 25 cm in diameter composed of 4 bars with a length

of 25 cm and a rectangular section of  $5 \times 5$  cm that was self-rotating at a speed of  $10^\circ$  per video frame (see [Figure 1A](#)). The use of an angular shaped target that is self-rotating generated a modification of successive video frames without changing the center position of the target. The orientation of the target was managed in order to continuously face the virtual camera while being displayed. Since participants could not see the virtual target, it was only perceivable through the soundscapes.

#### 2.2.2. Video acquisition

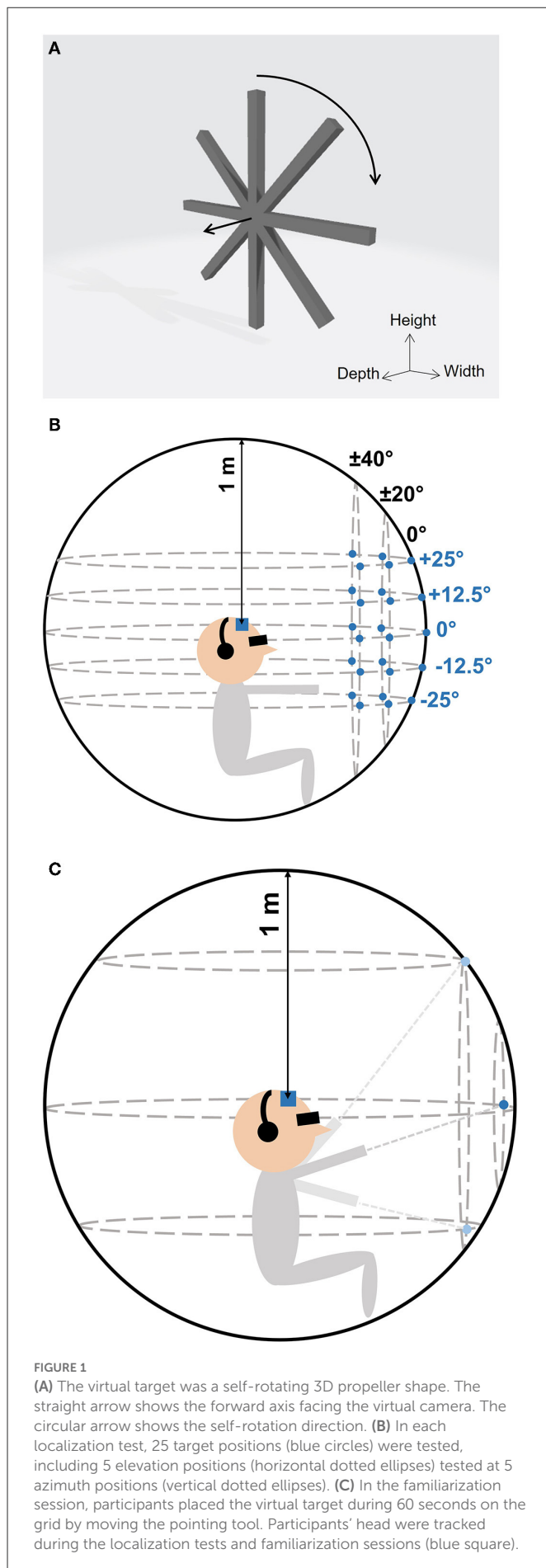
The virtual camera position was set at the beginning of each trial using the position of the head tracker attached on the participants' forehead. Images were acquired with a virtual camera with a field of view of  $90 \times 74^\circ$  (Horizontal  $\times$  Vertical) and a frame rate of 60 Hz. The resulting image was using a grayscale encoding (0–255 gray levels) of a depth map ( $0.2 \text{ m} = 0$ ,  $5.0 \text{ m} = 255$ ) of the virtual scene although in this experiment we did not manipulate the depth parameter.

#### 2.2.3. Video processing

Video processing principles are similar to those used by [Ambard et al. \(2015\)](#), aiming to convey only new visual information from one frame to another. Video frames are grayscale images with gray levels ranging from 0 to 255. Pixels of the current frame are only conserved if the gray level pixel-by-pixel absolute difference with the previous frame (frame differencing) is larger than a threshold of 10. The processed image is then rescaled to a  $160 \times 120$  (Horizontal  $\times$  Vertical) grayscale image where 0-gray-level pixels are called “inactive” (i.e., no new visual information contained) and the others are “active” graphical pixels (i.e., containing new visual information). Active graphical pixels are then converted into spatialized sounds following a visual-to-auditory encoding in order to generate a soundscape ([Figure 2](#)), as explained in the following section.

#### 2.2.4. Visual-to-auditory conversion

The visual-to-auditory conversion consists in the transformation of the processed video stream into a synchronized audio stream that acoustically encodes the extracted graphical features. Each graphical pixel is associated with an “auditory pixel” which is a stereophonic sound with auditory cues specific to the position of the graphical pixel it is associated with. The conversion from a graphical pixel to an auditory pixel follows an encoding that is explained step-by-step in the following sections. Each graphical pixel of a video frame is first associated with a corresponding monophonic audio pixel (detailed in Section 2.2.4.1). The spatialization of the sound using HRTFs is then used to generate a stereophonic audio pixel that simulates a sound source with azimuth and elevation corresponding to the position of the graphical pixel in the virtual camera's field of view (detailed in Section 2.2.4.2). All the stereophonic pixels of a video frame are then compiled to obtain an audio frame (detailed in Section 2.2.4.3). Successive audio frames are then mixed together to generate a continuous audio stream (i.e., the soundscape). Two examples of stereophonic auditory pixels are provided in [Figure 2](#) for each of the three encodings, as well as two examples of soundscapes depending on the location of an object in the field of view of the virtual camera.



#### 2.2.4.1. Monophonic pixel synthesizing

Three visual-to-auditory encodings were tested in this study: the Noise encoding and 2 Pitch encodings (the Monotonic encoding and the Harmonic encoding). These methods varied in the elevation encoding scheme and in the spectral complexity of the monophonic auditory pixels but all three methods used afterwards the same method for the sound spatialization.

For the Noise encoding, the simulated sound source (i.e., monophonic auditory pixel) in the VAS was a white noise signal generated by inverting a Fourier representation of the auditory pixel with a flat spectrum and random phases.

For the Monotonic encoding, each monophonic auditory pixel was a sinusoidal waveform audio signal (i.e., a pure tone) with a random phase and a frequency related to the elevation of the corresponding graphical pixel in the processed image. For this purpose, we used a linear Mel scale ranging from 344 mel (bottom) to 1,286 mel (top) corresponding to frequencies from 250 to 1,492 Hz.

For the Harmonic encoding, we used the same monophonic auditory pixels as in the Monotonic encoding but instead of a pure tone, we added to it two other frequencies at the 2 following octaves with the same intensity and random phases.

Since the loudness depends on the frequency components of the audio signal, we minimized the differences in loudness between auditory pixels using the *pyloudnorm* Python-package (Steinmetz and Reiss, 2021). Auditory pixel spectrums were then adjusted to compensate for the frequency response of the headphones we used in this experiment (SONY MDR-7506).

#### 2.2.4.2. Auditory pixel spatialization

The azimuth and elevation associated with each pixel were computed based on the coordinates of the corresponding graphical pixel in the camera's field of view. Monophonic auditory pixels were then spatialized by convolving them with the corresponding KEMAR HRTFs from the CIPIC database (Algazi et al., 2001a). This database provides HRTFs recordings with a sound source located in various azimuths and elevations ranging in steps of 5 and 5.625°, respectively. For each pixel, the applied HRTFs were estimated from the database by computing a 4 points time-domain interpolation in which the Interaural Level Difference (ILD) and the convolution signals were separately interpolated using bilinear interpolations before being reassembled as in Sodnik et al. (2005) but using a 2D interpolation instead of a 1D interpolation.

