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REFRAMING HEARING AIDS – EXPLORING THE DESIGN SPACE OF ANALOGUE FASHIONABLE HEARING AIDS FOR USERS WITH MILD HEARING IMPAIRMENTS

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ABSTRACT

Contemporary digital in ear hearing aids are of significant importance for social participation of users with hearing impairments. Through the advancement of technology, extreme miniaturisation of these devices has been achieved. However, by no means all people who could benefit from a hearing aid actually use one. Cormack and Fortnum state that the majority (80%) of adults aged 55–74 years who would benefit from a hearing aid, do not use them. This is in line with Arnold and Makenzie who estimate a gap of a factor of 5 between people who would benefit from the use of a hearing aid than actually do acquire and use one. Even according to the statistics from the Federal Guild of Hearing Aid Acousticians in Germany, only 3.7 million use a hearing aid out of 5.4 million who have an induced hearing loss. This article explores the design space of fashionable analogue contemporary hearing aids.

Keywords: Inclusive design, Open innovation, Hearing Aid, Generative Design, User centred design

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1 INTRODUCTION

Today's hearing aids are incredibly sophisticated, with advanced digital signal processing, wireless connectivity, miniaturization and artificial intelligence (Mills 2011). Despite the remarkable gains in acoustic capabilities, miniaturization remains a key paradigm in hearing aid development and conventional hearing aids frame hearing impairment almost exclusively as a problem (Dörrenbacher and Hassenzahl 2019). As hearing aids become smaller, they also become more complex, requiring advanced circuitry and power sources. For even longer than the first hearing aids, people are using their hand as an additional reflector to guide the sound into the auditory canal (figure 1). In addition to the hearing improvement that can be achieved, this also has a communicative effect that contrasts with the invisibility of today's hearing aids. Hearing aids that are visible can have advantages in terms of communication (see Dörrenbacher & Hassenzahl) and ergonomics. In this paper we investigate low-tech hearing aids that incorporate these aspects and aim to create positive framing for divergent hearing.

Figure 1: Self-Portrait as a Deaf Man, approx. 1775, Sir Joshua Reynolds, © TATE Images 2022, (Photo: Tate)

Figure 2: Collection of hearing aids at Science Museum, London (Photo by the Authors)

Parallel to the remarkable gains in hearing aid development, demographic change has led to a substantial increase in the number of potential users with light to medium hearing disorders. However, adoption rates are still low: Cormack and Fortnum (2013) state that the majority (80%) of adults aged 55–74 years who would benefit from a hearing aid, do not use them. This is in line with Arnold and Makenzie (1998) who estimate a gap of a factor of 5 between people who would benefit from the use of a hearing aid than actually do acquire and use one. Even according to the statistics from the Federal Guild of Hearing Aid Acousticians in Germany, only 3.7 million use a hearing aid out of 5.4 million who have an induced hearing loss (Radtke 2022). This topic therefore seems worth extrapolating further. In particular, it is interesting to investigate the reasons for non-use and to explore alternative product concepts.

2 REASONS FOR NON-USE

The reasons for the lack of adoption are well documented by Arnold (1998), Cormack and Fortum (2013) and Cameron (2008). To illustrate the reasons for non-adoption, the following diagram borrows from McCormack's (2013) extensive meta-study to document the reasons for non-adoption (figure 3). Here, only the reasons that are covered by one study were systematically filtered out. Of particular interest are the reasons on the left where a relatively high percentage of respondents indicated that this is one of the reasons, they do not use a hearing aid. In this paper, the authors focus especially on usability (handling problems), background noise, comfort, financial factors, social acceptance and user experience as limiting factors for adoption and suggest a design space to potentially and partly address these factors for the scope of mild hearing impairments. For that, the authors are suggesting the exploration of the design space for a new generation of analogue hearing aids driven by contemporary research, optimisation, fabrication, and marketing as a context. This addresses some of the key reasons for non-use. The scope of this paper is to open up a design space for alternative analogue hearing aids, especially criticising contemporary digital hearing aids worn at the ear or in the hearing canal. This paper does not cover the well-established solutions for users with more intense hearing losses like cochlea implants, as these are intended for use cases with stronger medical indications. It also does not cover the recent developments in non-medical hearing aid functionalities found in earphones like AirPods. The later are relevant for the field of helping users with mild to medium hearing impairments as well but come at a high cost compared to open-source analogue hearing aids, are hard to recycle, more complex to use and only partially address the social stigma around hearing impairments.

