1 Sound source localization in virtual reality
2 with ambisonics sound reproduction

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10

11 Abstract

12 To reproduce realistic audio-visual scenarios in the laboratory, ambisonics is often
13 used to reproduce a sound field over loudspeakers and virtual reality (VR) glasses
14 are used to present visual information. Both technologies have been shown to be
15 suitable for research. However, the combination of both technologies, ambisonics
16 and VR glasses, might affect the spatial cues for auditory localization and thus, the
17 localization percept. Here, we investigated how VR glasses affect the localization of
18 virtual sound sources on the horizontal plane produced using either 1st, 3rd, 5th or
19 11th order ambisonics with and without visual information. Results showed that
20 with 1st order ambisonics the localization error is larger than with the higher orders,
21 while the differences across the higher orders were small.

22 The physical presence of the VR glasses without visual information increased the
23 perceived lateralization of the auditory stimuli by on average about 2°, especially in
24 the right hemisphere. Presenting visual information about the environment and
25 potential sound sources did reduce this HMD-induced shift, however it could not
26 fully compensate for it. While the localization performance itself was affected by
27 the ambisonics order, there was no interaction between the ambisonics order and
28 the effect of the HMD. Thus, the presence of VR glasses can alter acoustic
29 localization when using ambisonics sound reproduction, but visual information can
30 compensate for most of the effects. As such, most use cases for VR will be
31 unaffected by these shifts in the perceived location of auditory stimuli.

32

33 Introduction

34 With the recent increase in quality and availability, head mounted virtual reality
35 displays (HMDs) are now regularly used in combination with virtual sound
36 environments to create more realistic and immersive audiovisual experiments (e.g.,
37 [1–3]). Although for many studies, headphones might suffice as the playback
38 method for this acoustic environment, there are also many cases where
39 loudspeaker playback might be preferred to preserve the participants own head-
40 related transfer function or to be able to wear hearing aids or other ear-worn
41 devices. This is where potential problems can arise, as recent studies have shown
42 that HMDs affect the acoustic signals [4–6].

43 The shape of the ear, head and body modify sound as it reaches the ear,
44 resulting in interaural level differences, interaural time differences and spectral
45 changes which are used for the localization of sound sources (for an overview see
46 [7] or [8]). The added volume of the HMD modifies these cues, increasing the
47 lateralization of the perceived location of stimuli [4,6]. Such changes in the
48 perceived location of the sound could not only affect the perceived spatial location
49 of a sound, but also the integration of audio-visual stimuli.

50 Current experiments have only assessed the effect of the HMD when
51 presenting sound from a single loudspeaker. However, VR will regularly require
52 more complex playback methods to be able to present spatial audio from any
53 location, independent of the loudspeaker setup. Ambisonics is a commonly used
54 playback method for such a purpose. It encodes audio by decomposing a sound
55 field into spherical harmonics and can provide full-sphere surround sound [9]. In its

56 basic form (1storder ambisonics), four channels corresponding to the first four
57 spherical harmonics are used to encode the sound field. However, additional
58 spherical harmonics can be included to improve the directional resolution of the
59 reproduction [9–11], referred to as higher-order ambisonics (HOA). To accurately
60 reproduce the encoded sound field, the number of loudspeakers should match the
61 number of spherical harmonics used for the encoding. Thus, at least $(n + 1)^2$
62 loudspeakers are needed for a full spherical representation and $2n + 1$
63 loudspeakers for horizontal-only, where n is the ambisonics order. An increase in
64 ambisonics order has been shown to result in an increased localization accuracy
65 [10,12–14].

66 Ambisonics reproduces the sound field through interactions of the audio
67 signals from multiple loudspeakers simultaneously, independent of the direction of
68 the source. Thus, the effect of the HMD on sound localization that has been shown
69 with single loudspeaker playback, might be different when employing ambisonics
70 reproduction.

