Towards Plausibility of Audiovisual Simulations in the Laboratory: Methods and First Results from Subjects with Normal Hearing or with Hearing Impairment

Plausibilität audiovisueller Simulationen im Labor: Methoden und erste Ergebnisse von Probanden mit normalem Hörvermögen oder mit Hörbeeinträchtigung

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Abstract: This study addressed the replication of two everyday life communication conditions: an urban street and a conversation in a cafeteria, in the laboratory using virtual audiovisual environments, and compared subject experience in this audiovisual laboratory environment with the corresponding real-life condition. Experiences were assessed using questionnaires and interviews addressing relevant factors, in particular the general presence, spatial presence, involvement and realism. Data were collected with N = 21 users (51 to 72 yrs.) in two situations (street traffic and cafeteria), using two hearing aid (HA) modes (unaided and omnidirectional HA microphone mode) in seven experienced HA users (EXPU), in seven first-time HA users with hearing impairment (FTU), and in seven age-matched subjects with normal-hearing (NH). Both the questionnaire focusing on aspects of presence and the interview responses showed that the virtual acoustic replication in the laboratory condition was evaluated as being plausible compared to the real-life experience, whereas subjects found the visual simulation to be less plausible in terms of visual detail and the presentation of movement.

Keywords: Sense of presence, plausibility, hearing aids, hearing loss, audiovisual environments

Zusammenfassung: Diese Studie befasste sich mit der Replikation von zwei alltäglichen Kommunikationsbedingungen. Eine Stadtstraße und eine Unterhaltung in einer Cafeteria wurden im Labor als virtuelle audiovisuelle Umgebungen simuliert und für die Studie verwendet. Verglichen wurde die Erfahrung der Probanden in dieser audiovisuellen Laborumgebung mit entsprechenden realen Alltagsumgebungen. Die Erfahrungen wurden anhand von Fragebögen und Interviews bewertet, die relevante Faktoren, insbesondere die generelle Präsenz, räumliche Präsenz, Einbindung und Realität, berücksichtigten. Erhoben wurden die Daten in zwei Situationen (Straßenverkehr und Mensa) mit N = 21 Probanden im Alter von 51-72 Jahren in Bezug auf zwei Hörgerätemodi (HG) (unversorgt und omni-direktionaler HG-Mikrofonmodus) mit sieben erfahrenen HG-Nutzern (EXPU), sieben erstmaligen HG-Nutzern mit Hörminderung (FTU) und mit sieben gleichaltrigen Probanden mit normalem Hörvermögen (NH). Der Präsenzfragebogen und das Interviewmaterial zeigten, dass die virtuell akustische Replikation im Labor als plausibel im Vergleich zur realen Erfahrung bewertet wurde, während die visuelle Simulation in Bezug auf visuelle Details und Bewegung als weniger plausibel erlebt wurde.

Stichwörter: Präsenz, Plausibilität, Hörgeräte, Hörminderung, audiovisuelle Umgebungen

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List of abbreviations:
HI: Listeners with hearing impairment; NH: Subjects with normal hearing; HA: Hearing aids; FTU: First-time hearing-aid users
EXPU: Experienced hearing-aid users

1. Introduction

In previous research on hearing aids (HA), various traditional laboratory studies have been carried out (e.g., Ricketts and Mueller, 1999; Henry and Ricketts, 2003; Bentler, 2005; Brimijoin et al., 2014; Picou, et al., 2014; Latzel et al., 2018). The aim of these studies was to explore different characteristics of HA processing and to make HA functions more effective, helpful or beneficial. However, it remained unclear whether and how these results were indicators of day-to-day use of HA (Meis et al., 2018; Wolters et al., 2016).

In general, audiological research with regard to applied science is a trade-off between external validity and reliability (Bengel and Koch, 2013). On the one hand, experiments can be repeatedly carried out in conventional measuring booths, but everyday behavior of subjects can hardly be studied there. Research under everyday life conditions, on the other hand, is also associated with obstacles. Even though everyday behavior can be observed in daily life situations, environmental phenomena are not as reproducible or quantifiable as they are in controlled laboratory environments. Everyday life is still too complex to enable exploration of the operation modes of HA to satisfy the scientific criteria of reproducibility and reliability (Abbott, 2004; Brungart et al., 2014). Laboratories in which virtual realities are used may be an intermediate step for audiological research (Aspöck et al., 2018; Devesse et al., 2017; Grimm et al., 2016; Seeber et al., 2012; Stecker et al., 2018).