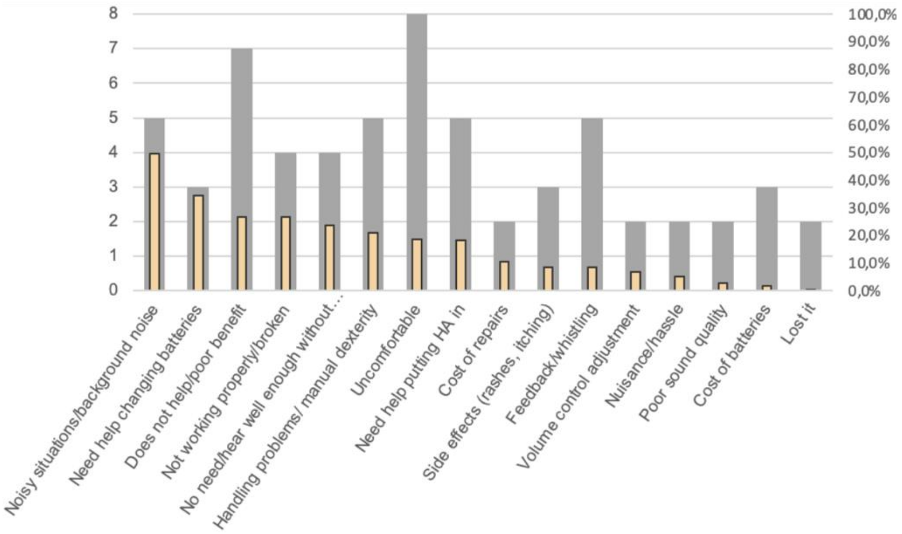

Figure 3: Reasons for not using hearing aids, sorted by median agreement with McCormack's (2013) reason for not using, shown as a percentage in the narrow beige bar; highlighted with the number of papers supporting this in the grey wider bar.

3 OPERATIONAL AND PRACTICAL ACTION RESEARCH APPROACH

The format of research-based learning used in university didactics led to the development of the Y-method in a semester project, based on an initial idea by Dieter Raffler and Hermann Klöckner. This method combines a systematic description of challenges with possible openly accessible resources/phenomena, largely derived from biomimicry and expired patents (figure 4).