71 In virtual audio-visual scenes the audio is not presented in isolation, but in
72 combination with visual information, which is known to strongly influence sound
73 localization (e.g., [15–17]). When audio and visual stimuli are presented in close
74 temporal and spatial proximity, they are integrated into one common percept,
75 increasing the accuracy and precision of localization (e.g., [18–20]). As a result of
76 this process, when the audio and visual stimuli are not exactly at the same position,
77 but still integrated, the perceived location of the auditory stimuli is shifted strongly
78 towards that of the visual stimulus (the so called ‘ventriloquist effect’, e.g., [18,21–

79 23]). Therefore, it is possible that potential shifts caused by the HMD can be
80 compensated for with visual information. Indeed, when presenting visual
81 information about the environment and potential sources, such as loudspeakers,
82 Ahrens et al. [6] saw a decrease in the effect of the HMD on sound source
83 localization, compared to when no visual information was presented.

84 The aim of the current study was, to investigate the effects and the
85 interactions between the HMD, ambisonics and visual information on the perceived
86 sound location. Therefore, a sound localization experiment with hand-pointing was
87 performed. Participants located sound sources which were simulated from angles
88 between -90° to 90° azimuth, using 1st, 3rd, 5th and 11th order ambisonics, with and
89 without an HMD. Participants were first tested blindfolded, to avoid biasing effects
90 of any visual information. Next, they performed the same localization task with
91 visual information to test if visual information can compensate for potential effects
92 of the HMD.

93

94 **Methods**

95 **Participants**

96 21 participants (9 females and 12 males, average 25 ± 3 years) were recruited to
97 participate in the experiment. To ensure normal hearing, audiometric thresholds
98 were measured at octave frequencies between 125 and 8 kHz. Data from
99 participant 7 were excluded due to audiometric thresholds above 20 dB HL. Data
100 from the remaining 20 participants were used in the analysis. The participants were

101 compensated with an hourly rate of 122 DKK. The experimental procedure was
102 approved by the Science-Ethics Committee for the Capital Region of Denmark (H-
103 16036391) and all participants provided written informed consent.

104

105 Acoustic reproduction

106 The experiment took place in the Audio-Visual-Immersion Lab (AVIL) shown in Fig
107 1, left panel. AVIL is an anechoic chamber containing 64 KEF LS50 loudspeakers,
108 placed in a 4.8 m diameter sphere around a height adjustable chair. For this
109 experiment, only the horizontal ring, containing 24 loudspeakers spaced
110 equidistantly (15° separation), was used for sound reproduction. Audio signals were
111 generated in MATLAB (The Mathworks, Natick, MA) and sent, via 2 TESIRA biamp
112 DSPs with TESIRA SOC-4 Audio DSP cards (biamp Systems, Beaverton, OR), to the
113 amplifiers (Sonible GmbH, Graz, Austria) that drive the loudspeakers.

114

115 **Fig 1. Experimental setup.** AVIL (left) and the 1:1 model of AVIL (right). The rightmost loudspeakers,
116 12 and 13, are not shown.

117

118 Visual reproduction

119 The virtual environment, shown in Fig 1 (right panel), was a 1:1 reproduction of
120 AVIL. This environment was created in UNITY3D (Unity Technologies, San Francisco,
121 CA) and presented via an HTC VIVE PRO (HTC Corporation, New Taipei City, Taiwan)
122 VR setup. Three HTC VIVE trackers at known positions were used to ensure the
123 spatial alignment between the real and virtual world, by recalibrating the virtual
124 world if discrepancies larger than 1 cm occurred (see Ahrens et al., 2019 for details).
125 When the HMD was not in use, it was placed in front of the participant in sight of
126 the HTC lighthouses that track the position of the HMD and the handheld
127 controllers, to ensure proper calibration of the virtual world also during the real-
128 world conditions.