Of course, the term virtual reality has many imprecisions. To clarify the research discourse, therefore, the concepts of telepresence and presence are proposed here, which are also used in information-theoretical research. The term telepresence refers to the passive experience of being present in simulated environments through technological tools. Presence, however, is experienced if a subject does not differentiate between whether sensory impressions are evoked because of technical artifacts or whether they are real. Telepresence refers to the factor of technological mediation, presence to the subjective experience (Thimm, 2004, p. 57, see also Lombard and Ditton, 1997). Recently, Bailenson (2018) analyzed the sense of presence in virtual worlds from a psychological perspective. He understood experience as a key analytic concept. In his opinion, the use of head-mounted displays meant that virtual environments are no longer experienced as an artificial, but as an actual experience. The reference to a screen still allows for real-world cues, whereas the use of head-mounted displays is perceived as fully immersive. A comparison to such technologies as head-mounted displays is not the aim here (Paluch, 2019). However, the work of Bailenson and colleagues demonstrates the relevance of presence, immersive technologies, and experience, for which reason we focus on the subjective experience in the form of presence (Cummings and Bailenson, 2016).

Recent studies have shown that including visual cues is important when evaluating hearing aids using measures related to movement behavior (Hendrikse et al., 2018b) and when evaluating the speech intelligibility (Meister et al., 2016). These studies have used animations to present the visual information. Nonetheless, it remained open to what extent the animated environments correspond to everyday life and whether they have an analogous influence on the behavior of the test subjects as do real-world environments.

Some earlier studies examined whether laboratories with virtual environments evoke everyday experiences (e.g., Bishop and Rohrmann, 2003; Luigi et al., 2015; van der Ham et al., 2015), but with no special emphasis on audiological research. For this reason, we conducted an exploratory study and evaluated the plausibility of an audiovisual laboratory. The test subjects (N = 21), seven subjects with normal hearing (NH), seven first time hearing-aid users (FTU), and seven experienced hearing-aid users (EXPU), participated in procedures under real-life conditions, which were then recreated in the laboratory. In twenty-eight study trails (the seven FTU participated both unaided and aided) they experienced the real street and the campus cafeteria and the corresponding virtual environments and pointed out similarities, differences and interrelations. Although the experimental procedures in the field were similar, it was not possible to standardize sound levels or to control environmental factors in the open-field situation (for a precise description see Paluch et al., 2017 and, for first open-field results, Paluch et al., 2018a). Each phase of the twenty-eight study trials in the open field thus represented an independent situation with independent characteristics (similar to Lindemann and Matsuzaki, 2014; Straub, 2016). However, the test subjects were able to compare the animated laboratory environments with the real-world environments (for first laboratory results see Paluch, 2019; Paluch et al., 2018b).

Ultimately, the goal of this work was to examine how plausible the virtual environment in the laboratory was. We measured plausibility using different techniques. Most importantly, we used standardized and open-ended questions addressing the sense of presence in laboratory virtual environments (Przyborski and Wohlrab-Sahr, 2009; Schubert et al., 1995; 2001). Our hypothesis was that hearing abilities and hearing-aid modes have an impact on the sense of presence in virtual environments.

2. Methods

The study was based on a mixed-methods approach. Both qualitative and quantitative evaluation tools were used to examine subjects' experiences of virtual auditory and visual information with regard to their hearing ability or hearing-aid mode. The qualitative evaluation tools included interviews, and the quantitative evaluation tools included questionnaires. We tested the interrelation between sense of presence, hearing ability and hearing-aid mode, by comparing the presence experience of NH vs. FTU (unaided) and FTU (aided) vs. EXPU. Please note that aided FTU and unaided FTU were the same test subjects, therefore we only compared HA unaided groups (NH vs. unaided FTU) and aided groups (aided FTU vs. EXPU) as between subject comparisons. The Commission for Research Impact Assessment and Ethics of the University of Oldenburg gave ethical approval to the study (Drs.-Nr. 1r69/2016).

2.1 Subjects

Twenty-one subjects (age range from 51 to 72 yrs.; mean age = 66.6 ± 4.90; eleven female and ten male) were recruited from the database of the *Hörzentrum Oldenburg* and divided into three groups, seven subjects with normal hearing (NH), seven first-time users (FTU) with no or little experience with HA, and seven experienced hearing-aid users (EXPU) (WHO, 2004). FTU participated under aided and unaided provision conditions. Both FTU and EXPU were bilaterally provided with hearing aids (see subsection Hearing-aid Provision).

In each group, the subjects had similar hearing thresholds. The mean PTA_4 in dB HL were as follows: average of 500 Hz, 1, 2, and 4 kHz for subjects with NH for the better ear PTA_4 = 7.1 dB HL (min. -1.3 dB HL, max. 16.3 dB HL, SD. 5.7 dB HL) and for the worse ear 11.3 dB HL (min. 5.0 dB HL, max. 18.8 dB HL, SD. 5.0 dB HL). For FTU the PTA_4 for the better ear was 34.5 dB HL (min. 31.3 dB HL, max. 38.8 dB HL, SD. 3.4 dB HL) and for the worse ear 37.9 dB HL (min. 33.8 dB HL, max. 41.3 dB HL, SD. 2.8 dB HL). For the group EXPU the PTA_4 of the better ear was 43.9 dB HL (min. 32.5 dB HL, max. 57.5 dB HL, SD. 9.0 dB HL) and for the worse ear 48.6 dB HL (min. 37.5 dB HL, max. 63.8 dB HL, SD. 12.7 dB HL).