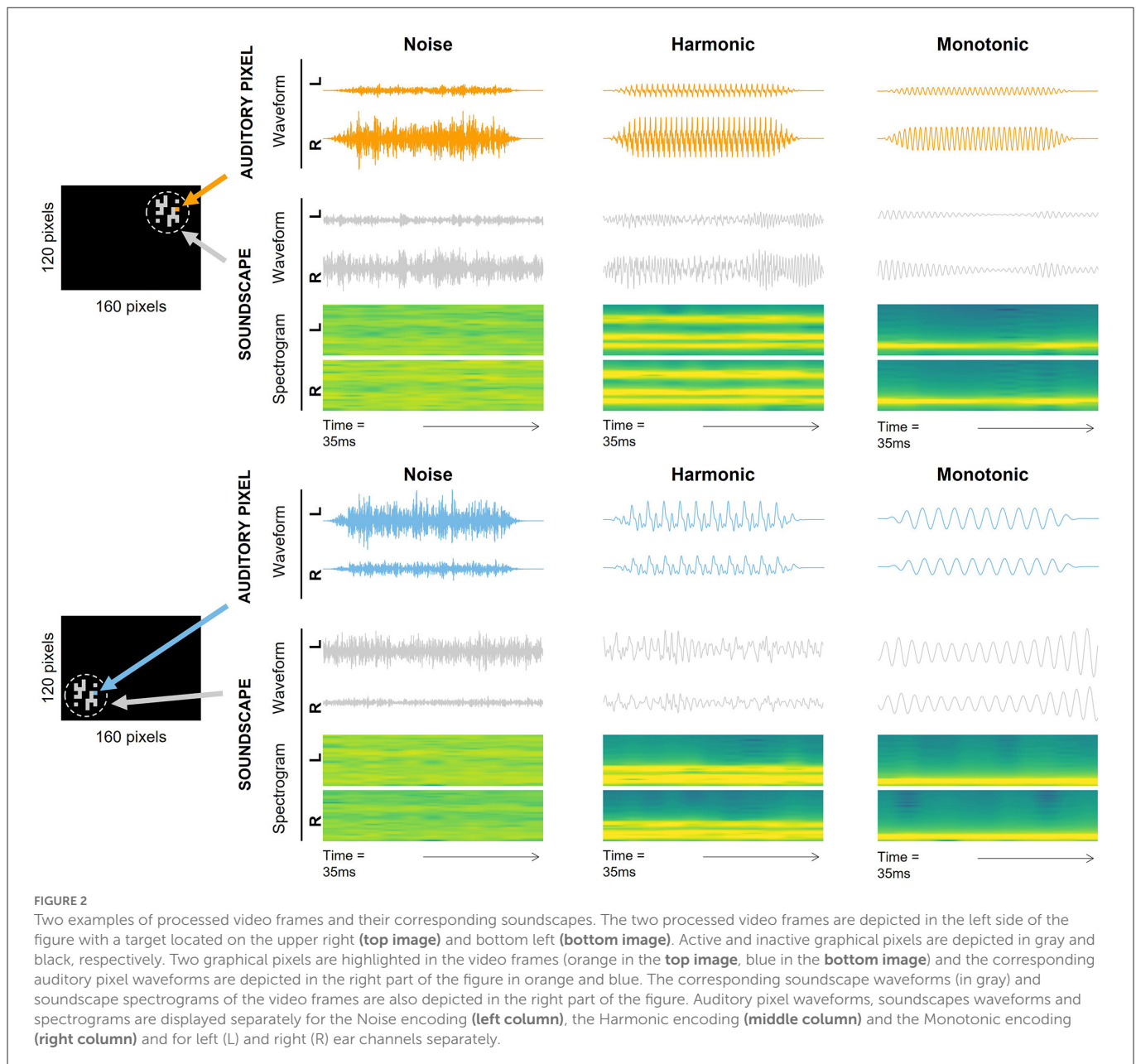
#### 2.2.4.3. Audio frame mixing

Each auditory pixel lasted 34.83 ms including a 5 ms cosine fade-in and a 5 ms cosine fade-out. All the auditory pixels corresponding to the active graphical pixels of the processed current video frame were compiled to form an audio frame. After their compilation, these fade-in and fade-out were still present at the beginning and at the end of the audio frame and they were used to overlap successive audio frames while limiting the artifacts of the auditory transition.

#### 2.2.5. Pointing tool and response collection

The pointing tool was a tracked gun pistol. Participants were instructed to indicate the perceived target position by pointing to it with the gun, with stretched arm. Participants logged their response by pressing a button with their index finger. They were instructed to hold the pointing tool with their dominant hand. The response position was defined as the intersection point of a virtual





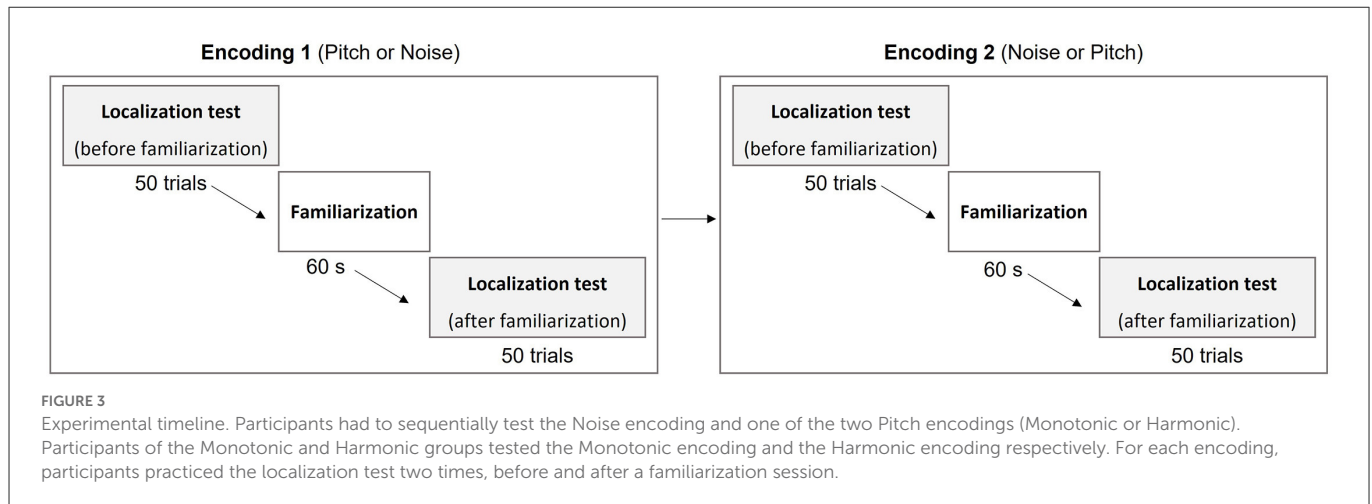
ray originating at the tip of the pointing tool and a virtual 1-m radius sphere with the origin at the location of the virtual camera. The response positions were declined in the elevation response and the azimuth response. The elevation and azimuth signed errors were also computed as the difference between the target position and the response position (in elevation and azimuth separately). A negative elevation signed error indicated a downward shift, and a negative azimuth signed error indicated a shift to the left in the response position. Unsigned errors were computed as the absolute value of the signed errors of each trial.

## 2.3. Experimental procedure

The experiment consisted in a 45-min session during which participants were seated comfortably in a chair at the center of a room surrounded by the virtual reality tracking system. The

participants were equipped with SONY MDR-7506 headphones used to deliver soundscapes. Figure 3 illustrates the timeline of the experimental session. Each participant had to test two visual-to-auditory encodings: the Noise encoding, and a Pitch encoding (Monotonic or Harmonic encoding depending on the group they belonged). Participants from the Monotonic group had to test the Noise encoding and the Monotonic encoding, and participants from the Harmonic group had to test the Noise encoding and the Harmonic encoding. The order of the two tested encodings was counterbalanced between participants so half participants of each group started with the Noise encoding and the other half started with the Pitch encoding.

For each encoding, the participants practiced 2 times the localization test: one without any familiarization or explanation of the encoding and one after a familiarization session. At the beginning of the experiment, participants were instructed to localize a virtual target by pointing to it while being blindfolded. The experimenter



explained that they will not be able to see the virtual target, but that they will only hear it and that the sound will depend on the position of the target. No indication was given about the way visual-to-auditory encodings worked. Participants were seated and blindfolded using an opaque blindfold fixed with a rubber band and could remove it during breaks. Participants were instructed to keep their head as still as possible during the localization tests. For control purposes, participants' head position was recorded with the tracker every 200 ms to check that they kept their head still. We measured the maximum distance of the head from its mean position for each trial and we found an average maximum distance of approximately 1.5 cm showing that the instructions were rigorously followed.

### 2.3.1. Localization test

The localization test consisted in 50 trials during which blindfolded participants had to localize the virtual target using soundscapes provided by the visual-to-auditory SSD. During each localization test, the target was located at 25 different positions distributed on a grid of 5 azimuths ( $-40^\circ$ ,  $-20^\circ$ ,  $0^\circ$ ,  $+20^\circ$ , and  $+40^\circ$ ) and 5 elevations ( $-25^\circ$ ,  $-12.5^\circ$ ,  $0^\circ$ ,  $+12.5^\circ$ , and  $+25^\circ$ ). Figure 1B illustrates the grid with the 25 tested positions. As an example, the position  $[0^\circ, 0^\circ]$  corresponded to the central position, i.e., the virtual target was centered with the participant's head tracker. For the position  $[-40^\circ, +12.5^\circ]$ , the target was  $40^\circ$  leftward and  $12.5^\circ$  upward from the central position  $[0^\circ, 0^\circ]$ . The order of the tested positions was randomized and each position was tested 2 times per localization test. The target was placed at 1-meter-distance from the participant's head tracker for all positions (on the virtual 1-meter radius sphere used to collect the response positions).

Each trial started with a 500 ms 440 Hz beep sound, indicating the beginning of the trial. After a 500 ms silent period, the virtual target was displayed at one of the 25 tested positions. Participants were instructed to point with the pointing tool to the perceived location of the target with stretched arm. No time limit was imposed for responding but participants were asked to respond as fast and accurately as possible. The virtual target was displayed until participants pressed the trigger of the pointing tool. The response position was recorded (see Section 2.2.5 for response position computing) and the target disappeared. After a 1,000 ms inter-trial

break, the next trial began with the 500 ms beep sound. No feedback was provided regarding response accuracy.

### 2.3.2. Familiarization session

In between the 2 localization tests of each of the 2 tested encodings, participants practiced a familiarization session which consisted in a 60-s period during which participants freely moved the pointing tool in the front field. Figure 1C illustrates the familiarization session. The virtual target was continuously placed (i.e., no need to press the trigger) on a 1-meter radius sphere centered with the camera position, on the axis of the pointing tool. Consequently, when participants moved their arm, the target was continuously placed at the corresponding position on the 1-meter radius sphere and they could hear the soundscape provided by the encoding corresponding to the processed target images within the camera's field of view. The virtual camera position was updated one time at the beginning of the 60-s timer.

## 2.4. Data analysis

Statistical analysis were performed using R (version 3.6.1) (Team, 2020). Localization performance during localization tests was assessed separately for azimuth and elevation dimensions, with error-based and regression-based metrics, both fitted with Linear mixed models (LMMs) in order to take into account participants as random factor. All trials of all participants were included in the models without averaging the response positions or the unsigned errors by participant. The LMMs were fitted using the *lmerTest* R-package (Kuznetsova et al., 2017). We used an ANOVA with Satterthwaite approximation of degrees-of-freedom to estimate the effects. *Post-hoc* analysis were conducted using the *emmeans* R-package (version 1.7.4) (Lenth, 2022) with Tukey HSD correction.

### 2.4.1. Error-based metrics with unsigned and signed errors

Localization performance was assessed through unsigned and signed errors. The elevation signed errors and azimuth signed errors were computed as the difference between target position and response

position in each trial. A negative elevation signed error indicated a downward shift, and a negative azimuth signed error indicated a shift to the left in the response. Only descriptive statistics were conducted on the signed errors. The unsigned errors were computed as the absolute value of the signed error for each trial. They were investigated using LMMs including Encoding (Noise or Pitch), Group (Monotonic or Harmonic) and Phase (Before or After the familiarization) as fixed factors. Therefore, the positions of the target were not included as a factor in the LMMs of the unsigned error. Participants were considered as random effect in both models.