129

130 Pointing apparatus

131 A handheld HTC VIVE controller was used to record the localization judgements of
132 the participants in all conditions. By pressing the trigger button on the back of the
133 controller, their judgement was recorded. A model of this controller was rendered
134 in the virtual environment, however there was no physical representation of the
135 participants themselves in the virtual environment. As it was hypothesized that
136 visual information of the body could affect pointing, a condition was included to
137 measure the difference in pointing at visual targets in the real and virtual
138 environment. In the conditions where this pointing bias might have affected data

139 (i.e., when participants had access to visual information), a correction for this
140 pointing bias was applied.

141

142 **Stimuli and spatialization**

143 The stimuli were created in MATLAB. The auditory stimulus consisted of a 240 ms
144 pink noise burst with a 20 ms ramp, raised cosine window. The stimuli were
145 presented, on average, at 65 dB sound pressure level (dB SPL). To reduce directional
146 loudness cues [24,25] the sound level was roved by values drawn from a uniform
147 distribution between ± 3 dB. The stimuli were spatialized using ambisonics panning
148 [9]. The highest order ambisonics that can be reproduced with a 24-loudspeaker
149 array in the horizontal plane is 11th order. To decrease the ambisonics order, the
150 number of loudspeakers used to produce the stimulus was reduced and the
151 decoder was adjusted accordingly. In this manner stimuli were presented in 1st, 3rd
152 and 5th order ambisonics, using, respectively, 4, 8 and 12 loudspeakers, spaced
153 equidistantly. The individual loudspeakers used to reproduce each ambisonics
154 order are indicated in Fig 2. Stimuli were presented from -90° to 90° azimuth in 7.5-
155 degree steps, i.e., at each loudspeaker and halfway in between each loudspeaker.
156 Each position was repeated five times for each condition.

Fig 2. Loudspeakers used per ambisonics order. The loudspeakers used for the reproduction of 1st, 3rd, 5th and 11th order ambisonics, respectively. The loudspeaker pictogram indicates the loudspeaker positions and the colouring the loudspeakers that were used for each of the ambisonics order conditions.

Pointing bias

To measure the potential pointing bias, participants were asked to point, both in the real environment and in the virtual environment, at static visual targets, namely the loudspeakers. As shown in Fig 1, the loudspeakers, that were positioned between -90° to 90° azimuth, were numbered from 1 to 14. In this task, participants were shown a number, either on a virtual screen in VR or on an iPad that was placed in front of the participant, and then pointed, in the same manner as in the auditory localization task, at the center of the loudspeaker with that number. The iPad and the virtual screen were only present during this task.

Experimental conditions

The experiment consisted of six conditions, presented in three blocks (see table 1). The blocks were presented in a fixed order, but within a block, the order of the

conditions was counterbalanced across participants. The various ambisonics orders were tested interleaved, i.e., within each condition the stimuli were presented in all ambisonics orders. To investigate the effect of the HMD, without any visual biases, participants performed the localization experiment blindfolded in the first block. For the condition with the HMD, the HMD was placed over the blindfold. The second block then investigated if visual information could compensate for the potential effects of the HMD found in the first block. Finally, in the third block, the potential pointing bias, due to the lack of a physical representation of the participants in VR, was measured. Since participants did not have access to any potential biasing visual information in the blindfolded condition, no corrections were applied here. Each acoustic condition started with 20 training trials to ensure participants understood and followed the instructions with regards to pointing and how to proceed through the block. The different conditions are summarized in table 1 below.

Table 1. Experiment conditions.

<i>Block</i>	<i>Condition</i>	<i>Visual information</i>	<i>HMD</i>	<i>Stimulus</i>
1	1	Blind-folded	No	Acoustic
	2	Blind-folded	Yes	Acoustic
2	3	Real environment	No	Acoustic
	4	Virtual environment	Yes	Acoustic
	5	Real environment	No	Visual

3

6

Virtual environment

Yes

Visual

191 The experiment was divided into six conditions presented in three blocks. Blocks were presented in a
192 fixed order, but within a block, conditions were counterbalanced across participants.