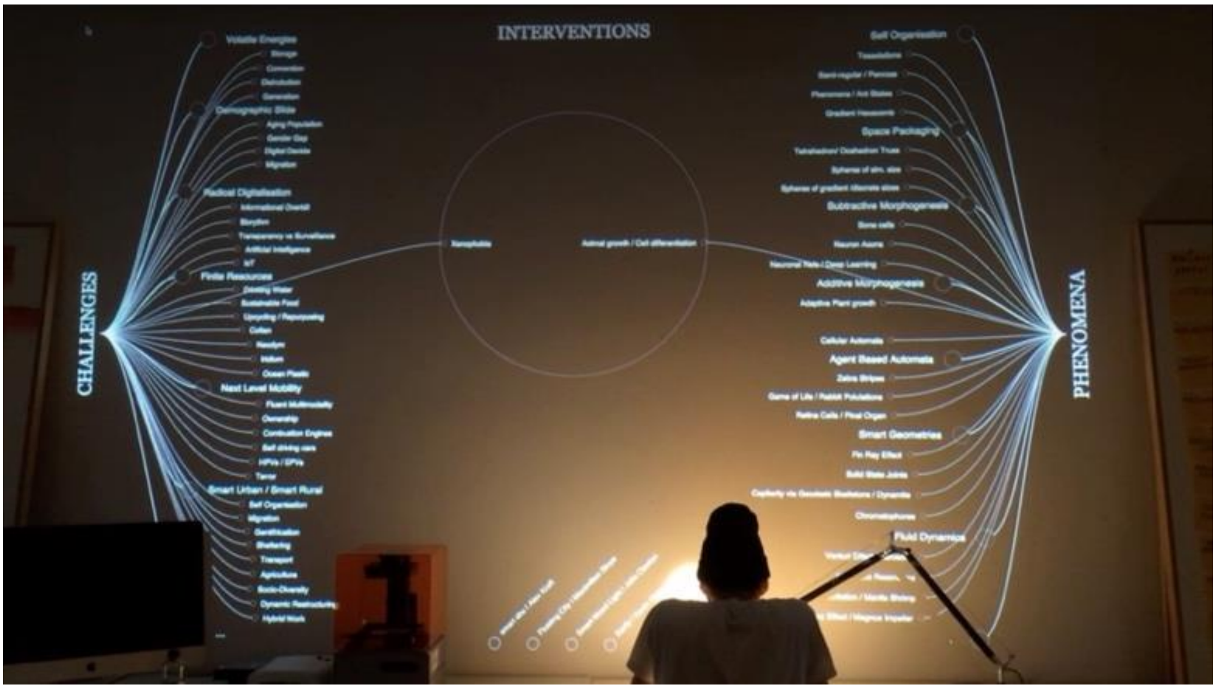

Figure 4: Y-Method software combining phenomena and challenges

In an action research-based bachelor thesis, a student named Kevin Klebs combined the challenge of rampant hearing deficits with the phenomenon of acoustic resonance. He developed a first concept for 3D-printed analogue hearing aids as pentatonically tuned spherical resonators, inspired by Helmholtz (1875/1895) (Figure 4 and 5)

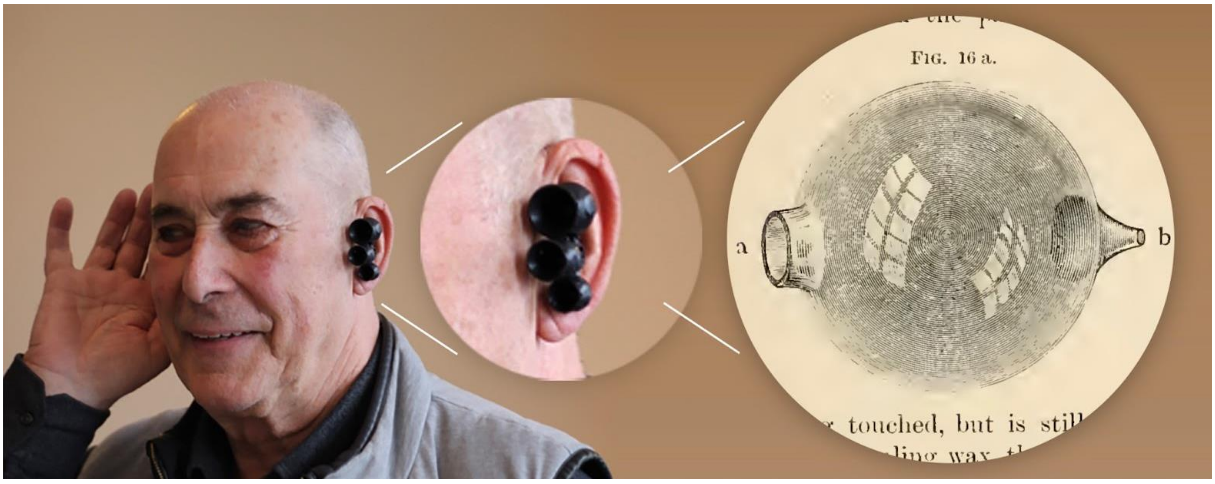

Figure 5: Prof. Dieter Raffler in 2017 with initial resonance-based prototype based on Helmholtz Resonator tuned to resonate with specific frequency Helmholtz (1875/1895)

During the tests, the team observes promising potential in amplification and directional hearing while avoiding background noise (figure 5). However, the main focus of achieving a clear sounding, understandable human voice remains to be desired. The Helmholtz resonators yield a subjectively acoustic interesting result, while leaving frequency balance to be desired. Nevertheless, the team establishes the initial concept of affordable, 3D printed analogue hearing aids. Initial acceptance tests with visitors to a laboratory exhibition indicate a promising potential in practice, especially if it is possible to frame them as jewellery. This insight and the action research-based approach to explore possible solutions by combining problems with physical principles form the basis for further exploration.

To find an extended OPERATIVE AND PRACTICAL ACTION RESEARCH APPROACH the authors conducted further research on amplification principles and systematic development of the project. While maintaining the main characteristic - directional non-electrical amplification - the authors focused on the exploration of the possible design space for contemporary analogue hearing aids.

According to Brocke et al. (2020), the foundation of any research approach in design research is the interplay between problem space, solution space, and the type of evaluation. In our study, the achievable hearing amplification serves as the evaluation metric. The problem space encompasses mild hearing impairments as well as ergonomic issues with miniaturized hearing aids, communication barriers, and the absence of positive framing. To explore the Solution Space, we will use the Y-method and make it tangible through Generative Design and Rapid Prototyping techniques.

The research question of this article is: 'Can the combination of generative design to explore the solution space in depth and reframing based on physical principles to explore the solution space in width in a little considered context of low-tech visible hearing aids lead to higher amplification effects and social acceptance?'

