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3D printing as assistive technology for individuals with deafblindness: perspectives of rehabilitation professionals

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Abstract

There is a growing body of evidence on practical applications of three-dimensional (3D) printing to support the rehabilitation of individuals with sensory impairments. However, applications in the field of deafblindness, or the combination of vision and hearing impairment, remain scarce. Therefore, the present study aimed to explore actual and potential applications of 3D printing in deafblindness rehabilitation from the perspective of rehabilitation professionals in two focus group discussions that involved orientation and mobility specialists, vision rehabilitation specialists, audiologists, and braille technicians. Participants exchanged on 1) 3D printing applications to address their clients' rehabilitation needs, 2) factors that can impact its integration into their practice, and 3) the ideal logistics for producing and delivering 3D printed products. Educative models and functional adaptations were identified to improve communication, learning, mobility, and independent living skills for individuals with deafblindness. Professionals agreed that the main barriers limiting 3D printing adoption were linked to time constraints and insufficient awareness or knowledge about this technology, while the most crucial facilitator was the promotion of interdisciplinary collaborations with 3D printing experts. The present findings thus emphasize the need for global collaborations, knowledge dissemination, and ongoing research and validation of 3D printing applications to support individuals with deafblindness.

Introduction

Deafblindness, also known as dual-sensory impairment, is characterized by a combination of hearing and vision impairments (1, 2) that globally affects from 0.2 to 2% of the population, totaling approximately 150 million individuals (3). This condition manifests across a diverse spectrum (4): it can be congenital, (i.e., congenital Rubella Syndrome) or acquired later in life due to the progression of congenital (i.e., Usher syndrome) or age-related (i.e., age-related macular degeneration and presbycusis) conditions (1, 5, 6). Consequently, deafblindness is more complex and limiting than singular hearing or vision impairment, and its consequences impact both environmental interactions and interpersonal relationships (5, 7, 8). Individuals living with deafblindness encounter substantial barriers to communication, social participation, and interpersonal relationships, resulting in limited information access, mobility challenges, social isolation, and reduced quality of life (1, 3, 9). Moreover, individuals with deafblindness are more likely to have lower education and employment outcomes compared to those with other disabilities (1, 3, 9).

3D printing as assistive technology

As a result, developing new intervention strategies and new assistive technologies can facilitate communication between individuals with deafblindness and other people, such as rehabilitation professionals, and improve learning and retaining essential knowledge and skills that improve independence. As assistive technologies hold considerable potential to enhance the functioning and social participation of individuals with deafblindness (1, 3, 10-12), our team previously investigated various technologies, needs, and priorities of the deafblind community (13). Most recently, we conducted a scoping review of the literature to explore the potential of additive manufacturing, commonly known as three-dimensional (3D) printing, as a tool for producing assistive devices and adapted material, with a specific focus on its application in the rehabilitation of individuals with deafblindness (14).

In synthesizing the available evidence, we underscored the substantial potential of 3D printing to effectively overcome barriers to accessibility faced by individuals with deafblindness. Notably, 3D printing enables the crafting of tactile and interactive products that can be personalized to the unique needs of individuals with deafblindness. These have noteworthy advantages in life domains, such as communication, mobility, and learning. In actuality, 3D printing is already viewed as a valuable tool for producing educational material (15-19) as well as tactile maps (20, 21) to learn geography and facilitate mobility by learning the layout of new environments (i.e., a new school). 3D printing also emerged as potentially effective in reducing communication barriers, particularly with those unfamiliar with tactile sign language, by creating no-tech communication cards (22). Its potential extends beyond producing new material as it can complement and even enhance existing tactile graphics (23, 24), making educational materials more engaging, especially for children whom teachers and rehabilitation professionals can consult during the design process (24-26). Furthermore, integrating 3D printing with other do-it-yourself (DIY) technologies like electronics could enable the creation of communication devices and interactive prototypes for educational or orientation and mobility purposes (23, 25, 27-30). The use of 3D-printed products had the parallel effect of increasing the motivation and participation of students and clients (23).

Objective of the present study

Within the limited number of available sources, the scoping study highlighted many unexplored avenues and little validation of the effectiveness of 3D-printed products in rehabilitation settings. Therefore, we aim to expand further the literature on the potential applications of 3D printing in deafblindness rehabilitation from the perspective of rehabilitation professionals. For this purpose, based on this prior scoping study, we developed a set of questions addressing the current lack in the literature. These questions guided two focus group discussions involving professionals in deafblindness rehabilitation and technicians with knowledge or expertise in 3D printing. The discussions revolved around how these actors could collaborate and use 3D printing to meet the needs of their clients in the context of their own practice and work limitations.