193

194 Procedure

195 The experiment was conducted in two sessions with a maximum of 2.5 hours, with
196 at least three enforced breaks per session (halfway through and in-between
197 blocks). At the start of the experiment, participants were told that sounds would
198 be presented using an ambisonics sound system which could simulate sounds from
199 anywhere in the room. They were instructed to face forward from their seated
200 position before and during each stimulus, and to point with the controller at the
201 direction where they perceived the sound originated from. After stimulus
202 presentation, the participants were allowed to freely turn around while pointing.
203 After indicating the perceived origin of the stimulus, participants faced forward
204 again and 1.5 seconds after recording the response, the next stimulus played
205 automatically. Participants were instructed to use their entire arm and fixate their
206 wrist whilst pointing and to maintain the same pointing method throughout the
207 experiment. Finally, participants were encouraged to take additional breaks during
208 the experiment (besides the aforementioned three breaks per session) if they
209 needed them.

210 Participants were then guided into the experimental room, seated at the
211 center of the array and were shown the VR headset. In the first block they were

212 then blindfolded and, depending on the condition, were either fitted with headset
213 or the headset was placed in front of them. In the conditions with visual information
214 participants were fitted with the headset and given the option to adjust the settings
215 to their preferences. The non-rotating chair was then raised to ensure their ears
216 were positioned at height of the loudspeakers.

217

218 **Analysis**

219 **Pointing bias**

220 For the calculation of the pointing bias, responses with an error larger than 15°
221 were treated as outliers and removed from the analysis. 0.011% of the visual trials
222 were rejected based on this criterion. For every participant, the mean pointing bias
223 was then calculated per visual stimulus location in both the real and virtual
224 environment. For the stimuli presented in between loudspeakers, where no
225 pointing bias was measured, the subtracted pointing bias was calculated by linearly
226 interpolating the nearest measured pointing biases. Each response in the second
227 block (with visual information) was then corrected by subtracting the individual
228 pointing bias, i.e., same participant, environment, and location. The visual
229 localization data itself (without the interpolated data points) was also analyzed. For
230 this, a mixed linear model was fitted to the responses with the stimulus location
231 and experimental condition as fixed effects, while the participants and repetitions
232 were considered as random effects. For the computational analysis, the statistical
233 software R [26] was used together with the “lmerTest” package [27].

234 Auditory localization

235 No outlier removal was conducted on the acoustic localization data. As participant
236 20 was left-handed, data from the left and right hemisphere was flipped for the
237 analysis. For the statistical analysis of the auditory localization responses, a mixed
238 linear model was fitted to the azimuth error using the same computational
239 methods as for the pointing bias. The stimulus location, ambisonics order and
240 condition were considered fixed effects, while the participants and repetitions were
241 considered as random effects. To investigate how the different factors affected the
242 localization performance, post-hoc analyses of within factor comparisons were
243 performed. To determine the effect of the HMD, the blindfolded conditions with
244 and without the HMD were compared. To find the effect of visual information on
245 this effect, results between block one and two were compared.

246

247 Results

248 Pointing bias

249 Fig 3 shows the signed pointing error to visual objects for the real (blue) and virtual
250 (orange) environment. The pointing error is defined as the difference between the
251 response angle and the source angle in degrees azimuth. A large variation in
252 pointing behavior across participants can be seen, especially at more eccentric
253 angles. Additionally, a shift in the pointing direction towards the left side (negative
254 angles) can be seen in the virtual environment relative to the real environment. The
255 statistical analysis of the responses showed a significant difference between the

256 pointing in the real environment versus pointing in the virtual environment [$F_{1,2563}$
 257 $= 166.294$, $p < 0.0001$]. The post-hoc comparison estimated the effect size between
 258 the real and the virtual environment to be 1.76° [$t(2563) = 12.896$, $p < 0.0001$].
 259 Additionally, an effect of the stimulus location was found [$F_{12,2563} = 49.953$, $p <$
 260 0.0001], but no significant interaction between the environment and the stimulus
 261 location [$F_{12,2551} = 1.309$, $p = 0.2058$].