In considering this research question, the incorporation of aesthetic, ergonomic and communicative aspects naturally plays a role and is integrated into the action research approach. In our approach, we deliberately refrain from taking a closer look at the very well illuminated solution area of amplification by electronics. Instead, we focus on a more flexible exploration of the almost forgotten areas of the solution space by reframing. The result of this suggestion opens up a design space consisting of objects relying on the exploitation of known physical principles, the potential of contemporary mass (customized) production and additive manufacturing like complex shapes out of mono-materials, new business models based on open-source hardware blueprints, accessible empowerment for communities in developing countries and the possibilities of the developments of new aesthetics for functional jewellery. These factors are the scope of the considerations in the following paragraphs.

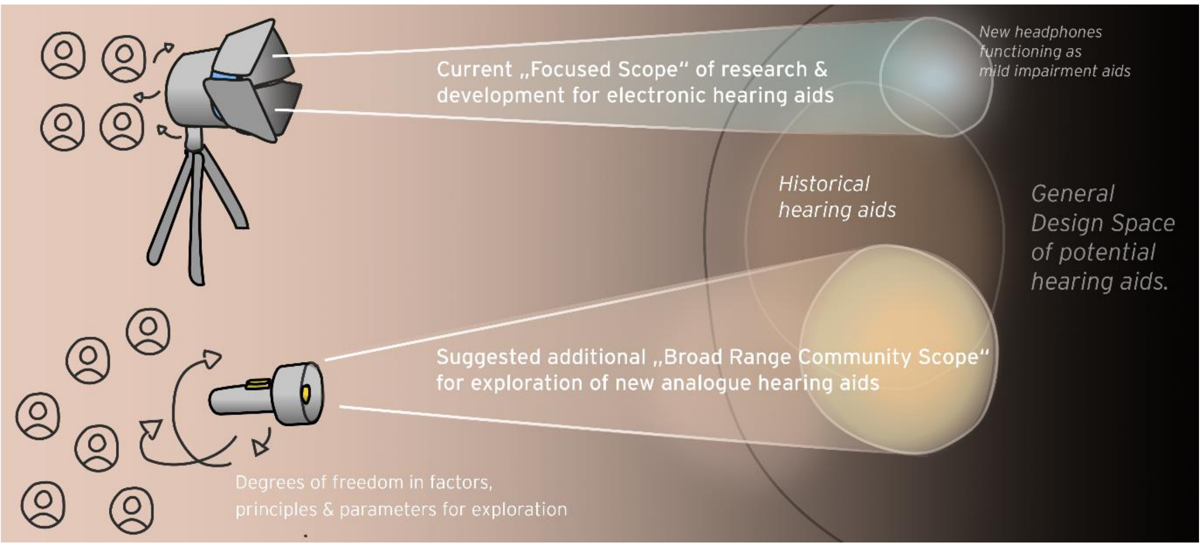

Figure 6: Illustration of a community-oriented exploration style in contrast to the more focused orientation of research and development in digital hearing aids

In our approach, we deliberately refrain from taking a closer look at the very well illuminated solution area of amplification by electronics. Instead, we focus on a more flexible exploration of the almost forgotten areas of the solution space (figure 6). Thus, the authors suggest a new exploration of a design space, where the degrees of freedom A) are to be defined without the usage of electronics in the final products, that sound quality in general, specifically amplification and dynamic precise compression are partly loosened in order to focus on mild to medium hearing impairments, which make up for the majority of potential users and that miniaturization is released to a range of object sizes in the order of magnitude of the ergonomics ~ 3cm to 8cm of the human ear and hand. The result of this suggestion opens up a design space consisting of objects relying on the exploitation of known physical principles, the potential of contemporary mass (customized) production and additive manufacturing like complex shapes out of mono-materials, new business models based on open-source hardware blueprints, accessible empowerment for communities in developing countries and the possibilities of the developments of new aesthetics for functional jewellery. The factors described above are the scope of the considerations in the following paragraphs.