### 2.4.2. Regression-based metrics with response positions

LMMs were also used for the analysis of the response positions. LMMs included Encoding (Noise or Pitch), Group (Monotonic or Harmonic), Phase (Before or After the familiarization), and Target position as fixed effects. The target elevation only, and the target azimuth only, were included in the elevation response LMM, and in the azimuth response LMM, respectively. Participants were considered as random effect in both models. We used the LMMs predictions to approximate the elevation and the azimuth gains and biases. The gains and biases were obtained by computing the trends (slopes) and intercepts of the models expressing the response position as a function of target position. Note that an optimal localization performance would be obtained with a gain value of 1.0 and a bias of  $0.0^\circ$ .

## 3. Results

### 3.1. Performance in elevation localization

The elevation unsigned errors are depicted in Figure 4, left, all target positions combined. Table 1 shows the elevation signed and unsigned errors for each Target elevation, Phase, Encoding and Group. The ANOVA on elevation unsigned errors showed a significant interaction effect of Phase  $\times$  Encoding  $\times$  Group [ $F_{(1,7556)} = 6.23, p = 0.0126, \eta_p^2 = 0.0008$ ]. *Post-hoc* analysis were conducted to investigate the interaction.

The elevation response positions are depicted in Figure 5. The ANOVA showed a significant interaction effect of Phase  $\times$  Target Elevation  $\times$  Encoding [ $F_{(1,7548)} = 38.84, p < 0.0001, \eta_p^2 = 0.005$ ]. We conducted *post-hoc* analysis to investigate the elevation gain (the trend of the model) and bias (the intercept of the model) depending on the Phase and the Encoding. Although the interaction effect of Phase  $\times$  Target Elevation  $\times$  Encoding  $\times$  Group was not significant [ $F_{(1,7548)} = 0.50, p = 0.48, \eta_p^2 = 0.00007$ ], *post-hoc* analysis were also performed for a control purpose in order to check for differences between the Monotonic and Harmonic groups. The elevation response positions are provided separately for each participant in the Supplementary Figures S1, S2.

#### 3.1.1. Elevation localization performance before the familiarization

Before the practice of the familiarization session, and depending on the encoding, the elevation unsigned errors were comprised between  $31.54 \pm 27.19^\circ$  and  $40.19 \pm 37.02^\circ$ . For the Monotonic

group, the elevation unsigned errors were significantly lower with the Monotonic encoding ( $M = 31.54, SD = 27.19$ ) than with the Noise encoding ( $M = 40.19, SD = 37.03$ ) [ $t_{(7556)} = 7.457, p < 0.0001$ ], suggesting a lower accuracy with the Noise encoding. There was no significant difference in the Harmonic group regarding the elevation unsigned error between the Harmonic encoding ( $M = 34.14, SD = 33.69$ ) and the Noise encoding ( $M = 35.51, SD = 33.69$ ).

The elevation response positions before the familiarization are depicted in the left panels of the Figures 5A, B for the Monotonic group and the Harmonic group, respectively. The elevation gains were significantly different from 0.0 for all encodings: 0.62 [95% CI = [0.5, 0.74],  $t_{(7548)} = 10.118, p < 0.0001$ ] with the Harmonic encoding, 0.61 [95% CI = [0.49, 0.73],  $t_{(7548)} = 9.94, p < 0.0001$ ] with the Monotonic encoding, and 0.29 [95% CI = [0.17, 0.41],  $t_{(7548)} = 4.728, p < 0.0001$ ] and 0.35 [95% CI = [0.23, 0.47],  $t_{(7548)} = 5.746, p < 0.0001$ ] with the Noise encoding of the Harmonic and Monotonic groups, respectively. It suggests that participants could discriminate different elevation positions with the three encodings even before the familiarization.

However, elevation gains were significantly lower than the optimal gain 1.0 with all encodings: with the Harmonic encoding [ $t_{(7548)} = -6.173, p < 0.0001$ ], with the Monotonic encoding [ $t_{(7548)} = -6.351, p < 0.0001$ ], and with the Noise encoding of the Harmonic group [ $t_{(7548)} = -11.562, p < 0.0001$ ] and of the Monotonic group [ $t_{(7548)} = -10.544, p < 0.0001$ ]. It depicts a situation where although some variations in elevation seemed to be perceived with the three encodings, participants had difficulties to estimate it before the familiarization.

The participants tended to localize the elevation with a higher performance with the Harmonic or Monotonic encoding than with the Noise encoding. Indeed, the participants from the Harmonic group showed a higher elevation gain with the Harmonic encoding than with the Noise encoding with a significant difference of 0.33 [ $t_{(7548)} = -3.811, p = 0.0008$ ]. For the Monotonic group, the elevation gain was also significantly higher with the Monotonic encoding than with the Noise encoding with a difference of 0.26 [ $t_{(7548)} = -2.97, p = 0.016$ ]. There was no significant difference regarding the elevation gain between the Harmonic and the Monotonic encodings.

The participants tended to underestimate the elevation position of the targets with the three encodings, as indicated by downward bias and negative elevation errors. In the Monotonic group, the elevation bias were  $-26.02^\circ$  (95% CI =  $[-31.9, -20.16]$ ) with the Noise encoding and  $-19.52^\circ$  (95% CI =  $[-25.4, -13.65]$ ) with the Monotonic encoding. In the Harmonic group, the elevation bias with the Noise encoding and with the Harmonic encoding were  $-16.33^\circ$  (95% CI =  $[-22.2, -10.47]$ ) and  $-5.73^\circ$  (95% CI =  $[-11.6, 0.14]$ ), respectively. With the exception of the Harmonic encoding for which there was just a trend [ $t_{(44,9)} = 1.97, p = 0.055$ ], all the elevation bias mentioned above were significantly negative [all  $|t_{(44,9)}| > 5.61$ , all  $p < 0.0001$ ].

To sum up, participants appeared partially able to perceive a variation of the elevation position of the target with the three encodings before the audio-motor familiarization. Interestingly, participants seemed better able to localize the elevation with the Harmonic and Monotonic encodings.

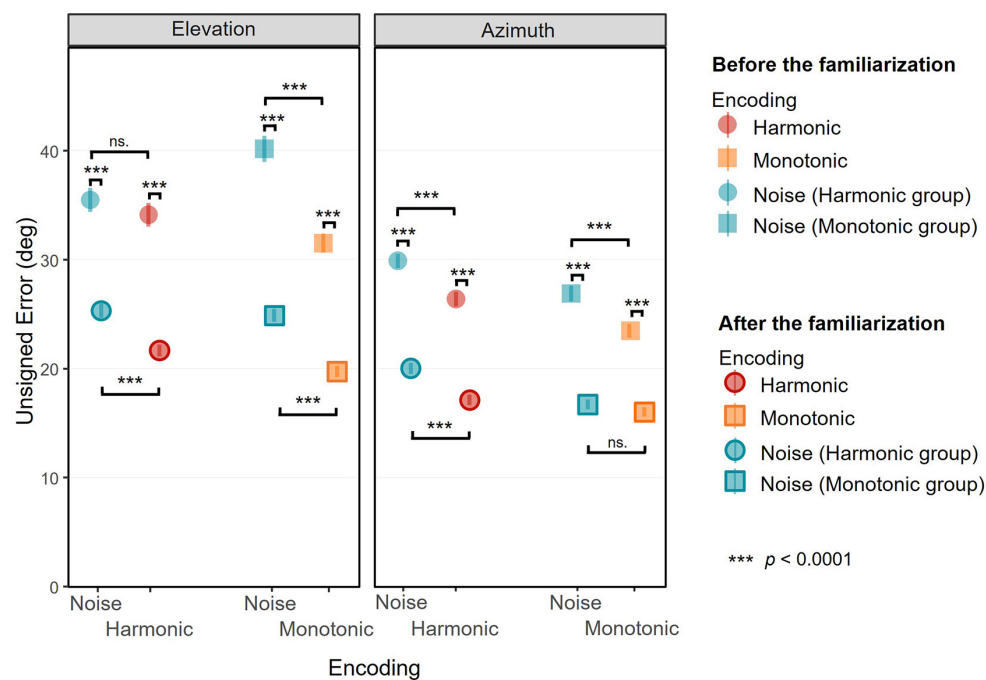


FIGURE 4

Unsigned error in elevation (left) and in azimuth (right) as a function of the encoding, all target positions combined. Mean unsigned errors (in degree) before (non-surrounded) and after (surrounded) are depicted separately for the Monotonic group (squares) and Harmonic group (circles) and for the three visual-to-auditory encodings: the Noise (blue), the Monotonic (orange) and the Harmonic (red) encodings. Error bars show standard error of the unsigned error.

### 3.1.2. Elevation localization performance after the familiarization

After the familiarization, the elevation unsigned errors were significantly higher with the Noise encoding than with the 2 pitch-based encodings (Monotonic or Harmonic encodings). With the Noise encoding, the elevation unsigned errors were  $24.90 \pm 18.40^\circ$  in the Monotonic group and  $25.35 \pm 20.31^\circ$  in the Harmonic group. With the Harmonic and Monotonic encodings, the elevation unsigned errors were  $21.70 \pm 16.72^\circ$  and  $19.75 \pm 16.25^\circ$  respectively. In the Monotonic group, the elevation unsigned errors were significantly lower with the Monotonic encoding ( $M = 19.75$ ,  $SD = 16.25$ ) than with the Noise encoding ( $M = 24.90$ ,  $SD = 18.40$ ) [ $t_{(7556)} = 4.44$ ,  $p < 0.0001$ ]. Unlike before the familiarization, the difference was also significant in the Harmonic group. The elevation unsigned errors with the Harmonic encoding ( $M = 21.70$ ,  $SD = 16.72$ ) were lower than with the Noise encoding ( $M = 25.35$ ,  $SD = 20.31$ ), [ $t_{(7556)} = 3.15$ ,  $p = 0.0016$ ]. Interestingly, the elevation unsigned errors significantly decreased after the familiarization with all the encodings [all  $|t_{(7556)}| > 8.75$ , all  $p < 0.0001$ ], suggesting that participants localized more accurately the elevation after the familiarization.