We only recruited participants with a symmetrical hearing loss, because it was important to ensure that all participants had the basis for the perception of spatial cues in the virtual acoustical scenario. For the group NH, the mean interaural difference of the PTA_4 was 3.2 dB HL (max. 6.3 dB HL, SD. 2.3 dB HL), for FTU 3.4 dB HL (max. 5.0 dB HL, SD. 1.2 dB HL), and for EXPU 4.6 dB HL (max. 8.8 dB HL, SD. 2.9 dB HL).

2.2 Hearing-aid Provision

Two provision conditions were selected: subjects were (1) unaided and/or (2) aided with HA in omnidirectional microphone mode (Paluch 2018a, p. 40). In this study, an omnidirectional microphone mode was examined to ensure the fullest possible perception of space, allowing a better comparison with the data of the subjects with normal hearing. The data can thus also serve as a reference for later studies that investigate the influence of directivity.

Phonak Audéo V90-312 HA were used for the subjects with hearing impairment (FTU and EXPU). "These were fitted in accordance with the *Adaptive Phonak Digital* fitting formula (Latzel, 2013). All HA were receiver-in-canal (RIC) models with open domes" (Paluch, 2018a, p. 40).

2.3 Tests and Situations

Data were obtained in with N = 21 subjects in 28 study trials, and the FTU users were measured in the unaided as well as in the aided condition. The tests were carried out in a laboratory using virtual audiovisual scenes. The task of the subjects was to describe the environment and their responses to experiences gained during the tests. Subjects were explicitly asked to compare their experiences with other everyday situations, to identify differences and similarities.

No subjects were afflicted with migraine or epilepsy. As recommended by Llorach et al. (2014), simulator sickness was anticipated with the subjects. Subjects had the opportunity to quit the experiment at any time. In addition, the procedure was similar to that of Llorach et al. (2014, p. 139), since an experimenter was in the vicinity of the subjects to ensure safety and help if needed.

2.4 Evaluation Tools

2.4.1 Semi-Structured Interviews

Interviews with the subjects were carried out (Przyborski and Wohlrab-Sahr, 2009, pp. 138–145). Following Przyborski and Wohlrab-Sahr (2009), who described different forms of interviewing, semi-structured interviews were chosen, i.e., subjects were asked the same questions in the same order using an interview guide. In these interviews, the subjects were able to provide open answers and evaluate the simulations with regard to previously selected topics and questions.

The subjects were primarily instructed to evaluate the plausibility of the situation. They were asked how real the simulated street and cafeteria appeared compared to the open-field street and cafeteria. Additionally, the subjects were able to suggest improvements regarding the animations and to evaluate how they experienced the interaction with the animated characters.

2.4.2 Questionnaires

The Igroup Presence Questionnaire (IPQ, Schubert et al., 1995; 2001) was used to compare the sense of presence in both the animated street environment and the animated cafeteria environment. The assessments were conducted using 14 items on a 5-point scale (Likert type, e.g., 1 = completely different to the real world to 5 = indistinguishable from the real world. Response options varied for most items). Four factors were central to the IPQ questionnaire. The first factor was general presence. The general presence evaluates the extent to which a subject has the impression of being present in one place. Additionally, presence was divided into general presence and spatial presence. The third factor was involvement. Involvement refers to how much a subject related to a particular environment with regard to their attention. The item "I was completely captivated by the virtual world" makes it clear whether a person had the feeling that they were in the virtual world or merely in a laboratory with a projector screen. Finally, the factor of realism was examined in the sense of experienced reality. Items related to realism allowed subjects to evaluate how real the virtual scene was to them (Felnhofer et al., 2015, p. 51).

For the evaluation, the four factors were calculated by averaging the ratings of the 14 questions (general presence: question 1; spatial presence: questions 2 to 6; involvement: questions 7 to 10, realism: questions 11 to 14). The items of the IPQ questionnaire were extended by two more items: "How real did the virtual acoustic world seem to you?" and "How real did the virtual visual world seem to you?" Through this distinction, it was possible to examine whether and to what extent acoustic cues or visual cues influenced the accuracy of the virtual environments (Paluch et al., 2018b, p. 2).