4 PHYSICAL PRINCIPLES FOR SOUND ADAPTATION

To define the solution space for an analogue hearing aid, it is meaningful to take a closer look at the physical principles that can be used. We were able to find the following four acoustic principles that seemed relevant and interesting 1. Acoustic mirrors 2. Quarter wavelength resonators 3. Helmholtz resonators 4. Acoustic Transformer effect 5. Material with increased sound impedance. Quarter-wave resonators correspond to our ear canal, as it is open at one end and closed at the other by the drumhead. Every lengthening or shortening therefore also changes the resonance frequency of this naturally existing resonator. A Helmholtz resonator is not contained in our ears; it could be used, for example, to damp the frequencies, but this does not seem to be our focus for the time being. The acoustic transformer effect is called this because it is used on most wind instruments to intensify the higher frequencies. It must have a precisely defined length and slow expansion. The last effect is the utilization of impedance. In contrast to a more dampening material that our ear is made of, alternative stiffer materials could have a slight hearing enhancement effect. Through initial testing and based on inspiration from the patents by A. Klöckner (1984) for ocean waves and similar approaches in the optical field in the main author's invention of optical caustic encryption principle for the "river is" installation for ART+COM (2012) Through the experience of the potentials gained, generative acoustic mirrors and quarter wavelength resonators have been especially considered as a focus for further investigation (figure 7).

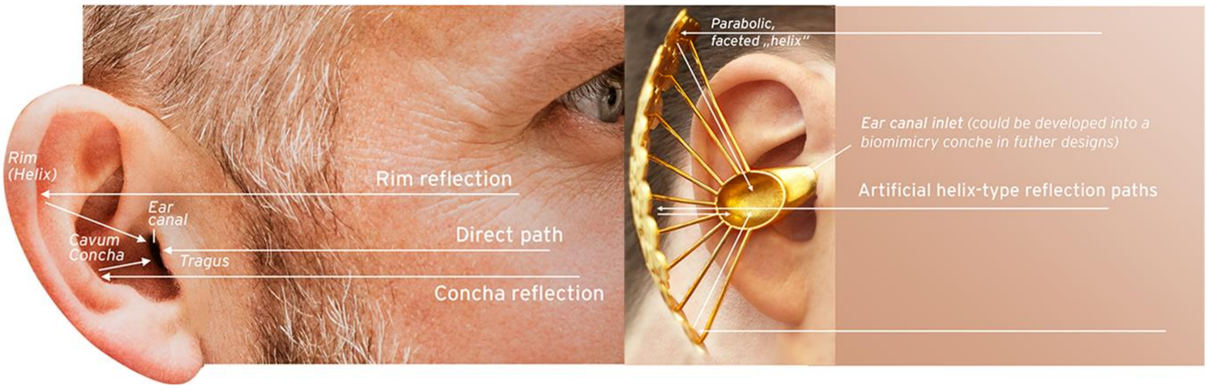

Figure 7: Left: Natural outer ear reflection path via helix, concha and tragus into ear canal. (After Algazi 2007, Photo: Stadtgoeren) Right: sound's pathway with faceted parabolic hearing aid (Photo: Author)

The main sound path being used in the biomimicry designs suggested, is the concha and rim-type reflection described by Algazi (2007) while suppressing direct acoustic path into the ear canal. The suggested consequence is an optimized signal to noise ratio for face-to-face communications because of audio focus ahead of the user. An assumed disadvantage of this focus on an "artificially amplified concha reflection" is reduced directional hearing. This disadvantage is common in most electronical hearing aids not using beam forming technology as well. And while limiting the surrounding noises might be disadvantageous in certain situations, it is assumed to be beneficial in direct conversations.

5 EVALUATION CRITERIA

When we consider the outputs of the optimization system, it is of central importance to improve the following dimensions (here we follow DIN EN 60118): Gain over frequency band (especially in the speech range 200 Hz to 5000 Hz); Speech intelligibility; Speech intelligibility in background noise (signal to noise ratio) However, with our pragmatic approach, we have not yet been able to fulfil all the requirements of a measurement system according to DIN and we have also not yet been able to carry out the systematic speech intelligibility tests. To improve the measurement system to a fully DIN-compliant one, we or the community must still set the input sound pressure level exactly to 60 dB and we must keep a free space of at least 1/4 of the lowest wavelength (at 200 Hz: 43cm) to any wall and there have to be suitable absorbers.

6 EXPLORATION BY PHYSICAL PRINCIPLES

During the shape development process, it becomes clear that numerous variants, fundamentally distinct and not limited to parameter changes, must be tested. As such, simulations are avoided and a methodology is adopted that involves generating 3D printed shapes and evaluating them via a measuring system.