Methods

The study received ethical approval from the *Comité d'éthique de la recherche clinique* (CERC # 2021-1133) of the *Université de Montréal* and from the Institutional Review Board of the *Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain* (CRIR-1515-0121).

Participants and Procedures

Two focus group sessions were conducted between September 2021 and January 2022 with 11 participants from two different rehabilitation centers specialised in vision impairments (in the presence or absence of comorbidities) in the province of Québec, Canada. All participants provided written informed consent. The sessions were led online using Zoom (Zoom Video Communications, San Jose, California, United States).

Focus group 1 was conducted in French and included six participants from a rehabilitation center with significant 3D printing infrastructure, while focus group 2 was conducted in English and involved five participants from a rehabilitation center with no established 3D printing infrastructure. For both focus groups, recruitment was led by a research coordinator from each rehabilitation center. Participants were included based on the following criteria: they had to be 1) rehabilitation professionals working with clients diagnosed with deafblindness or 2) technicians who create accessible materials for individuals with vision impairments and/or have experience or knowledge about 3D printing. Participants' demographics were recorded through a questionnaire before meeting the research team (see Table 1).

Table 1. Participants information

Gr	ID	Age & Gender	Profession	Educational level	Experience in sensory rehabilitation

1	P1	46 M	Orientation and Mobility Specialist	Masters	> 10 years
1	P2	40 F	Audiologist	Masters	> 10 years
1	P3	38 M	Braille Technician	Collegial	> 10 years
1	P4	43 F	Clinical Activity Specialist	Bachelor	> 10 years
1	P5	57 F	Clinical Activity Specialist	Masters	> 10 years
1	P6	40 F	Vision Rehabilitation Therapist	Specialized Graduate Diploma	> 5 years, < 10 years
2	P7	45 F	Orientation and Mobility Specialist	Specialized Graduate Diploma	> 10 years
2	P8	60 F	Vision Rehabilitation Therapist	Masters	> 10 years
2	P9	29 M	Audiologist	Masters	> 1 year, < 5 years
2	P10	36 F	Audiologist	Masters	> 10 years
2	P11	45 F	Braille Technician	Bachelor	> 10 years

The two focus groups conducted lasted 60 and 90 minutes respectively and were moderated by a research team member who has extensively worked with 3D printing in their research and academic background. The role of the moderator within the focus group was to initiate and facilitate discussions by 1) giving a short, 10-minute PowerPoint presentation on the basic principles of 3D printing and how he uses it in his practice (i.e., tactile maps, educational anatomic models); 2) probing participants with thematic cues, or ‘probes’ (see table 2); 3) encouraging the involvement of all participants and balancing the discussion among participants to allow everyone to contribute. The moderator employed a list of six open-ended questions with probes (see Table 2) to encourage discussions exploring the main themes that had emerged from a prior literature review conducted by the team (14). These included the potential use of 3D printing for/by individuals with deafblindness, factors impacting the integration of this technology in their practice, and the potential collaboration with 3D printing experts and rehabilitation experts. Before each focus group, participants received information about the process. They received the six questions to reflect on the subject and prepare the ideas they wanted to discuss. They were also encouraged to meet with their team and to brainstorm with them beforehand.

Table 2. Questions and Probes

#	Questions	Probes
1	*What are the current rehabilitation needs of individuals with deafblindness for which professionals would consider the use of 3D printing? Do you have any ideas on how it could or should be used in your field?*	*School learning, work, leisure, mobility, adaptation of existing tools, socialising*
2	*How would the 3D printed objects need to be presented to clients with deafblindness, how would you plan to use such models, and why?*	*Raw vs refined: special textures, braille inscriptions, high color contrast, special training,*
3	*How do you think of providing 3D printed objects to clients and how to produce them?*	*Delivery delays, inventory management, clients' requests*
4	*Barriers: What are the factors that would make the usability of 3D printing difficult for you as professionals?*	*Inherent to the 3D printing process, the training required, time or delivery delay, inherent to the patient profile*
5	*Facilitators: What are the factors that would make the usability of 3D printing easier for you as professionals?*	*Training, cost sharing or subsidies for caregivers*
6	*What would be the ideal process (and communication process) to get the required objects (3D models or objects) from the printing service (or other)?*	*Collaboration with a 3D printing service, training in rehab for engineers and modelers, rehabilitation center employee using 3D printer*

Data Transcription and Analysis

Each focus group session was video recorded and later transcribed verbatim by a team member (MB). The completed transcript was then verified by another team member (WW) using the video tape. To perform thematic analysis on the data (31), two independent reviewers (MB and WW) read the transcriptions and viewed the video recordings on multiple occasions for full immersion and understanding. They then conducted open coding of the content in Microsoft Word (32), using the highlight function, before synthesizing the main themes into an Excel file. Then the reviewers collaboratively agreed upon the final main themes and subthemes and identified quotations most reflective of those themes. These quotations, presented in the results section, were adjusted for comprehension without the context of the discussions, while those translated from French to English by the team were marked with asterisks (*).