The elevation response positions after the familiarization are depicted in the Figures 5A, B for the Monotonic and Harmonic groups, respectively. After the familiarization, the elevation gains were still significantly higher than 0.0 [all  $|t_{(7548)}| > 2.9152$ , all  $p < 0.0036$ ] with all encodings in the 2 groups. The elevation gains were 1.112 (95% CI = [0.99, 1.23]) with the Harmonic encoding and 1.015 (95% CI = [0.89, 1.14]) with the Monotonic encoding. For the participants of the Harmonic group and the Monotonic group, the

elevation gains with the Noise encoding were 0.179 (95% CI = [0.06, 0.30]), and 0.278 (95% CI = [0.16, 0.40]), respectively.

The elevation gains were significantly higher with the Harmonic and Monotonic encodings than with the Noise encoding. We measured a difference of 0.74 [ $t_{(7548)} = -8.49$ ,  $p < 0.0001$ ] in the Harmonic group and a difference of 0.93 [ $t_{(7548)} = -10.75$ ,  $p < 0.0001$ ] in the Monotonic group. Inter-group analysis showed that the difference in elevation gain between the Monotonic and the Harmonic encodings did not significantly differ [ $t_{(7548)} = 1.12$ ,  $p = 0.95$ ].

The elevation gains with the Harmonic and the Monotonic encodings significantly improved after the familiarization to get closer than the optimal gain 1.0. With the Harmonic encoding, the elevation gain significantly increased from 0.62 to 1.112 [ $t_{(7548)} = 5.66$ ,  $p < 0.0001$ ] after which it was not significantly different from the optimal gain 1.0 [ $t_{(7548)} = 1.832$ ,  $p = 0.067$ ]. With the Monotonic encoding, the elevation gain significantly increased from 0.61 to 1.015 [ $t_{(7548)} = 4.665$ ,  $p < 0.0001$ ], and was also no more significantly different from the optimal gain 1.0 [ $t_{(7548)} = 0.246$ ,  $p = 0.806$ ]. However with the Noise encoding in both groups, the familiarization did not improve the elevation gains. In the Harmonic and Monotonic groups, the elevation gains decreased from 0.29 to 0.179 and from 0.35 to 0.278, respectively, but, as previously reported, the decreases were not significant.

Participants kept tending to underestimate the elevation position of the targets with all three encodings, as indicated by persistent negative bias. In the Monotonic group, the elevation bias with the Noise encoding and with the Monotonic encoding were  $-14.82^\circ$  (95% CI = [-20.7, -8.96]) and  $-14.15^\circ$  (95% CI = [-20.0, -8.28]),



TABLE 1 Elevation signed error and unsigned error (in degree) for each encoding and target elevation, before, and after the familiarization session.

Encoding	Target elevation (degree)	Elevation signed error (degree) Mean $\pm$ standard deviation		Elevation unsigned error (degree) Mean $\pm$ standard deviation	
		Before familiarization	After familiarization	Before familiarization	After familiarization
Monotonic	+25	$-26.71 \pm 41.40$	$-13.21 \pm 20.02$	$37.79 \pm 31.55$	$18.55 \pm 15.17$
	+12.5	$-28.09 \pm 33.09$	$-16.55 \pm 22.28$	$33.45 \pm 27.62$	$21.99 \pm 16.89$
	0	$-18.83 \pm 36.41$	$-11.94 \pm 22.73$	$31.63 \pm 26.01$	$19.60 \pm 16.55$
	-12.5	$-15.14 \pm 34.95$	$-13.23 \pm 24.95$	$27.30 \pm 26.50$	$20.73 \pm 19.14$
	-25	$-8.82 \pm 34.34$	$-15.81 \pm 15.18$	$27.51 \pm 22.29$	$17.89 \pm 21.65$
Harmonic	+25	$-17.66 \pm 47.39$	$-13.73 \pm 26.16$	$36.66 \pm 34.76$	$23.03 \pm 18.45$
	+12.5	$-7.18 \pm 45.40$	$-6.61 \pm 26.46$	$33.41 \pm 31.47$	$20.73 \pm 17.67$
	0	$-5.68 \pm 45.71$	$-10.28 \pm 28.07$	$32.91 \pm 32.14$	$24.06 \pm 17.67$
	-12.5	$-1.10 \pm 48.75$	$-16.43 \pm 21.80$	$33.44 \pm 35.40$	$22.23 \pm 15.81$
	-25	$2.99 \pm 48.76$	$-15.85 \pm 16.08$	$34.28 \pm 34.72$	$18.44 \pm 13.01$
Noise (Monotonic group)	+25	$-42.69 \pm 52.91$	$-33.92 \pm 27.00$	$56.49 \pm 37.73$	$37.54 \pm 21.64$
	+12.5	$-32.93 \pm 45.45$	$-23.24 \pm 23.54$	$43.63 \pm 35.23$	$28.00 \pm 17.56$
	0	$-25.49 \pm 43.51$	$-12.98 \pm 24.78$	$36.61 \pm 34.62$	$23.09 \pm 15.73$
	-12.5	$-20.61 \pm 43.35$	$-7.09 \pm 22.23$	$32.93 \pm 34.88$	$19.02 \pm 13.46$
	-25	$-8.40 \pm 47.90$	$3.11 \pm 22.32$	$31.30 \pm 37.15$	$16.86 \pm 14.90$
Noise (Harmonic group)	+25	$-34.74 \pm 46.47$	$-33.67 \pm 28.35$	$47.86 \pm 32.71$	$36.96 \pm 23.87$
	+12.5	$-24.89 \pm 45.12$	$-21.25 \pm 27.08$	$40.59 \pm 31.66$	$27.87 \pm 20.16$
	0	$-15.68 \pm 42.71$	$-12.20 \pm 25.02$	$32.41 \pm 31.87$	$22.15 \pm 16.81$
	-12.5	$-7.03 \pm 44.28$	$-3.40 \pm 25.66$	$28.84 \pm 34.27$	$19.68 \pm 16.76$
	-25	$0.69 \pm 43.84$	$8.72 \pm 25.46$	$27.84 \pm 33.81$	$20.10 \pm 17.85$

respectively. In the Harmonic group, the elevation bias with the Noise encoding and with the Harmonic encoding were  $-12.36^\circ$  (95% CI =  $[-18.2, -6.49]$ ) and  $-12.58^\circ$  (95% CI =  $[-18.4, -6.72]$ ), respectively. All the elevation bias were significantly negative [all  $|t_{(44.9)}| > 4.24$ , all  $p < 0.0001$ ].

To sum up, after the familiarization, the perception of elevation with the Harmonic and Monotonic encodings improved with elevation gains getting closer to the optimal gain. However, the familiarization did not induce any significant improvement in the perception of elevation with the Noise encoding, with persistent low elevation gains in both groups. Additionally, the underestimation elevation bias decreased with the Monotonic and Noise encodings, but not with the Harmonic encoding for which it increased.

### 3.2. Performance in azimuth localization

The azimuth unsigned errors are depicted in Figure 4, right, all target positions combined. Table 2 shows the azimuth signed and unsigned errors for each Target azimuth, Phase, Encoding and Group. The ANOVA on azimuth unsigned errors showed a significant interaction effect of Phase  $\times$  Encoding [ $F_{(1,7556)} = 5.15$ ,  $p = 0.023$ ,  $\eta_p^2 = 0.00068$ ], but the interaction including the group was not significant.

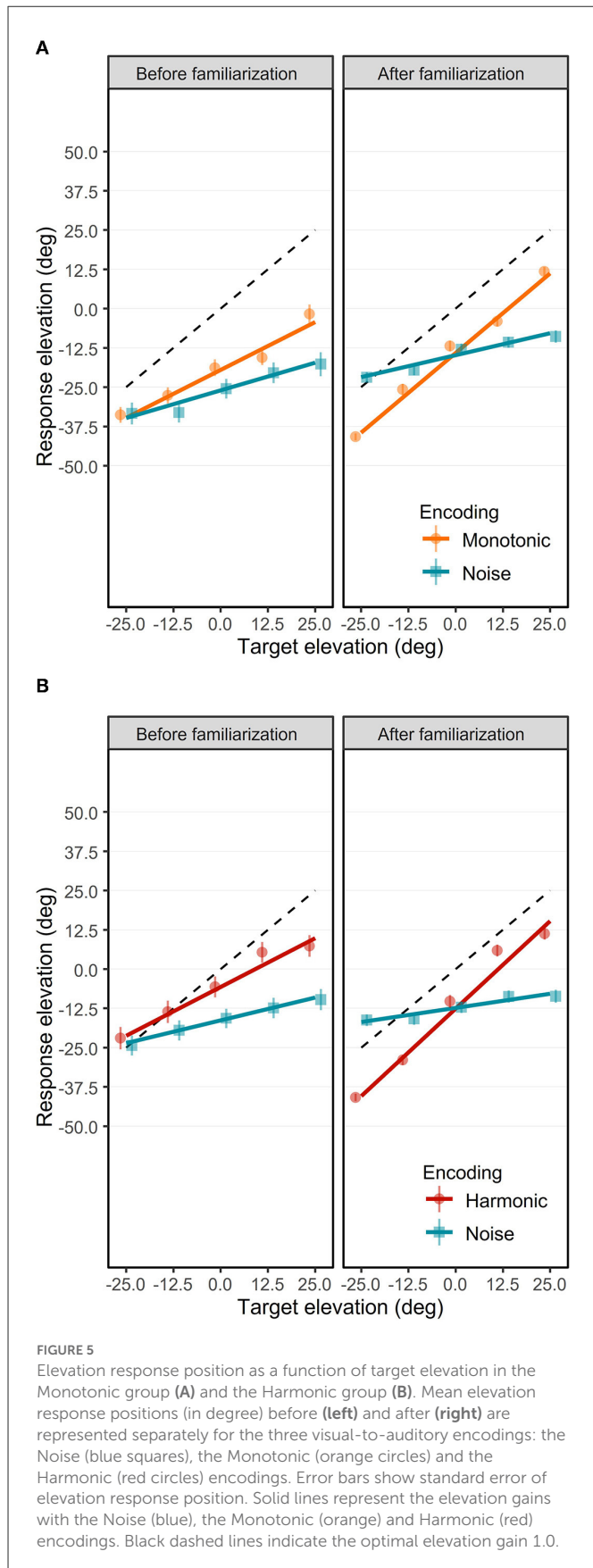
The azimuth response positions are depicted in Figure 6. The ANOVA yielded a significant interaction effect of Phase  $\times$  Target Azimuth  $\times$  Encoding [ $F_{(1,7548)} = 12.69$ ,  $p = 0.0004$ ,  $\eta_p^2 = 0.00005$ ].