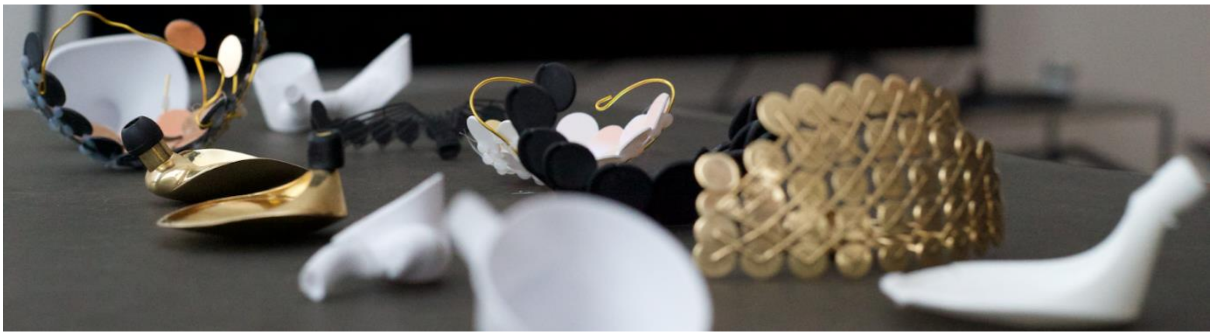

Figure 8: Variety of prototypes out of design space. (Photo by authors)

Initial trials of Fresnel-inspired reflectors, generated using a generative design approach, are aesthetically pleasing but yield minimal auditory amplification, primarily limited to very high frequencies. Subsequently, an algorithm is programmed that optimizes the reflector configuration to ensure that sound waves arrive in phase in the ear canal, resulting in noticeable improvement.

However, the hearing gains remain inadequate. Consequently, other physical principles like the horn effect are explored in the solution space, resulting in a simple design that produces the first significant effects. Further trials involving different quarter-wave resonators reveal that lengthening the ear canal has a positive effect. This geometry is subsequently optimized as a parabolic in-ear variant (a). Now, the working geometry is being mixed with the Fresnel reflectors to come up with both aesthetically interesting and measurably hearing-enhancing properties (b), combining both approaches. The polynomial trend line clearly shows a steady improvement, whereby the last two prototypes are summarised in one generation, as they represent the current state of development (figure 9).

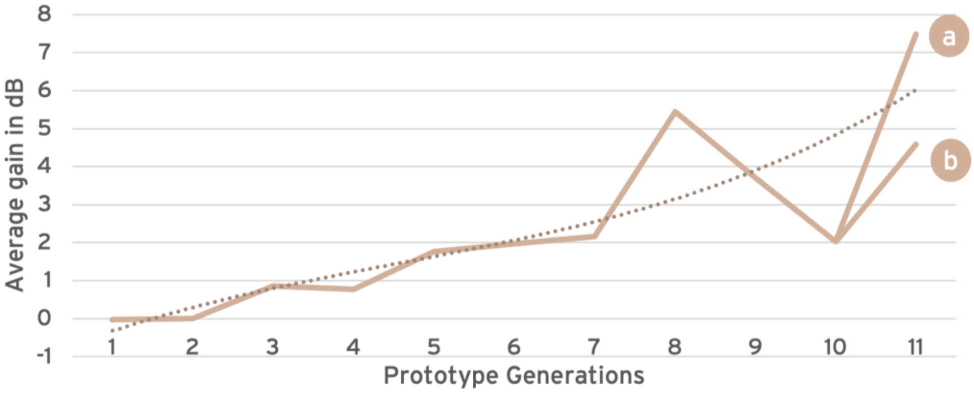

Figure 9: Average amplification of prototypes throughout development generations

Generative and parametric design plays a vital role in exploring the potential design space. Specialized software accelerates the exploration, and personalization is introduced with additive manufacturing, such as 3D-scanning the user's outer ears using IR sensors for individual ergonomic and acoustic adjustment. Specific frequencies and focal characteristics are explored when working with multi-reflector arrays, where the size of the voids between individual facets drives the amplification of specific frequencies while damping others (figure 10). To optimize and customize mass production, authors develop software to drive a Fibonacci-spiral arrangement of Fresnel-lens like fractured reflectors. The software equips the individual facets with a "search behaviour" to drive the focus sweet spot in a generative shape-finding process while avoiding facet collisions and occlusions on the sounds path to the tragus and the hearing channel. Finally, the custom software exports a 3D geometry and configurations for production.

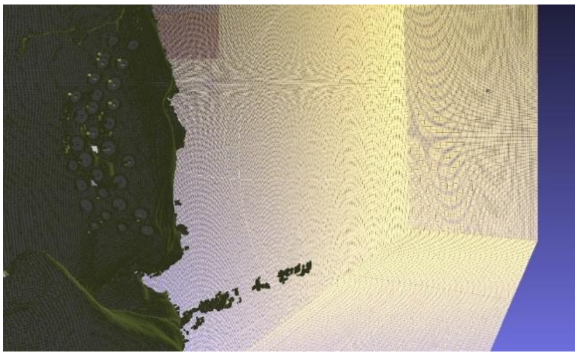

Figure 10: Author's generative software for personalisation, customisation and phase-matched reflection output.