262
 263 **Fig 3. Pointing bias with (orange) and without HMD (blue).** The pointing bias in the visual pointing
 264 task is shown per angle for both the virtual (VE) and the real (RE) environment. The dots indicate the
 265 mean pointing error per person and the boxplot shows the distribution. The boxes extend from the
 266 first to the third quartile, with the median shown as the center black line.

267

268 Effect of ambisonics order

269 Fig 4 shows the signed localization error, that is the difference between the
 270 response angle and the source angle in degrees azimuth, as a function of the source
 271 angle for the different ambisonics orders. As no interaction between the conditions
 272 and the ambisonics order was found, data from all conditions are included in this

273 figure. The localization error was found to vary with the stimulus location [$F_{24,39806}$
 274 = 142.178, $p < 0.0001$] and ambisonics order [$F_{3,39806} = 29.631$, $p < 0.0001$]. Moreover,
 275 a significant interaction between the ambisonics order and the stimulus location
 276 was found [$F_{72,39806} = 73.144$, $p < 0.0001$]. A discrepancy between 1st order
 277 ambisonics responses and higher order ambisonics responses can be seen. This
 278 difference was significant at all angles, except at 7.5°-22.5° (1st - 3rd, [7.5°: $t(39806)$
 279 = -0.618, $p = 1.00$], [15°: $t(39806) = -1.372$, $p = 1.00$], [22.5°: $t(39806) = -2.175$, $p =$
 280 0.1778]; 1st - 5th, [7.5°: $t(39806) = -1.207$, $p = 1.00$], [15°: $t(39806) = -1.372$, $p = 1.00$];
 281 1st - 11th, [7.5°: $t(39806) = -1.015$, $p = 1.00$]). As can be seen in Fig 4, for the 1st order
 282 ambisonics results, the absolute localization error increased with the absolute
 283 source azimuth. Such consistent increase of error with azimuth was not found when
 284 higher ambisonics orders were used to simulate the sources. For all ambisonics
 285 orders, at the outermost angles, i.e., ± 82.5 -90°, the simulated sources were
 286 perceived insufficiently lateralized. Here again results were most pronounced when
 287 1st order ambisonics was used. With the 1st ambisonics order, the localization error
 288 reached $\pm 30^\circ$ at $\pm 90^\circ$ azimuth, i.e., participants perceived the source two entire
 289 loudspeakers closer to the center. For sources reproduced using higher ambisonics
 290 orders this discrepancy was highly reduced, although not fully diminished. Few
 291 differences were found between the perceived location of the presented sources
 292 with the ambisonics orders larger than one; a small decrease in error was observed
 293 when increasing the ambisonics order at the outer source angles (3rd-5th, [90°:
 294 $t(39806) = -4.172$, $p = 0.0002$]; 3rd-11th, [82.5°: $t(39806) = -3.889$, $p = 0.0006$], [90°:
 295 $t(39806) = -4.099$, $p = 0.0002$]). Besides that, there was a small difference between

296 3rd and 5th order at -67.5 ° [$t(29806) = 2.727, p = 0.0384$] and 5th and 11th order
 297 ambisonics at 52.5° [$t(29806) = -2.770, p = 0.0337$]. At all other angles no significant
 298 difference within the higher ambisonics orders were found.

299
 300 **Fig 4. Localization error for the various ambisonics orders.** The perceived source angle is plotted as a
 301 function of the stimulus position. Data from all acoustic conditions are included in the figure, except
 302 for 450 outliers (1.125 %) that occurred outside of the figure boundaries (localization error larger than
 303 $\pm 65^\circ$). Data are separated by the ambisonics order used to produce the stimuli. The boxes extend
 304 from the first to the third quartile, with the median shown as the center black line. Responses that
 305 exceeded 1.5 times the interquartile range are considered outliers and are indicated as dots.