2.5 Laboratory Setup

The laboratory study environment consisted of several networked computer systems and a tent-like structure (wall height 2 m, center height 2.5 m, diameter 3.4 m). The black duvetyn tent consisted of several steel girders with loudspeakers attached (16 loudspeakers placed every 22.5 degrees, starting at 11.25 degrees azimuth from the frontal direction. Loudspeaker type: *Genelec 8020B*). The subjects thus sat in a loudspeaker circle, approximately 1.8 m away from the speakers. The software TASCAR (Grimm et al., 2015) was used to control the loudspeakers and to acoustically display the scenes (horizontal seventh order Ambisonics panning with max-rE decoding, see Daniel et al., 1998). In addition to this loudspeaker circle, a cylindrical projection screen stood in front of the subjects (3.4 m diameter). Virtual audiovisual scenes were presented by a projector (NEC U321H with a 2 m high, 120 degree field-of-view). As in a movie theater, the subjects sat in a chair (distance to the picture 1.7 m) and faced the acoustically transparent projection screen. The Blender game engine was used to animate the images (version 2.78a, Roosendaal, 1995). The reverberation time T60 was approx. 0.13 sec. (measured between 100 Hz an 8 kHz, acoustically treated listening room) (see also Hendrikse et al., 2018b, pp. 72-74; Paluch, 2019).

2.6 Simulated Situation and Procedure

The virtual environments partially simulated existing areas of the city of Oldenburg, and partially added a fictitious area with lower urban density (Paluch et al., 2018, p. 44). A street network with a total length of approximately 4.5 km was modeled, with about 150 buildings, 100 trees and bushes, and 50 vehicles (e.g., cars, trucks, buses, bicycles and trains). The acoustic model incorporated a total of 806 dynamic sound sources (including reflections at the street surface and some house façades) (Fig. 1, left). The animated street situation took about twenty-four minutes. The sound-pressure levels of the street scenes varied according to different dynamic sound sources.

The subjects experienced the audiovisual scenes as follows: They sat on an adjustable sit/stand chair and a virtual street scene was projected in front of them. The subjects leaned against this chair to imitate walking on the street. Several pedestrians, bicycles, cars, trucks, buses and an ambulance were created as virtual audio-visual objects to simulate a busy street environment. The unweighted sound-pressure level (averaged across 25 seconds, Leq25) of the busy street fluctuated, for example, between 68 and 76 dB SPL, with a maximum of 76 dB SPL or 70 dB(A). With regard to the projection, the subjects were situated in the simulated environment on a sidewalk, whereas the vehicles drove on the street.

At a virtual bus stop, the subjects were stopped and asked closed-ended questions by a female animated character. During the examination, the researcher noted the subjects' answers. After this, the "virtual walk" was continued. In the second part of the street scene, the subjects were in a quiet environment in which e.g. animated birds could also be heard. Only now and then did animated cyclists, cars or buses drove by. In this quiet street environment an animated character also appeared at a bus stop, who asked the subject questions about their experience in the virtual environment. The unweighted sound-pressure level of the quiet street fluctuated between 64 and 68 dBSPL, with a maximum of 68 dB SPL or 62 dB(A).

A cafeteria situation was also simulated (Fig. 1, right). Subjects experienced a virtual, audiovisual cafeteria and listened to the conversation of four animated characters (two female, two male, at the azimuth directions 45°, 15°, -15° and -45°) (Hendrikse et al., 2018a). A spectral energy-based vocal tract model was used, which was controlled by the clean speech signal (Llorach et al., 2016). In the cafeteria situation, the subject sat in a chair (height 0.47 m) on a pedestal (height 0.32 m; the median ear position was at 1.6 m ear level). The subjects sat here on a typical chair to imitate sitting at a table. Additionally, in the cafeteria environment, a diffuse background noise (first order Ambisonics recording in the cafeteria on the university campus), as well as some cutlery noise, were reproduced, with an unweighted sound pressure level of 65 dB SPL, corresponding to an A-weighted level of 60 dB SPL. The cafeteria noise was recorded with a Core Sound TetraMic (http://www.core-sound.com/TetraMic/1.php). The sound was converted into Ambisonics B-Format using the tool tetraproc (Adriaensen, 2007). The sound file was edited so as not to contain nearby speakers. This cafeteria-situation sequence took about six minutes (Paluch, 2019).

2.7 Statistics

The available data exhibit a single-peak symmetry, i.e. normal distribution, and therefore non-parametrical statistical analyses were used (SPSS vers. 22). A U-test was used for independent data, a Wilcoxon test for the comparison of related samples. We compared on the one hand the effect of hearing loss, and on the other hand the effect of the experience with hearing-aid provision.

The number of cases per group (N = 7) being comparatively low, a conservative statistic is appropriate. Because of multiple comparisons

Figure 1: Laboratory animations. Left: Simulation of a noisy street in the city of Oldenburg. The subjects focused on what is happening in front of them. On the right side of the street are two cars, while two female pedestrians approach at the same time. Right: Simulation of the campus cafeteria of the University of Oldenburg. The subject is facing virtual characters who are seated at a table. In the background, the interior of the animated facility is visible.