*Post-hoc* analysis were conducted to investigate the azimuth gain (the trend of the model) and bias (the intercept of the model) depending on the Phase and the Encoding. Although the interaction effect of Phase  $\times$  Target Elevation  $\times$  Encoding  $\times$  Group was not significant [ $F_{(1,7548)} = 1.64$ ,  $p = 0.20$ ,  $\eta_p^2 = 0.0002$ ], we conducted *post-hoc* analysis to check for differences between the Monotonic and Harmonic groups for a control purpose. The azimuth response positions are provided separately for each participant in the Supplementary Figures S3, S4.

#### 3.2.1. Azimuth localization performance before the familiarization

Before the practice of the familiarization session, and depending on the encoding, the azimuth unsigned errors were comprised between  $23.48 \pm 19.48^\circ$  and  $29.91 \pm 20.38^\circ$ . In the Monotonic group, the azimuth unsigned errors were significantly lower with the Monotonic encoding ( $M = 23.48$ ,  $SD = 19.48$ ) than with the Noise encoding ( $M = 26.92$ ,  $SD = 22.58$ ) [ $t_{(7556)} = 4.64$ ,  $p < 0.0001$ ]. The azimuth unsigned errors in the Harmonic group were also significantly lower [ $t_{(7556)} = 4.73$ ,  $p < 0.0001$ ] with the Harmonic encoding ( $M = 26.41$ ,  $SD = 20.63$ ) than with the Noise encoding ( $M = 29.91$ ,  $SD = 33.69$ ).

The azimuth response positions over all participants before the familiarization are depicted in the left panels of the Figures 6A, B for the Monotonic and Harmonic groups, respectively. Before the familiarization, the participants were able to interpret soundscapes to



localize the target azimuth. First, the participants perceived different azimuth positions. Indeed, azimuth gains were significantly different

from 0.0 with all encodings: 1.81 (95% CI = [1.75, 1.87],  $t_{(7548)} = 70.397$ ,  $p < 0.0001$ ) with the Harmonic encoding, 1.59 [95% CI = [1.54, 1.65],  $t_{(7548)} = 61.996$ ,  $p < 0.0001$ ] with the Monotonic encoding, and 1.88 [95% CI = [1.82, 1.93],  $t_{(7548)} = 73.0624$ ,  $p < 0.0001$ ] and 1.74 [95% CI = [1.68, 1.80],  $t_{(7548)} = 67.710$ ,  $p < 0.0001$ ] with the Noise encoding for the participants in the Harmonic and Monotonic groups, respectively.

Interestingly, the azimuth gains were significantly higher than the optimal gain (i.e., higher than 1.0) with the Harmonic encoding [ $t_{(7548)} = 31.492$ ,  $p < 0.0001$ ], the Monotonic encoding [ $t_{(7548)} = 23.091$ ,  $p < 0.0001$ ], and the Noise encoding in the Harmonic group [ $t_{(7548)} = 34.156$ ,  $p < 0.0001$ ] and the Monotonic group [ $t_{(7548)} = 28.804$ ,  $p < 0.0001$ ]. These gains higher than the optimal gain reflect a lateral overestimation (i.e., left targets localized too much on the left and right targets localized too much on the right) that can be seen with the three encodings.

In the Monotonic group, the overestimation observed with the Noise encoding was significantly higher than with the Monotonic encoding [ $t_{(7548)} = 4.04$ ,  $p = 0.0003$ ]. In the Harmonic group, the overestimation with the Noise encoding compared to the Harmonic encoding was also higher but not significantly. Inter-group comparison of the azimuth gains obtained with the Noise encoding shows a small but significant higher azimuth gain in the Harmonic group [difference of 0.14:  $t_{(7548)} = 3.784$ ,  $p = 0.0009$ ]. As inter-group comparison, we also observed a slight but significant higher overestimation pattern with the Harmonic encoding in comparison with the Monotonic encoding [difference of 0.22:  $t_{(7548)} = 5.94$ ,  $p < 0.0001$ ].

Another interesting result is the tendency to show a left shift as indicated by negative azimuth bias with the three encodings. With the Noise encoding in the Harmonic group, the leftward azimuth bias of  $-5.03^\circ$  was significant [ $t_{(47.2)} = 2.84$ ,  $p = 0.0066$ ]. However, leftward azimuth bias with the other encodings were not significantly different from  $0.0^\circ$  (Harmonic group, Noise encoding:  $-3.23^\circ$ ; Monotonic group, Noise encoding:  $-2.0^\circ$ ; Monotonic group, Monotonic encoding:  $-1.233^\circ$ ).

In summary, before the familiarization and with the three encodings, participants were able to localize the azimuth of the target accurately with a tendency to overestimate the lateral eccentricity and a tendency to point too much on the left.

### 3.2.2. Azimuth localization performance after the familiarization

After the participants practiced the familiarization session, and depending on the encoding, the azimuth unsigned errors were comprised between  $16.05 \pm 13.38^\circ$  and  $20.05 \pm 15.77^\circ$ . In the Harmonic group, the azimuth unsigned errors were significantly lower with the Harmonic encoding ( $M = 17.16$ ,  $SD = 14.97$ ) than with the Noise encoding ( $M = 20.05$ ,  $SD = 15.77$ ) [ $t_{(7556)} = 3.91$ ,  $p = 0.0001$ ]. The azimuth unsigned errors were not significantly different anymore between the Monotonic encoding ( $M = 16.05$ ,  $SD = 13.38$ ) and the Noise encoding ( $M = 16.73$ ,  $SD = 13.50$ ). Importantly, the azimuth unsigned errors significantly decreased after the familiarization session for all three encodings [all  $|t_{(7556)}| > 10.06$ , all  $p < 0.0001$ ], suggesting that participants localized more accurately the azimuth after the familiarization.

The azimuth response positions after the familiarization are depicted in the right panels of the Figures 6A, B for the

TABLE 2 Azimuth signed error and unsigned error (in degree) for each encoding and target azimuth, before, and after the familiarization session.

Encoding	Target azimuth (degree)	Azimuth signed error (degree) Mean $\pm$ standard deviation		Azimuth unsigned error (degree) Mean $\pm$ standard deviation	
		Before familiarization	After familiarization	Before familiarization	After familiarization
Monotonic	+40	17.79 $\pm$ 23.73	4.39 $\pm$ 18.25	23.16 $\pm$ 18.5	13.97 $\pm$ 12.5
	+20	25.34 $\pm$ 25.50	12.06 $\pm$ 18.35	28.71 $\pm$ 21.61	17.14 $\pm$ 13.69
	0	-7.75 $\pm$ 25.39	-5.02 $\pm$ 19.33	17.95 $\pm$ 19.52	15.21 $\pm$ 12.90
	-20	-25.25 $\pm$ 21.81	-15.02 $\pm$ 18.10	26.93 $\pm$ 19.69	18.68 $\pm$ 14.27
	-40	-16.27 $\pm$ 20.33	-5.34 $\pm$ 19.40	20.68 $\pm$ 15.79	15.23 $\pm$ 13.11
Harmonic	+40	23.26 $\pm$ 19.59	5.43 $\pm$ 21.49	24.9 $\pm$ 17.45	15.83 $\pm$ 15.48
	+20	27.17 $\pm$ 20.26	12.98 $\pm$ 18.80	28.17 $\pm$ 19.61	17.23 $\pm$ 14.98
	0	-6.89 $\pm$ 23.03	-6.02 $\pm$ 18.49	16.89 $\pm$ 17.36	14.15 $\pm$ 12.97
	-20	-32.76 $\pm$ 23.38	-16.61 $\pm$ 19.93	33.16 $\pm$ 22.81	21.6 $\pm$ 14.35
	-40	-27.45 $\pm$ 23.93	-7.03 $\pm$ 22.08	29.25 $\pm$ 21.68	16.68 $\pm$ 16.05
Noise (Monotonic group)	+40	23.01 $\pm$ 25.34	7.27 $\pm$ 16.58	27.91 $\pm$ 19.79	14.35 $\pm$ 11.01
	+20	28.35 $\pm$ 29.17	11.96 $\pm$ 19.59	30.95 $\pm$ 26.38	18.11 $\pm$ 14.06
	0	-8.89 $\pm$ 24.82	-8.47 $\pm$ 14.79	16.78 $\pm$ 20.31	12.04 $\pm$ 12.05
	-20	-31.27 $\pm$ 25.61	-21.37 $\pm$ 17.24	33.42 $\pm$ 22.71	22.32 $\pm$ 15.98
	-40	-21.22 $\pm$ 24.10	-11.55 $\pm$ 16.88	25.53 $\pm$ 19.45	16.82 $\pm$ 11.59
Noise (Harmonic group)	+40	24.13 $\pm$ 23.85	9.86 $\pm$ 24.77	28.65 $\pm$ 18.12	19.17 $\pm$ 18.49
	+20	29.80 $\pm$ 24.77	15.02 $\pm$ 17.67	31.78 $\pm$ 22.16	18.94 $\pm$ 13.35
	0	-11.84 $\pm$ 27.02	-7.04 $\pm$ 20.76	21.10 $\pm$ 20.57	16.34 $\pm$ 14.57
	-20	-36.95 $\pm$ 20.92	-22.36 $\pm$ 18.41	37.28 $\pm$ 20.31	25.06 $\pm$ 14.48
	-40	-30.29 $\pm$ 17.83	-12.40 $\pm$ 23.27	30.71 $\pm$ 17.09	20.71 $\pm$ 16.28

Monotonic and Harmonic groups, respectively. As expected, after the familiarization, participants were still able to localize different azimuth positions by interpreting soundscapes. Azimuth gains were still significantly different from 0.0 with the Harmonic encoding [1.27, 95% CI = [1.22, 1.32],  $t_{(7548)} = 49.51$ ,  $p < 0.0001$ ], with the Monotonic encoding [1.23, 95% CI = [1.18, 1.28],  $t_{(7548)} = 47.96$ ,  $p < 0.0001$ ], and with the Noise encoding for the participants in the Harmonic group [1.41, 95% CI = [1.36, 1.46],  $t_{(7548)} = 54.84$ ,  $p < 0.0001$ ] and in the Monotonic group [1.35, 95% CI = [1.30, 1.41],  $t_{(7548)} = 52.711$ ,  $p < 0.0001$ ], respectively.