Figure 11: Initial 3D printed iteration of multi-faceted-approach. (Photo: Stadtgoeren, Author)

In the next step, the community could establish an online configurator and extend the functionalities for mass customization. Also, Monte-Carlo and Machine Learning assessments with integrated audio simulation would be relevant to explore. Here the help by more experts in the acoustic field would be beneficial. On the other hand, more relevant use cases are within the very low-cost sector, a simplistic parabolic design made from bioplastics would be relevant to explore, taking reference from the well investigated and internationally successful one-dollar-glasses by Martin Aufmuth (Carvalho 2019). With the help of the community, potentially similar effects might be achievable for hearing. 3D printing allows for customisation according to ear geometry, customised hearing focus (e.g. for orchestral players) and accessible distribution models.

7 RESULTS OF THE TWO HEARING AID PROTOTYPES

The measurement setup makes it possible to show the amplification effects over the frequency curve for both prototypes. We are particularly interested in the frequency range from 1000 to 4000 Hz. This range is crucial for speech understanding. The results can be illustrated well in the following diagram, in which the hearing level without hearing aid forms the zero line.

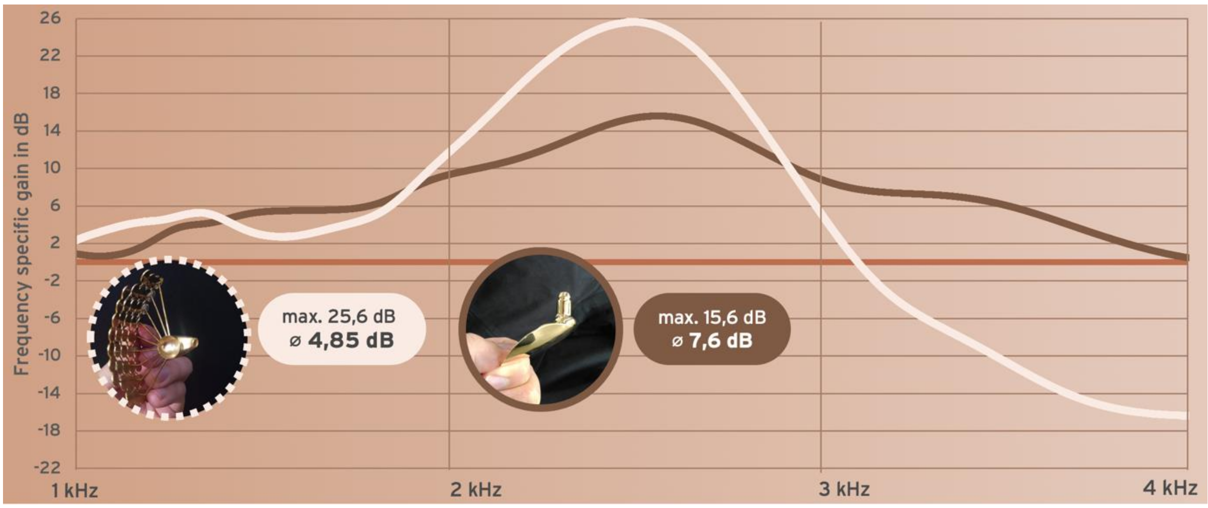

Figure 12: Measurement results of faceted and continuous hearing aid prototypes

The brown line in the diagram illustrates the gain effect of the parabolic design and the beige line illustrates the gain/loss effect of the faceted parabolic design. The faceted parabolic design has a larger maximum gain of 25.6 dB in contrast to the 15.6 dB of the parabolic design. However, the mean gain value of the faceted parabolic design is lower at 4.85 dB than the 7.6 dB of the parabolic design in this frequency range (figure 12). Both gains are estimated to improve with further geometry improvements and size adjustments. Although the measurements do not currently meet international hearing aid standards, they have served to iteratively optimize the designs through a uniform internal process. The measurement system is currently being fine-tuned to comply with DIN EN 60118, and soon we will be able to report measured values in accordance with the standard as proof of hearing amplification. To develop a new hearing aid design, two variants were investigated: a) the parabolic design and b) the faceted parabolic design. Both variants are based on the helix and antihelix geometry of the natural ear and direct sound into the ear canal via the tragus.