Abbildung 1: Laboranimationen. Links: Simuliert wird eine laute Straße in der Stadt Oldenburg. Der Proband konzentriert sich auf das, was vor ihm geschieht. Auf der rechten Straßenseite fahren zwei Autos, während gleichzeitig zwei Fußgängerinnen sich ihm nähern. Rechts: Simuliert wird die Mensa der Universität Oldenburg. Der Proband ist virtuellen Charakteren zugewandt, die sich an einem Tisch befinden. Im Hintergrund ist das Innere der animierten Einrichtung sichtbar.

within the comparison of unaided groups (12 comparisons) and the aided groups with also 12 comparisons, we set the significance level at an alpha level of $p < 0.0042$ (Bonferroni) for each group comparison. Additionally, we report statistical tendencies of promising results with values of $p < 0.05$, because of the explorative character of the study.

3. Results

This section gives the results of the quantitative analysis. The questionnaires relate to the assessment of the sense of presence. For a finer analysis of the quantitative data, some qualitative data were used to support the statements.

3.1 Sense of Presence (IPQ Results)

In Table 1, the results of the IPQ questionnaire are shown and the assessments of the NH vs. unaided FTU and aided FTU vs. EXPU are compared.

Both the simulated street and the simulated cafeteria were analyzed. With a Bonferroni correction ($p < 0.0042$), there are no significant results. However, tendencies are noticeable. The subjects with NH and unaided FTU showed differences in the evaluation of the two scenes. The general sense of presence was stronger for subjects with NH (both MD = 3.5) than unaided FTU (both MD = 2.0). Compared to the subjects with NH, there was a tendency for an interesting difference in the cafeteria situation ($p = 0.029$, Wilcoxon). Also in the dimension of realism, there was a tendency for differences in the simulated cafeteria between NH and unaided FTU ($p = 0.040$). The spatial sense of

*Table 1: Comparison of NH vs. FTU (unaided) and FTU (aided) vs. EXPU (N=21) regarding general presence, spatial presence, involvement, and realism, both in the animated street and in the animated cafeteria. Scale range from 1 to 5. 1 = completely different to the real world, 3 = neither different nor indistinguishable, 5 = indistinguishable from the real world. Calculation of the factors was by averaging the rating for the corresponding questions (general presence: question 1; spatial presence: questions 2 to 6; involvement: questions 7 to 10, realism: questions 11 to 14). *statistical tendencies of promising results with values of p < 0.05.*

Tabelle 1: Vergleich von NH vs. FTU (unversorgt) und FTU (versorgt) vs. EXPU (N = 21) bezüglich allgemeiner Präsenz, räumlicher Präsenz, Einbindung und Realismus, sowohl in der animierten Straße als auch in der animierten Cafeteria. Skalenbereich von 1 bis 5. 1 = wie eine vorgestellte Welt, 3 = weder vorgestellt noch ununterscheidbar, 5 = nicht zu unterscheiden von der realen Welt. Berechnung der Faktoren durch Mittelung der Bewertung für die entsprechenden Fragen (allgemeine Präsenz: Frage 1; räumliche Präsenz: Fragen 2 bis 6; Einbindung: Fragen 7 bis 10, Realismus: Fragen 11 bis 14).
**statistische Tendenzen von beachtenswerten Ergebnissen mit Werten von p < 0.05.*

(IPQ)	NH N=7			FTU (unaided) N=7				FTU (aided) N=7			EXPU N=7			
General presence	M	SD	MD	M	SD	MD	P	M	SD	MD	M	SD	MD	p
Street	3.1	1.0	3.5	2.0	0.8	2.0	.054	2.1	0.7	2.0	3.4	1.5	4.0	.097
Cafeteria	3.3	1.2	3.5	1.9	0.4	2.0	.029*	2.0	0.6	2.0	2.7	1.4	2.0	.383
Spatial presence														
Street	3.1	1.0	3.1	2.5	0.8	2.4	.336	2.5	0.7	2.6	3.2	0.9	3.4	.073
Cafeteria	3.3	0.9	3.5	2.4	0.8	2.2	.072	2.3	0.8	2.6	3.2	1.3	3.6	.165
Involvement														
Street	2.8	0.9	2.9	2.2	0.5	2.3	.232	2.1	0.6	2.0	2.5	0.7	2.5	.259
Cafeteria	3.0	0.7	3.0	2.6	0.5	2.3	.281	2.2	1.0	2.5	2.8	0.7	3.0	.259
Realism														
Street	2.3	0.5	2.5	2.1	0.7	2.0	.536	2.1	0.4	2.3	2.7	0.4	2.8	.017*
Cafeteria	3.1	0.4	3.3	2.3	0.7	2.3	.040*	2.2	0.5	2.0	2.4	1.2	1.8	.902
Realism-acoustics#														
Street	4.5	0.5	4.5	4.1	0.7	4.0	.397	3.4	1.0	4.0	3.9	1.3	4.0	.383
Cafeteria	4.5	0.5	4.5	4.1	0.7	4.0	.397	3.4	1.0	4.0	3.9	0.7	4.0	.620
Realism-rendering#														
Street	2.6	1.3	2.0	2.1	1.2	2.0	.536	2.0	1.1	2.0	2.6	1.1	2.0	.383
Cafeteria	3.4	0.7	3.5	2.6	1.2	2.0	.189	2.6	1.3	3.0	3.0	0.8	3.0	.620