306

307 Effect of the HMD

308 The localization error in the blindfolded conditions is shown in Fig 5. Data without
 309 the HMD are shown in blue and data with the HMD are shown in orange. The
 310 localization error varied with presentation angle [$F_{24,39806} = 142.178, p < 0.0001$] and
 311 depended on the condition, i.e., with or without the HMD [$F_{3,39806} = 59.077, p <$

0.0001]. Additionally, a significant interaction was found between the presentation angle and the condition [$F_{72,39806} = 12.819$, $p < 0.0001$]. At negative angles, i.e., in the left hemisphere, the localization error tended to be more negative, i.e., sources were perceived more to the left, when wearing the HMD, compared to when participants were not wearing the HMD. At positive angles, i.e., in the right hemisphere, instead sounds were perceived more to the right when wearing the HMD. The post-hoc analysis showed that the increase in the perceived lateralization of the sound sources when wearing the HMD was larger in the right hemisphere than in the left hemisphere. In the right hemisphere the difference in the conditions was significant at all angles ($7.5^\circ - 67.5^\circ$, $p < 0.0001$; 75° , $p = 0.0001$; 82.5° , $p = 0.0073$; 90° , $p = 0.0152$). In the left hemisphere, the effect of the HMD only reached statistical significance at -82.5° [$t(39806) = 3.209$, $p = 0.0080$] and -37.5° [$t(39806) = 2.692$, $p = 0.0427$]. Furthermore, the difference between the conditions with and without HMD was less pronounced in the left hemisphere; the maximum difference between the RE (without HMD) and VE (with HMD) was 3.5° in the left hemisphere, and between 3.7° and 8.4° in the right hemisphere.

Fig 5. The localization error in the blindfolded conditions with (orange) and without (blue) HMD.

Due to the discrepancy in the first versus higher order ambisonics data, only higher order (3rd, 5th, 11th) ambisonics data is included in the figure. The boxes extend from the first to the third quartile, with the median perceived response shown with black lines. Responses that exceeded 1.5 times the interquartile range are considered outliers and are indicated as dots. 158 outliers (0.527%) are not shown as they occurred outside of the figure boundaries (localization error larger than $\pm 65^\circ$).

Effect of visual information

Fig 6 shows the effect of the HMD when visual information is present. Data from the condition without the HMD is shown in blue and data from the condition with the HMD is shown in orange. Although, at most angles, the disparity between the two conditions was reduced either partially or fully, compared to the disparity in Fig 5, significant differences between the RE and VE condition remained. In the left hemisphere a significant difference was still found at -60° azimuth [$t(39806) = 3.181$, $p = 0.0088$], while in the right hemisphere significant differences remained at several angles ($[0^\circ: t(39806) = -3.386$, $p =$

0.0043], [7.5°: $t(39806) = -4.238$, $p = 0.0001$], [22.5°: $t(39806) = -3.629$, $p = 0.0017$],
 [45°: $t(39806) = -2.643$, $p = 0.0493$], [52.5°: $t(39806) = -5.223$, $p < 0.0001$], [60°:
 $t(39806) = -3.677$, $p = 0.0014$], [67.5°: $t(39806) = -2.822$, $p = 0.0287$]). These
 difference between Figs 5 and 6 shows that visual information of the loudspeaker
 locations affected the localization error.

Fig 6. Boxplot of the (pointing bias corrected) localization error with (orange) and without HMD (blue) in the conditions with visual information. Only higher order ambisonics data is included in the figure. The boxes extend from the first to the third quartile, with the median perceived response shown with black lines. Responses that exceeded 1.5 times the interquartile range are considered outliers and are indicated as dots. 142 outliers (0.473%) are not shown as they occurred outside of the figure boundaries (localization error larger than $\pm 65^\circ$).