The parabolic design (a) offers better suitability for low-cost mass production and is more stable for daily use due to its construction. It has a compact shape and provides an overall gain that is with or partially higher than that of the simple "hand behind the ear" gesture, which is often cumbersome, especially for both ears. However, the appearance of the hearing aid is reminiscent of natural ears, which may limit aesthetic acceptability. However, the choice of material and shape can help compensate for this. Compared to the two analogue hearing aids on the market (1) 'Earglasses' (Riley 2022) and (2) 'Orette' (Maurer et al. 2022), however, it seems subjectively much more acceptable.

The faceted parabolic design (b) offers more potential for customization and personalization. Due to the perforation, it has more frequency-dependent properties that need further investigation. The overall gain in the human voice range is not as high as in a), but the frequency-dependent properties offer the possibility to adapt the geometry to individual listening tests. A neon-coloured secondary reflector, which acts like the tragus, may even give the interlocutor the impression that he or she is in the best gain range, since the facets of the hearing aid light up according to the natural reflection. The shape of the hearing aid is less based on natural ears and more oriented towards floral elements or the wheel of a peacock. This could make the hearing aid less creepy, but it is also more fragile and may interfere with hair or other accessories like eyeglasses.

Overall, both designs offer different advantages and disadvantages, and it depends on individual needs and preferences which one is preferred, but user acceptance represents an upcoming project. To progress towards answering the research question of this article, it is worthwhile to look at the successive improvement of the listening performance of the different prototypes. From the results it can be concluded that the combination of generative design and reframing based on physical principles successively leads to improved gain effects in low-tech visible hearing aids (figure 9). Generative design, the hypothesis confirms, allows exploration of the solution space in depth, while reframing based on physical principles allows exploration of the solution space in width and helps when one is trapped in a local maximum. By combining these two approaches, it is possible to achieve a comprehensive and efficient design process.

Figure 13: The two final prototypes for this paper. Faceted for enhanced aesthetics and frequency specific amplification, simplistic parabolic design for accessible mass production. Brass for hygienic and aesthetic properties (Photo by authors, Model Emily Glombitza)

8 SUMMARY AND CRITICAL REFLECTION

In summary, the research question raised has been partially answered by the exploration of the design space and related tests. Further studies by the interdisciplinary community are needed in order to fully understand both the scientific and the practical impact of the author's findings. The reframing process for investigating the design space of hearing aids is being carried out by a small important to note that this involvement is limited to hallway testing, which means that the integration of users, experts, and stakeholders is non-systematic and non-documented. While the authors have opened up a new field of exploration, they acknowledge that their knowledge of related fields is limited, potentially hindering their ability to create real relief for the user community. Despite the known and unknown limitations of their proposed design, the authors suggest openly exploring the design space for contemporary analog hearing aids. As a roll-out strategy, the authors plan to publish their results as an open-source initiative for further development with interdisciplinary input. They are providing their software, tests, and designs to stakeholders in medicine, acoustics, digital fabrication, fashion, and social business. The authors define a heuristic benchmark of achieving or exceeding the effect of the casual "hand-behind-the-ear-gesture" while providing ease of use for extended conversations. In summary, this has been widely achieved. The principles of the provided prototypes are in fact related to the acoustic principles involved in the “hand-behind-the-ear-gesture" – however, with improved geometry, acoustic properties, ergonomics, and style. While not a full replacement for digital hearing aids, the authors hope the interdisciplinary community will build on their findings to create a meaningful addition with practical impact to the field. However, it is important to elaborate on the approach outlined by the authors. While open-source initiatives in this area are desirable and the approach of reframing through physical principles and investigations through generative design also seems transferable in principle, the fact that the authors acknowledge their limited knowledge in related fields raises concerns about the feasibility and long-term applicability of their proposed designs so far. Furthermore, the outlined limitations and partially sceptical users, possible interference with glasses and masks, and potential further problems, raise questions regarding the practicality and social acceptance of their proposed designs in the design space outlined in this paper. Regarding the addressed reasons for non-use, it is important to ask to which extend this design improves the ergonomic problems addressed in the introduction. The battery change has been eliminated, so there are no more problems, but only if this is the only hearing aid. Putting the hearing aid on and taking it off is improved in that the new design offers more areas to touch. It is also important to note that while the authors claim that their proposed design will help users focus on their conversation partners and contribute to their social lives, it is unclear how effective their proposed design will be in achieving these goals. User tests on speech comprehension and subjective added value are lacking in this regard. Furthermore, the authors acknowledge that their proposed design is not a complete replacement for digital hearing aids, but rather a potential addition when elaborated on by the interdisciplinary community.

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