Legend:
NH= subjects with normal hearing; FTU=first time HA users; EXPU=experienced HA users
M=mean, SD=Standard deviation, MD=Median, p= probability of differences between groups by chance NH vs. FTU (unaided) and FTU (aided) vs. EXPU, statistical tendencies indicated with*
# questions additional to the IPQ

presence did not have such noticeable differences (MD = 3.5 for the subjects with NH in the cafeteria vs. MD = 2.2 for unaided FTU), similar to the involvement (MD = 2.9 for the subjects with NH in the street vs. 2.3 MD = for unaided FTU).

Unaided FTU stated furthermore that the acoustic representation of the laboratory scenes was comparatively real (MD = 4.0), and were thus somewhat more critical than NH (MD = 4.5). They were also more critical in the visual representation of the cafeteria scene (MD = 2.0) when compared to the NH (MD = 3.5).

The comparison between FTU (aided) and EXPU did not show such significant differences. For the EXPU, the general presence in the street was stronger (MD = 4.0) than in the cafeteria (MD = 2.0), whereas in both situations the FTU (aided) did not experienced much general presence (MD = 2.0). Furthermore, the spatial presence and involvement of the EXPU showed greater approval of the virtual environment. However, there were also some differences. Although in the street the EXPU experienced their general presence (MD = 4.0) more strongly than the aided FTU (MD = 2.0), in the cafeteria both groups gave the same rating (MD = 2.0). Regarding the spatial presence, the FTU (aided) experienced no differences between the perception of the street and the cafeteria (both MD = 2.6) and the EXPU barely differed in their assessments (MD = 3.4 in the street and MD = 3.6 in the cafeteria).

Involvement was also judged similarly. Both the aided FTU and the EXPU rated the animated cafeteria and the animated street as artificial or somewhat real (aided FTU, MD = 2.0 for the street and MD = 2.5 for the cafeteria; EXPU, MD = 2.5 for the street and MD = 3.0 for the cafeteria). Although the virtual cafeteria was more real for the aided FTU (MD = 2.0) than for the EXPU (MD = 1.8), this was a minor difference. Much more critical was the experience of reality when looking at the street situation. The animated street tended to be less real (p = 0.017) for the FTU (aided) (MD = 2.3) than for the EXPU (MD = 2.8). If the differentiation between acoustic and visual virtual representation were included, there were no major differences regarding the questionnaire data between aided FTU and EXPU. Both FTU (aided) and EXPU rated the acoustic representation as good (MD = 4.0) in both scenes.

3.2 Results of the Semi-Structured Interviews

On the basis of the interview material obtained in the laboratory, qualitative analyses revealed several factors and codes that corresponded to the experiences of the interview participants. During coding, the data was conceptualized, with the code corresponding to the product of the respective analysis. Thus, a code corresponds to a labeled phenomenon (Strauss, 1987, pp. 20-21). For the street and cafeteria situation, five factors were identified: a) perception and sensation, b) experiencing inadequacy, c) pleasant experiences, d) comparing the virtual world with reality, and e) experiencing the virtual characters. The codes varied due to the different situations in the virtual world. A total of 23 codes were formed for the street and 30 for the cafeteria. In this section, we focus on experiencing inadequacy and the comparison of virtuality and reality to show where the environment was implausible. This offers possibilities for improvement, which are discussed in the outlook.

Thus NH subjects, unaided FTU, and EXPU were compared. Aided FTU were not included, since FTU were interviewed twice, first unaided and then aided, and the second interview was thus not comparable with the first one. In general, eight of twenty-one subjects (three NH, three unaided FTU, and two EXPU) mentioned that the artificiality of the street was unpleasant and four of twenty-one subjects (one NH, two unaided FTU, and one EXPU) mentioned that the artificiality of the cafeteria was inadequate (“The simplified presentation bothered me. It was like a cartoon”; “The blur of the picture was exhausting”; “It [the picture] twitches quite a lot”). Additionally, six of twenty-one subjects (one NH, one unaided FTU, and four EXPU) said in the interviews that the volume of the simulated cafeteria conversation was inadequate (“It was difficult to understand the spoken words”).

In the animated cafeteria situation, the subjects with hearing impairment said that they did not understand the virtual characters. Seventeen of twenty-one subjects (three NH, seven unaided FTU, and seven EXPU) mentioned the poor speech intelligibility of the virtual characters (“I did not understand her, and I also think that it has to do with these virtual characters”).