Moreover, a pattern in the localization error was found, which was consistent with participants pointing at visual loudspeakers locations. From Fig 6 it can be seen that the error is smaller at integer multiples of 15° than at the other angles. As sound was presented not only at exact loudspeaker positions (integer multiples of 15°), but also halfway in between, it was hypothesized that the visual information of the

loudspeaker location might have an effect on the response pattern. To more clearly investigate this behavior, data from Fig 6 (right hemisphere only) was replotted in Fig 7.

Fig 7. Violin plot of the (pointing bias corrected) localization error with (orange) and without HMD (blue) in the conditions with visual information, right hemisphere data only. The distributions of the localization error are shown as function of the azimuth location when visual information is presented. Both the environment (RE and VE) as well as the presence of a loudspeaker at the azimuth location are color-coded. The violin plot shows the spread of the responses per angle and per condition, in the form of a sideways histogram. Only higher order ambisonics data, right hemisphere, are included. 86 outliers (1.103%) are not shown as they occurred outside of the figure boundaries (localization error larger than $\pm 65^\circ$).

Fig 7 shows the data from Fig 6, as a violin plot, where the probability density of the responses is shown per azimuth angle. Darker colors indicate that the sound was simulated at an angle with a loudspeaker, while the lighter colors indicate that sound was presented halfway in-between loudspeakers. At small angles, when sound sources were simulated at loudspeaker locations, the errors were unimodally distributed around 0° localization error. When sound was instead simulated in

380 between loudspeakers, responses were bimodally distributed, i.e., responses were
 381 split between the two closest loudspeakers. At larger source angles, multiple peaks
 382 can be seen in the distributions. The centers of these peaks remain consistent with
 383 loudspeaker locations.

384

385 Mean results

386 Fig 8 shows the mean absolute localization error for the acoustic conditions,
 387 separated by ambisonics order and condition. The benefit of using higher order
 388 ambisonics, compared to 1st order ambisonics is clearly visible in the reduced
 389 localization error. Additionally, visual information, indicated in light colors,
 390 decreases the localization error when higher order ambisonics is used. Finally, the
 391 effect of the HMD can be seen when comparing the blue and the orange boxes, as
 392 an increase in the localization error for the higher ambisonics orders.

393

394 **Fig 8. The mean absolute localization error per condition, separated by ambisonics order.** The
 395 average localization error was grouped by angle, condition, and azimuth, after which the mean
 396 localization error was calculated. The boxes extend from the first to the third quartile, with the median

397 perceived response shown with black lines. Responses that exceeded 1.5 times the interquartile range
398 are considered outliers and are indicated as dots.

399

400 Discussion

401 Shift in the perceived location due to the HMD

402 As in Ahrens et al. [6] and Gupta et al. [4], we found that the HMD increased the
403 perceived lateralization of the stimuli. Interestingly, despite the symmetric setup,
404 this effect was found to be stronger in the right hemisphere. In the left hemisphere,
405 there was a similar trend in the data, but it was much smaller and not significant.
406 In contrast, Ahrens et al. [6] found the larger effect in the left hemisphere (although
407 significance levels were only reached at few stimulus positions, which might be
408 related to fewer participants). In both the RE blindfolded and VE blindfolded
409 indications of bias were found. In the RE participants tended to point slightly more
410 to the left, whereas in the VE participants tended to point slightly more towards
411 the right. Together these biases might have increased the effect of the HMD in the
412 right hemisphere, while decreasing the effect in the left hemisphere. Interestingly
413 this difference remained also in the visual condition, although strongly reduced.
414 The distribution of the responses showed that, when in doubt, participants tended
415 to favor the closest loudspeaker to the left more often in the RE, whereas in the VE
416 they tended to favor the closest loudspeaker to the right. To confirm this, we
417 calculated the percentage of responses that occurred to the right of the actual
418 position. In the right hemisphere, 38.05% of the responses occurred to the right of

419 the speaker in the RE, compared to 49.85% in the VE. That the effect occurred in
420 both the blindfolded and the visual condition suggests that there was some
421 consistent effect of the HMD. It could be that the HMD affects pointing also when
422 there is no visual information, potentially due the size and weight of the HMD.