The overestimation pattern was still present, as indicated by azimuth gains still significantly higher than the optimal gain 1.0 with all encodings: the Harmonic encoding [ $t_{(7548)} = 10.61$ ,  $p < 0.0001$ ], the Monotonic encoding [ $t_{(7548)} = 9.06$ ,  $p < 0.0001$ ], the Noise encoding in the Harmonic group [ $t_{(7548)} = 15.93$ ,  $p < 0.0001$ ] and in the Monotonic group [ $t_{(7548)} = 13.81$ ,  $p < 0.0001$ ].

Although the lateral overestimation was still significant, it significantly decreased compared to the same localization test before the familiarization. Indeed, the azimuth gains decreased and reached values closer than the optimal gain 1.0 with the 3 encodings. There were significant decreases in azimuth gains of a magnitude of 0.54 [ $t_{(7548)} = 14.77$ ,  $p < 0.0001$ ] and 0.36 [ $t_{(7548)} = 9.92$ ,  $p < 0.0001$ ] with the Harmonic and Monotonic encodings, respectively. The decreases in azimuth gains with the Noise encoding in the Harmonic and the Monotonic groups were also significant with a decrease of a magnitude of, respectively, 0.47 [ $t_{(7548)} = 12.897$ ,  $p < 0.0001$ ] and 0.39 [ $t_{(7548)} = 10.61$ ,  $p < 0.0001$ ].

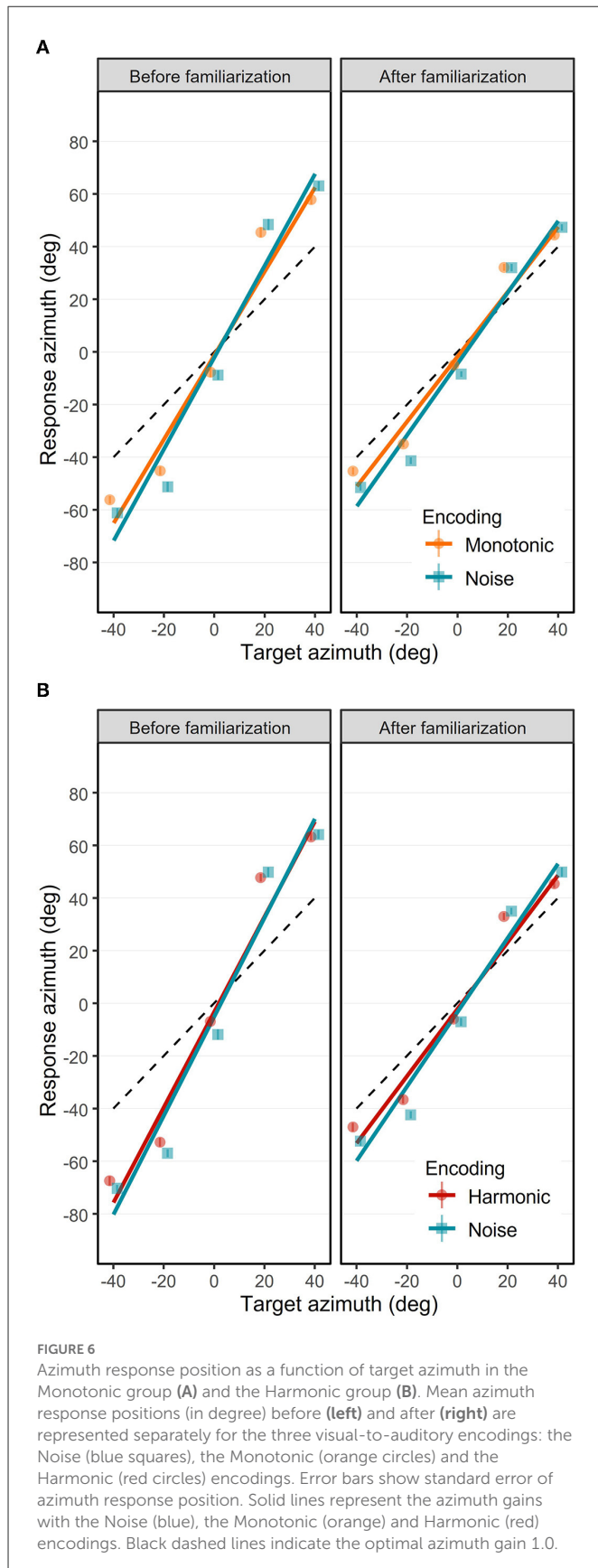
Additionally, after the familiarization, participants tended to localize the azimuth with a higher performance with the Harmonic and Monotonic encodings than with the Noise encoding. This is suggested by a more pronounced lateral overestimation with the Noise encoding in both groups: the azimuth gains were 0.14 higher [ $t_{(7548)} = 3.76$ ,  $p = 0.0042$ ] and 0.12 higher [ $t_{(7548)} = 3.36$ ,  $p = 0.018$ ] with the Noise encoding in comparison with the Harmonic and Monotonic encodings, respectively.

The slight tendency to show a left shift bias in azimuth was still present with the three encodings. With the Noise encoding in the Monotonic group, the leftward azimuth bias of  $-4.43^\circ$  was significant [ $t_{(47.2)} = 2.502$ ,  $p = 0.0159$ ], but in the Harmonic group the bias of  $-3.38^\circ$  was just a tendency [ $t_{(47.2)} = 1.911$ ,  $p = 0.0621$ ]. The leftward azimuth bias with the Harmonic encoding ( $-2.25^\circ$ ) and Monotonic encoding ( $-1.79^\circ$ ) were also not significant.

To sum up the accuracy in azimuth localization, participants were able to localize target azimuths accurately even before the audio-motor familiarization. After the familiarization, the accuracy increased with a decrease in both the tendency to overestimate the lateral position of lateral targets and the tendency to point too much on the left.

## 4. Discussion

In this study, we investigated the early stage of use of visual-to-auditory SSDs based on the creation of a VAS (Virtual



Acoustic Space) for object localization in a virtual environment. Based on soundscapes created using non-individualized HRTFs, we investigated blindfolded participants' abilities to localize a virtual target with three encoding schemes: one conveying elevation with

spatialization only (Noise encoding), and two conveying elevation with spatialization and pitch modulation (Monotonic and Harmonic encodings). The two pitch-based encodings varied regarding the sound spectrum complexity: one narrowband with monotonies (Monotonic encoding) and one more complex with 2 additional octaves (Harmonic encoding). In order to compare the localization abilities for the azimuth and the elevation with the different visual-to-auditory encodings, we collected the response positions and angular errors of the participants during a task consisting in the localization of a virtual target placed at different azimuths and elevations in their front-field.

## 4.1. Elevation localization abilities using the visual-to-auditory encodings

### 4.1.1. Elevation localization performance only based on non-individualized HRTFs is impaired

With the spatialization-based only encoding (Noise encoding), the target was localized before the familiarization with an elevation unsigned error between  $27.84 \pm 33.81^\circ$  and  $56.49 \pm 37.73^\circ$ . After the familiarization, the elevation unsigned errors decreased to reach values comprised between  $16.86 \pm 14.90^\circ$  and  $37.54 \pm 21.64^\circ$ . As a comparison, in [Mendonça et al. \(2013\)](#) where the same HRTFs database was used with a white noise sound, the mean elevation unsigned error of participants was  $29.3^\circ$  before practicing a training. The elevation unsigned errors in [Geronazzo et al. \(2018\)](#) without any familiarization and with a white noise sound were comprised between  $15.58 \pm 12.47^\circ$  and  $33.75 \pm 16.17^\circ$  depending on participants, which is comparable to our results after the familiarization. However, as shown by elevation gains below 0.4 before or after familiarization, the participants had difficulties to discriminate different elevations with this encoding.

The abilities to localize the elevation of an artificially spatialized sound are known to be impaired in comparison with azimuth ([Wenzel et al., 1993](#)). Those difficulties arise from the spectral distortions that are specific to individual body morphology ([Blauert, 1996](#); [Xu et al., 2007](#)). When using non-individualized HRTFs, these spectral distortions are different from the participant's specific distortions, causing misinterpretation of elevation location. Additionally, the abilities to localize the elevation position of a sound source (virtual or real) are modulated by the spectral content of the sound ([Middlebrooks and Green, 1991](#); [Blauert, 1996](#)).

In our study, the difficulty with the spatialization-based only encoding to localize the elevation of the target, even after the audio-motor familiarization, could be explained by a too brief training period to get used to the new auditory cues. Actually, some studies showed an improvement of localization abilities with non-individualized or modified HRTFs after 3 weeks of training in [Majdak et al. \(2013\)](#) or [Romigh et al. \(2017\)](#), or after 2 weeks in [Shinn-Cunningham et al. \(1998\)](#) or 1 week in [Kumpik et al. \(2010\)](#), and about 5 h in [Bauer et al. \(1966\)](#). Moreover, [Mendonça et al. \(2013\)](#) showed the positive long term effect (1-month long) of training in azimuth and elevation localization abilities with a sound source spatialized using the same HRTFs database that was used in the current study. It suggests that the exclusive use of HRTFs to encode spatial information in SSDs might require a long training period or a long process to acquire individualized HRTFs.



#### 4.1.2. Positive effects of cross-modal correspondence on elevation localization

The participants' abilities to localize the elevation of the target using the 2 pitch-based encodings were significantly better than with a broadband sound spatialization encoding. Before the audio-motor familiarization, with the narrowband encoding (Monotonic) and the more complex encoding (Harmonic), the unsigned errors in elevation were comprised between  $27.30 \pm 26.50^\circ$  and  $37.79 \pm 31.55^\circ$  depending on the target elevation.