In addition, six of twenty-one subjects (three NH and three EXPU) mentioned that the lip movement of the animations was not synchronized with the acoustic speech signal (“You cannot read from the lips”). In particular, the subjects with hearing impairment stated that they refer to the mouth movement of a counterpart in order to better understand them (“I could not transfer the mouth movement to the speech. That was a problem for me”; “The mouth movements were not very good”).

With regard to the animated street, four of twenty-one subjects (three NH and one EXPU) said that the passivity was unpleasant (“You can see that you are moving, but you are not moving. That does not fit together”) and eleven of twenty-one (three NH, two unaided FTU, and six EXPU) noted that the simulated movement felt strange (“At the interfaces it was too fast”). In the animated cafeteria, eight of twenty-one subjects (three NH and five unaided FTU) said they would need more movement in the background (“There were some [characters] sitting in the back, but nothing happened in the background”; “Maybe there can be more movement, so that people pass by at the side”; “It was not very lively”). Ten of twenty-one subjects (two NH, three unaided FTU, and five EXPU) experienced mild forms of simulator sickness during our study. Llorach et al. (2014) stated that fast turns could cause simulator sickness. This was in line with the observations of this study, as the subjects in the street scene experienced simulator sickness more often, because there were more horizontal rotations.

4. Discussion

In our data, 21 subjects were a good sample for the explorative and qualitative procedure and some promising tendencies were shown. Relating to our hypothesis that the sense of presence is influenced by hearing abilities and hearing-aid modes, during the interviews the subjects said that they needed the feeling of being able to participate in a simulated scene. The scene was simply presented to them, thus they did not feel involved. They reported that they felt just like passive spectators, without being able to actively influence their environment. Straub (2016) showed that there is a connection between the complexity of a situation and the presence experience. Robotic experiments revealed that when a robot showed movements, the subjects felt more social presence through the interaction. Similar results were reported by Harth (2017), who analyzed the interaction with animated characters.

Similar statements were made regarding the acoustic information. To participate in the virtual environment, the animated characters needed to be understood in order to avoid the feeling of exclusion. Subjects with hearing impairment more often struggled to understand the animated characters, reporting more frequently that they did not feel part of the situation. In contrast to the unaided FTU, NH subjects tended to feel different regarding general presence or experience realism during the conversation in the simulated cafeteria (see Tab. 1).

For the EXPU, the realism in both situations tended to be stronger than for the aided FTU. This contributes to the assumption that the FTU had more difficulty in perceiving the environment as plausible due to their hearing ability with hearing aids. With reference to the spatial experience, it may be assumed that they did not feel like they were in a virtual street or cafeteria, but that the room ended in front of the projector screen. One reason might be that the FTU must first acclimatize to the HA in order to use them properly (Dawes et al., 2014; Dawes and Munro, 2017). If acclimatization to the HA had not taken place, then virtual environments would also be rated more poorly with respect to the different dimensions. This might mean that the subjects were relying on visual cues, so they had difficulty allocating sound sources in the acoustic environment. However, directional microphone modes were not tested in this study, thus the results are only partially generalizable. In subsequent studies, directional signal processing options should be tested, to examine any influence on the subjective experience of presence.

In the interviews, the test subjects also volunteered information about the visual rendering. They mentioned that the pictures looked like a cartoon, the visualization was unclear and too insubstantial. This contributed to the fact that the test subjects could not get involved with what was shown and therefore had no sense of presence. If the test subjects have to focus too much on the images, then the presence experience is limited because they are constantly reminded that this is an artificial environment (Bishop and Rohrmann, 2003; Maempel and Horn, 2018). To what extent this lack of involvement also applies due to the acoustic perception should be investigated in further studies. It may be assumed that limited auditory perception results in a limited presence experience. On the other hand, understanding less can also correspond to the everyday experience of the test subjects.

Although subjects with hearing loss could not properly understand the animated characters, this was not justified by the speech comprehension in the lab but by the visual implementation. The conversations did not contain Lombard speech and were therefore probably more difficult to understand, even though the SNR corresponded to real-life values. For the test subjects, the lip-syncing of the characters did not correspond to that observed in everyday life. In everyday conversations, the test subjects would be able to compensate greatly by lip reading, which they could not with the animated characters. In this case, too, the visualization resulted in a lack of presence and the environment was perceived as implausible.

It is not, however, sufficient to simply focus on rendering or display as a factor. The test subjects also noted that their own scope for action was too limited and the passivity as such was considered as suboptimal. Although the visualization was again addressed here, e.g., the simulated movements were carried out too quickly, the main problem was a contradiction of the subjects' body feeling. The simulation showed an active movement, whereas they were just leaning against or sitting passively on a chair. For a more plausible simulation, the test subjects would also need the ability to act in the environment themselves. Such a realization would increase the sense of presence and improve the plausibility (Bailenson, 2018).