423

424 Ambisonics order does not influence the effect of the 425 HMD

426 Although it was hypothesized that the effect of the HMD might vary with
427 ambisonics order, no such interaction was found. Localization itself, however, was
428 clearly affected by ambisonics order. Firstly, when using 1st order ambisonics,
429 stimuli were consistently perceived slightly more towards the center, especially at
430 the most extreme angles. This difference between the intended location and the
431 perceived location was large enough that responses were regularly shifted by an
432 entire loudspeaker at the outer angles in the condition where visual information
433 was available. This suggests that the 1st order ambisonics system could not fully
434 achieve the intended lateralization. This “under lateralization” of the stimuli was
435 also found by Pulkki & Hirvonen [12], who also found that the lateralization
436 appeared capped between 60-70° azimuth. As in previous studies [10,12–14],
437 increasing the ambisonics order from 1st to 3rd, greatly improved lateralization.
438 Increasing the ambisonics order further, however, did not improve localization
439 much, again in line with previous studies [14]. Similar effects of the ambisonics
440 order have also been shown for speech intelligibility [11].

441 **Some compensation from visual information**

442 Visual information strongly affected the responses of the participants and reduced
443 the effect of the HMD at many locations. However, due to stimuli being presented
444 also in between loudspeakers, it did not always improve localization. Similarly, the
445 tendency to point at loudspeakers also increased the effect of the HMD at some
446 locations where the HMD shift affected which loudspeaker was perceived as the
447 nearest (see for example Fig 6, 52.5°). In the right hemisphere visual information
448 reduced the effect of the HMD at almost all angles. In the left hemisphere, the
449 results were mostly unaffected by visual information, as the difference between
450 the VE and RE were already very small. Nevertheless, significant differences
451 between localization with and without the HMD remained. However, these
452 remaining differences can also be the result of the correction applied.

453

454 **Limited impact on VR**

455 As visual information compensated for most of the effect of the HMD, it is likely
456 that in most use-cases, such as playing audiovisual recordings, VR games etc. the
457 effects of the HMD will be negligible. Even if the effects are not fully compensated
458 for, it is likely that presence (“the feeling of being there”), one of the key factors of
459 VR, remains unaffected. Presence has been shown to be facilitated by audio [28–
460 31], especially spatialized audio [32,33]. However, the accuracy of the spatialized
461 audio was found not to influence presence [32]. Moreover, the shift in the
462 perceived location in the frontal area (where we are most sensitive to spatial

audiovisual disparities) is within the spatial distance where visual and auditory stimuli are integrated [22,23,34,35], as a result, integration of the audiovisual scenes should be mostly unaffected. However, because a shift in the perceived location of the auditory stimulus is present, it will be important to take the effect of the HMD into account in experiments where the exact positioning of the stimuli is relevant, such as audio (-visual) localization experiments.

Conclusion

In line with previous studies, we found that the HMD increased the perceived lateralization of auditory stimuli, especially in the right hemisphere. In the left hemisphere the effect was much smaller and only significant at a few angles. However, significant effects mostly occurred in the right hemisphere. Although an interaction between the ambisonics order used to present the stimuli and the effect of the HMD was hypothesized, no such interaction was found. Localization itself, however, was found to be strongly affected by the ambisonics order. Sounds presented with 1st order ambisonics were generally perceived to be originating from a more central location. This “under lateralization” of the stimuli increased with azimuth, reaching an error of up to 30° at a source angle of 90°. Increasing the ambisonics order from 1st to 3rd order greatly improved the accuracy of the reproduction, however increasing the order beyond this only minimally affected the localization accuracy at a few angles. Finally, visual information lead to a compensation for most of the effect of the HMD, but not fully, as significant

485 differences between the RE and VE conditions remained. The impact of this shift in
486 the perceived location is likely small, but in cases where the exact location of the
487 stimuli is important, it will be important to account for effects of the HMD on the
488 auditory stimuli.

489

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496

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