Before the familiarization, participants did not receive any information about the way the sound was modulated depending on the target location. In other words, they did not know that low pitch sounds were associated with low elevation locations, and conversely. However, the individual results of each participant for the elevation (Supplementary Figures S1, S2) suggest that even before the familiarization, several participants interpreted the pitch to perceive the target elevation, using high pitch for high elevation and low pitch for low elevation. We suppose that participants were able to guess that the pitch of the sound varied with the target elevation because the experimenter explicitly told them that sound features were modulated as a function of the location of the target although no details regarding this modulation were provided. Two participants (S12 from the Harmonic group and S15 from the Monotonic group) reversed the pitch encoding by associating a low pitch to high elevations and a high pitch to low elevations, but they reversed this miss-representation after the familiarization. Our study showed that after the audio-motor familiarization, the elevation unsigned errors significantly decreased with both pitch-based encodings to reach values comprised between  $17.67 \pm 22.23^\circ$  and  $24.06 \pm 17.67^\circ$ , which are lower elevation unsigned errors than the mean elevation error of  $25.2^\circ$  immediately after the training in Mendonça et al. (2013).

In the visual-to-auditory SSD domain, the artificial pitch mapping of elevation is used by several existing visual-to-auditory SSDs and relies on the audiovisual cross-modal correspondence between visual elevation and pitch (Spence, 2011; Deroy et al., 2018). In the current study, the frequency range was between 250 Hz and about 1,500 Hz with the Monotonic encoding and between 250 Hz and about 6,000 Hz with the Harmonic encoding (i.e.,  $1,500 \text{ Hz} \times 2 \times 2$ ). The floor value of 250 Hz was chosen to provide frequency steps of at least 3 Hz between each of the 120 auditory pixels in a column, to fit to the human frequency discrimination abilities (Howard and Angus, 2009). We used the Mel scale (Stevens et al., 1937) to take into account the perceived scaling in sound frequency discrimination. All the SSDs using a pitch mapping of elevation use different frequency ranges, resolutions (i.e., number of used frequencies) and frequency steps. The vOICe SSD (Meijer, 1992) uses a larger frequency range than the current study (from 500 to 5,000 Hz) following an exponential scale with a 64-frequency resolution. The EyeMusic SSD (Abboud et al., 2014) uses a pentatonic musical scale with 24 frequencies from 65.785 Hz to 1577.065 Hz. The SSD proposed in Ambard et al. (2015) also uses 120 frequency steps but following the Bark scale (Zwicker, 1961) and with a larger frequency range (from 250 Hz to about 2,500 Hz). Technically, increasing the range of frequencies might increase discrimination abilities between target elevations and improve localization abilities. Although, as sound frequency increases the sound feels unpleasant (Kumar et al., 2008). We can postulate that SSD users should be able to modulate some of the parameters in order to adapt the encoding scheme to their own auditory abilities and perceptual preferences.

Our results suggest that a pitch mapping of elevation can quickly be interpreted, even without any explicit explanation of the mapping rules. They also suggest that the pitch mapping provides acoustic cues that are easily interpretable at the early stage of use of a SSD to localize an object. In terms of spatial perception, our study shows that adding abstract acoustic cues to convey spatial information can be more efficient than an imperfect synthesizing of natural acoustic cues. It is difficult to assert that the differences in the results between the Noise encoding and the Pitch encodings are entirely due to the cross-modal correspondence between elevation and pitch since modifying the timbre of the sound by reducing its spectral content also modified how the HRTFs spatialize the sound. Therefore, it would be interesting to investigate the localization performance with monotonic or harmonic sounds in which the pitch is constant (i.e., not related to the elevation of the target) and by conducting an experiment where HRTFs convolution is computed to convey azimuth only, with for instance a constant elevation of  $0^\circ$ .

#### 4.1.3. Insights about the pitch-elevation cross-modal correspondence

Although the aim of this study was not to directly investigate the multisensory perceptual process, the results might bring insights about the pitch-elevation cross-modal correspondence. In the SSD research, it has been suggested that the pitch-based elevation mapping is intuitive in an object recognition task (Stiles and Shimojo, 2015). Based on the results of the current study, it also seems intuitive in a localization task. However, it remains to be further investigated with, for instance, a comparison of elevation localization abilities with a similar pitch-based elevation encoding and another encoding where the direction of the pitch mapping is reversed (i.e., low pitch for high elevation and high pitch for low elevation). The current study also raises the question regarding the automaticity of the cross-modal correspondences as discussed in Spence and Deroy (2013). In the current study, the facilitation effect of the cross-modal correspondence probably relies on voluntary multisensory perceptual processes. The way the instructions were given to the participants intrinsically induced a goal-directed voluntary strategy in order to infer which modifications in the sound could convey information about the location of the object.

These insights about multisensory process should also be investigated in the blind. Since the pitch-elevation cross-modal correspondence has been suggested to be weak in this population (Deroy et al., 2016), and since auditory spatial perception of the elevation can be impaired in this population (Voss, 2016), it remains to investigate whether similar results would be obtained with blind participants. For this reason, the procedure of the current study was designed in a way to be reproducible with blind participants.

#### 4.1.4. No positive effects of harmonics on elevation localization

The elevation-pitch encoding adds a salient auditory cue while reducing the frequency range where the HRTFs spectrum alterations can operate. To study the effect of the spectral complexity we used an encoding with harmonic sounds (monotonic and 2 following octaves) meant to be a trade-off in terms of spectral complexity between the broadband sound of the Noise encoding and the monotonies of the Monotonic encoding. Although pure tones were

used in the Monotonic encoding, it is important to keep in mind that soundscapes were not pure tones. Indeed, soundscapes were made of adjacent auditory pixels, resulting in narrowband but multi-frequency soundscapes (see [Figure 2](#)).

The results did not show inter-group differences in the localization accuracy between the Monotonic and the Harmonic encodings. It suggests that adding 2 octaves to the original sound (i.e., the Monotonic encoding) did not modulate the ability to perceive the elevation of the target. Using more complex tones with several sub-octave intervals in the Harmonic encoding might sufficiently modify the sound spectrum to obtain a significant difference with the Monotonic encoding. It could also be interesting to investigate the ability to perceive the elevation of the target with an encoding using sounds containing frequencies higher than the current ceiling frequency (6,000 Hz). However, as mentioned in Section 4.1.1, it seems that the benefits that could arise from the application of the HRTFs on a sound with a broader spectrum could only be perceivable after a long training period.

## 4.2. Azimuth localization using the visual-to-auditory encodings is accurate but overestimated

Depending on the encoding and the target eccentricity, the magnitude of the azimuth unsigned errors was comprised between  $16.78 \pm 20.31^\circ$  and  $37.29 \pm 20.32^\circ$ . As a comparison, [Mendonça et al. \(2013\)](#) spatialized white noise sounds using the same HRTFs database and their participants localized the azimuth with a mean unsigned error of  $21.3^\circ$  before the training practice. In [Geronazzo et al. \(2018\)](#), the azimuth unsigned errors of participants varied between  $3.67 \pm 2.97^\circ$  and  $35.98 \pm 45.32^\circ$ . In the SSD domain, [Scalvini et al. \(2022\)](#) found a mean azimuth error of  $6.72 \pm 5.82^\circ$  in a task consisting in localizing a target with the head. In the current study, after the familiarization, the magnitude of azimuth unsigned errors decreased and was comprised between  $12.04 \pm 12.05^\circ$  and  $25.06 \pm 14.48^\circ$  depending on the azimuth eccentricity which is comparable to the azimuth unsigned errors found in [Geronazzo et al. \(2018\)](#), without training. In [Mendonça et al. \(2013\)](#), immediately after the training, the mean azimuth unsigned errors also decreased and reached a magnitude of  $15.3^\circ$  which is also comparable to the current results.

In the current study, without any familiarization, and with the three visual-to-auditory encodings, participants were able to discriminate the different azimuths as suggested by gains higher than the optimal value of 1.0. After the familiarization, and with the three visual-to-auditory encodings, participants were able to localize the azimuth of the target with average azimuth gains comprised between 1.23 and 1.41 which were higher than the null value and than the optimal gain 1.0. It shows that the sound spatialization method used in the current study based on HRTFs from the CIPIC database ([Algazi et al., 2001a](#)) partly reproduced the natural cues used in free-field sound azimuth localization. These results are not surprising since azimuth is mainly conveyed through binaural cues including the Interaural Level Difference (ILD) and the Interaural Time Difference (ITD) that reflect audio signal differences between the two ears. ITD is mainly used when the spectral content of the audio signal does not include frequencies higher than 1,500 Hz and ILD is mainly used for frequencies higher than 3,000 Hz ([Blauert, 1996](#)). The used frequencies ranged from 250 Hz to about 1,500 Hz

with the Monotonic encoding, which is in a frequency domain where ITDs are mainly used to perceive the azimuth. With the Harmonic encoding, that added 2 octaves, the frequency range was between 250 and 6,000 Hz which already contains the ILD frequency domain. The Noise encoding with the broadband sound allows both cues (ITD and ILD) to be fully used, which can theoretically improve azimuth localization accuracy in comparison with sounds with a lower spectral complexity, as previously shown in [Morikawa and Hirahara \(2013\)](#). However, in the current study, these drastic changes in the spectrum did not strongly affect the participants' abilities, and the response patterns were similar. In other words, whatever the spectral complexity of the sound used in the encoding (white noise, complex tones or pure tones), binaural cues could be perceived and interpreted by the participants. It can be noticed that azimuth accuracy seems slightly higher with the two pitch-based encodings (the Harmonic and Monotonic encodings) in comparison with the spatialization-based only encoding (the Noise encoding). We did not find similar results in the scientific literature. This facilitation effect could result from a decrease in the cognitive load when the elevation is conveyed through the pitch modulation. As mentioned above, the pitch-based encodings seem more intuitive to localize the elevation, therefore it should globally decrease the cognitive load and thus facilitate the processing of the remaining dimension (i.e., the azimuth dimension). This effect does not seem to drastically shape the results and remains to be confirmed by other experiments.