All in all, the results from the interviews and questionnaires indicated that perception of acoustic and visual information is relevant for the sense of presence in virtual environments. The experience of space was perceived as implausible if the subjects did not receive enough information about that environment. Possibly, subjects with hearing impairment depended on visual information to orient themselves or to understand their counterparts. We assume that their auditory perception was limited and therefore they had to compensate by focusing on visual cues. Inadequate visual information was a distraction, because the subjects could not rely on it. In this respect, they showed reluctance to accept the virtual space.

However, with regard to the questionnaire data, it can be noted that the statistical power for the analyses was too limited, i.e. that the sample size was too small to test several factors. Therefore, the achieved level of plausibility still has to be established, e.g., with test-retest reliability and increase of study power with a larger sample size.

5. Outlook

In future, laboratories with audiovisual environments are likely to be able to evaluate hearing aids or hearing abilities of subjects with hearing impairment. As our study on the relevance of hearing ability, hearing-aid modes and sense of presence has shown, plausibility is an important factor for further investigations. To create a better sense of presence, the visual scenes need to be more detailed. There would have to be various cars on the street, differing trees, house fronts with rough surfaces, and so on. The subjects also suggested modifications to the animated characters. The subjects with hearing impairment pointed out that they needed accurate lip-syncing in order to understand a counterpart (see also Llorach et al., 2016). According to the subjects, the lip-syncing of the virtual characters was too simplistic, which contributed to an experience of inconsistency. Two important aspects of virtual environments can therefore be identified: The appearance of the animations and the movements of animations. If the appearance is too simple, it will cause the experience of artificiality, and if the entities in the virtual environment move inadequately, it also leads to a rejection of the simulated world.

To prevent impressions of mere animation, real video material could also make a scene more plausible, in particular, if real video material were connected to a realistic acoustic presentation (MPI-MMG 2016).

A further important point is the self-motion of the subjects: The subjects should be able to move more independently and thereby avoid the experience of simulator sickness (Lee et al., 2017). As a possible solution, a street environment is imaginable in which a person stands at a fixed point and virtual characters pass by and speak with each other. In such a scenario, the subjects could lean forward to better understand the animated characters. The image would not be limited to 120 degrees, but extended to almost 360 degrees, to enhance the experience of general presence, spatial presence, involvement, and realism. Thus, the laboratory would be extended by a larger screen, allowing the subjects to completely turn around. The subjects could also be granted a small degree of self-motion, since they could lean forward approximately 50 centimeters. Additionally, one could implement that the subjects are not guided through the scenes, but teleport autonomously from single points (e.g., from a bus stop to a cafeteria). This could also be realized with head-mounted displays (Bailenson, 2018).

Author Note

Parts of the description of the presence term, of the laboratory and the virtual scenes also appear in an edited volume in German (Paluch, 2019) and parts of the methods are based on Paluch et al., 2018a. First results were published in Paluch 2019, Paluch et al. 2018a, and Paluch et al. 2018b.

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Data Availability

Sensitive data was collected in this study. In addition to questionnaires, interviews with subjects were conducted and subjects were recorded on video. The subjects consented to the use of this data only for the purposes of this study. None of the subjects agreed that the data may be shared. Thus, a complete publication of the data would contravene consent of the subjects and the ethics approval.

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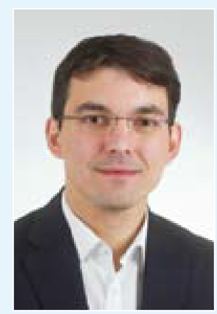
Foto: privat

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Foto: Hörzentrum Oldenburg

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Foto: HörTech gGmbH Oldenburg

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Foto: Universität Oldenburg

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Foto: Hörzentrum Oldenburg

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Doktorarbeit über die elektrophysiologische Beurteilung kognitiver Mechanismen, die dem Sprachverstehen zugrunde liegen

Jana Annina Müller

Die sprachliche Kommunikation ist ein komplexer und multifaktorieller Prozess, der von vielen verschiedenen Faktoren beeinflusst wird. Laute und störende Umgebungsgeräusche, akustische und linguistische Eigenschaften des Zielsignals, sowie individuelle kognitive Faktoren können sich auf das Sprachverstehen auswirken. Die selektive Aufmerksamkeit ermöglicht es, störende Geräusche aus der Umgebung zu unterdrücken und interessante Schallquellen zu selektieren. Zugleich können die Verarbeitungsdauer und die Höranstrengung auch bei hoher Sprachverständlichkeit individuell stark variieren. In der alltäglichen Kommunikation stehen Verarbeitungsdauer, selektive Aufmerksamkeit und Höranstrengung in engem Zusammenhang und sind mit dem Sprachverstehen verbunden. Das Ziel dieser Arbeit war es, diese drei kognitiven Mechanismen und ihren Beitrag zum komplexen Prozess der Sprachverarbeitung zu untersuchen und bestehende Methoden ihrer Messung zu optimieren.