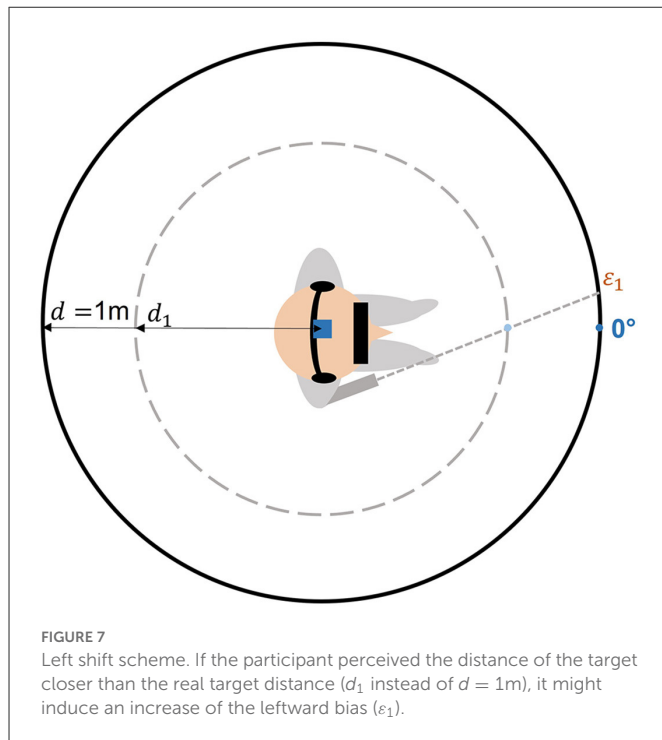
The participants tended to overestimate the lateral position of the lateral targets with the three visual-to-auditory encodings: a shift to the left for targets on the left, and a shift to the right for targets on the right. Some studies also showed an overestimation pattern of lateral sound sources while using non-individualized HRTFs ([Wenzel et al., 1993](#)), in a virtual environment while being blindfolded ([Ahrens et al., 2019](#)), using ambisonics ([Huisman et al., 2021](#)), and even with real sound sources ([Oldfield and Parker, 1984](#); [Makous and Middlebrooks, 1990](#)). A possibility to decrease this overestimation might be to rescale the used HRTF positions to fit to the perceived ones. For example one could rescale the azimuth angles of the HRTFs database to compensate for the non-linear shape that was measured as the perceived ones and measure if it could linearize the response profile.

The participants also tended to localize the targets with a leftward bias between  $-1.2$  and  $-5.03^\circ$  in average. This systematic error might be due to a wrong auditory localization but also to a misperception of target distance. Geometrical considerations shows that an underestimation of the distance of the sound source would generate a leftward bias as we see in the current results. Since no indication concerning the sound distance was given, the participants could estimate that the sound sources were located closer than one meter. [Figure 7](#) shows the effect of a misperception of target distance on the azimuth localization. However, for the same reason, a distance underestimation would have caused an overestimation of the elevation perception, which we did not measure.

## 4.3. A fast improvement in object localization performance

### 4.3.1. A short but active familiarization method

After a first practice followed by a very short familiarization, participants' abilities to localize an object with the visual-to-auditory



SSD were improved. The elevation gains were improved for all the encodings (especially for pitch-based ones), and for the azimuth, the decrease in the lateral overshoot suggests that the interpretation of acoustic cues provided by the ILD and ITD for the azimuth was improved. Since no feedback was given during the first practice, it can be supposed that the familiarization session mainly contributed to acquire sensorimotor contingencies (Auvray, 2004) through the mean of an audio-motor calibration (Aytekin et al., 2008).

In order to avoid a too long experimental session, we used a short audio-motor familiarization session (60 s) during which participants were active by controlling the position of the target, which is known to improve the positive effect of the training (Aytekin et al., 2008; Hüg et al., 2022). Other familiarization methods have been studied and have shown improvements in the use of SSDs. For example, prior to the experimental task, some studies simultaneously displayed to participants an image and its equivalent soundscape (Ambard et al., 2015; Buchs et al., 2021). In another study (Auvray et al., 2007), participants were enrolled in an intensive training of 3 h. Using only a verbal explanation of the visual-to-auditory encoding scheme as been shown to be efficient to understand the main principles of the encoding scheme (Kim and Zatorre, 2008; Buchs et al., 2021; Scalvini et al., 2022). The aim of the current study was not to directly investigate the effect of a short and active familiarization method on localization performance but it shows that a short practice might be sufficient to acquire the sensorimotor contingencies. The effect of the familiarization remains to be clearly assessed by comparing the efficiency of the existing methods with control conditions in order to optimize the SSD learning.

#### 4.3.2. Calibration of the auditory space improves localization abilities

In the current study, participants were not aware of the size of the VAS neither that the head tracker was associated with a virtual camera capturing and converting into sounds a limited portion of the virtual

scene in front of them. They only knew that the virtual target would appear at random locations in their front-field at different azimuth and elevation locations. As a consequence, they also did not know the spatial boundaries of the space where the target could be heard. After a short practice, the participants were able to build an accurate mental spatial representation of the virtual space where the visual-to-auditory encoding took place. For instance, the downward bias in elevation decreased after the familiarization session, suggesting that participants learned that the VAS was at a higher location. Also the decrease of the overestimation pattern in azimuth suggests that participants learned that the lateral VAS boundaries were closer.

It has to be noticed that the size of the VAS has an influence on the localization accuracy. The bigger the VAS is, the higher the localization error might be. Restricting the field of view of the camera would result in a smaller possible space in which an heard target could be placed, thus resulting in a lower angular error, but as a counterpart, it would cover a smaller subpart of the front-field without moving the head. For instance, for a target placed in a central position, a random pointing in a VAS with a field of view of  $45^\circ \times 45^\circ$  (azimuth  $\times$  elevation) would result in an error in azimuth and elevation with a standard deviation 2 times lower than with a field of view of  $90^\circ \times 90^\circ$  while covering a space 4 times smaller. Studying the effect of various VAS sizes in a target localization task in which the user can freely move the head to point to a target as fast as possible would probably give some insights about the optimal VAS size. However, in ecological contexts, a large VAS size would have the advantage of providing auditory information about obstacles placed with a larger eccentricity with respect to the forward direction of the head. For this reason, in a real context of use, this parameter should probably be customizable according to the habit of use.

## 5. Conclusion

Long trainings are required to master a visual-to-auditory SSD (Kristjánsson et al., 2016) because the used visual-to-auditory encodings are not enough intuitive (Hamilton-Fletcher et al., 2016b). In our study, we investigated several visual-to-auditory encodings in order to develop a SSD whose auditory information could quickly be interpreted to localize obstacles. In line with previous studies, our results suggest that a visual-to-auditory SSD based on the creation of a VAS is efficient to convey visuo-spatial information about azimuth through soundscapes. Our study shows that a pitch-based elevation mapping can be easily learn to compensate for elevation localization impairments due to the use of non-individualized HRTFs in the creation process of the VAS. Despite a very short period of practice, the participants were able to improve their interpretation of the used acoustic cues both for the azimuth and the elevation encoding schemes.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. The original contributions presented in the study will be made available in the following link: <http://leaderv.u-bourgogne.fr/en/members/maxime-ambard/pages/cross-modal-correspondance-enhances-elevation-localization>. Further questions should be directed to the corresponding author.

## Ethics statement

The studies involving human participants were reviewed and approved by Comité d’Ethique pour la Recherche de Université Bourgogne Franche-Comté. The patients/participants provided their written informed consent to participate in this study.

## Author contributions

CB and MA contributed to conception and design of the study and interpreted the data. CB executed the study and was responsible for data analysis and wrote the first draft of the manuscript in closed collaboration with MA. FS, CM, and JD provided important feedback. All authors have read, approved the manuscript, and contributed substantially to it.

## Funding

This research was funded by the Conseil Régional de Bourgogne Franche-Comté (2020\_0335), France and the Fond Européen de Développement Régional (FEDER) (BG0027904).

## Acknowledgments

Thanks to the Conseil Régional de Bourgogne Franche-Comté, France and the Fond Européen de Développement Régional (FEDER) for their financial support. We thank the Université de Bourgogne and le Centre National de la Recherche Scientifique (CNRS) for the providing administrative support and the infrastructure.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1079998/full#supplementary-material>

### SUPPLEMENTARY FIGURE 1

Elevation response position as a function of target elevation for each participant of the Monotonic group. Mean elevation response positions (in degree) before (**left**) and after (**right**) are represented separately for the Noise (blue squares) and the Monotonic (orange circles) encodings. Error bars shows standard error of elevation response position. Solid lines represent the elevation gains with the Noise (blue) and Monotonic (orange) encodings. Black dashed lines indicate the optimal elevation gain 1.0.

### SUPPLEMENTARY FIGURE 2

Elevation response position as a function of target elevation for each participant of the Harmonic group. Mean elevation response positions (in degree) before (**left**) and after (**right**) are represented separately for the Noise (blue squares) and the Harmonic (red circles) encodings. Error bars shows standard error of elevation response position. Solid lines represent the elevation gains with the Noise (blue) and Harmonic (red) encodings. Black dashed lines indicate the optimal elevation gain 1.0.

### SUPPLEMENTARY FIGURE 3

Azimuth response position as a function of target azimuth for each participant of the Monotonic group. Mean azimuth response positions (in degree) before (**left**) and after (**right**) are represented separately for the Noise (blue squares) and the Monotonic (orange circles) encodings. Error bars shows standard error of azimuth response position. Solid lines represent the azimuth gains with the Noise (blue) and Monotonic (orange) encodings. Black dashed lines indicate the optimal azimuth gain 1.0.

### SUPPLEMENTARY FIGURE 4

Azimuth response position as a function of target azimuth for each participant of the Harmonic group. Mean azimuth response positions (in degree) before (**left**) and after (**right**) are represented separately for the Noise (blue squares) and the Harmonic (red circles) encodings. Error bars shows standard error of azimuth response position. Solid lines represent the azimuth gains with the Noise (blue) and Harmonic (red) encodings. Black dashed lines indicate the optimal azimuth gain 1.0.



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