Results

After revising the transcripts, the team identified five main teams. These themes and their subthemes are presented here:

1) Potential 3D printing applications
   a) Learning abstract concepts
   b) Facilitating communication
   c) Manipulating objects for daily living
2) Presentation of 3D printing objects
3) Barriers to 3D printing adoption
   a) Dissemination of knowledge
   b) Time
   c) Required training
   d) Budget
4) Facilitators to 3D printing adoption
   a) Provision of training
   b) Infrastructure within rehabilitation centers
   c) Affordability
   d) Online resources and community
5) Logistical considerations for providing 3D Printed Objects

Theme 1. Potential 3D printing applications (Q1)

In exploring the current rehabilitation needs of individuals with deafblindness, professionals highlighted numerous applications for 3D printing to improve learning, communication, and daily living skills through meaningful adaptations that harness the sense of touch.

Subtheme 1.a. Learning abstract concepts

Most participants agreed that one of the most valuable contributions 3D printing can make in the field is the production of tangible, tactile models for educational purposes. Most importantly, the versatility of 3D printing may enable professionals to create scale models representing very small, very large, or abstract objects and concepts, including objects that could be concrete by nature for sighted individuals, but inaccessible, thus abstract, for those with deafblindness. Through that lens, 3D printing was seen as a valuable support in comprehending concepts such as the scale of buildings (i.e., skyscrapers), depth, clouds, trees, animals, and even more advanced chemistry concepts.

P8 (vision rehabilitation therapist, group 2): "[There are] items that could be 3D [printed], that are abstract. […] if we could make a product that would symbolize a cloud [or] trees […], examples of what is difficult for somebody to imagine […] for children in particular, [it] would be beneficial."

P11 (braille technician, group 2): "[to] understand concepts […], like the concept of depth […] there are a lot of concepts and things that are just going to be so much easier to understand if they are held in your hand, […] a [3D model] would do better than a picture."

Additionally, 3D-printed anatomy models were considered valuable tools in education (i.e., biology classes) and rehabilitation. For example, these could allow professionals to convey complex concepts, such as the anatomy of the inner ear and eye, as well as different pathologies, in a tangible and accessible manner. Participants in group 1 also specified they knew other professionals who were already using 3D printed anatomical models of the eye as support when explaining the etiology of different pathologies. As for audiologists, they expressed the possibility of using 3D printed models to demystify cochlear implants and the placement of their electrodes.

P8 (vision rehabilitation therapist, group 2): "For students learning biology, they could look at a picture of a heart on a page... but unless the 3D heart was produced, they could [not] feel it and really learn."

P5 (clinical activity specialist, group 1): "eye models […] to explain to clients different eye conditions like retinitis pigmentosa; what is happening in the eye and where […]"*

P10 (audiologist, group 2): "the cochlear implant is a really hard thing to imagine. […] we could have a 3D model of the head and ear and [show] where the electrodes [are]."

Other specialists were particularly interested in the ability to represent the content of a computer or phone screen with all their navigation elements. As evidenced by participant P6 who was in contact with a professional that used an 3D printed iPhone model during their lessons, such tools facilitate their clients' learning to use mainstream technologies for school or work:

P6 (vision rehabilitation therapist, group 1): "I thought [the iPhone 3D model] was great to explain the difference between the tab bar, the rest of the screen, and the status bar. For some clients, it is very difficult to have a mental representation of all that."*

For O&M specialists, tactile maps emerged as the prominent 3D printing application to aid in spatial orientation with representations of intersections, neighborhoods, cityscapes, and geographical maps.

According to them, 3D printed tactile maps would provide clients with a more tangible understanding of their surroundings when compared to traditional 2D tactile maps. One participant (P1) brought examples of 3D printed maps representing different intersections during the discussion and showed them to the group. Participant P3 also shared his experience in designing 3D models of buildings like museum and theaters.

P7 (orientation and mobility specialist, group 2): "[when I make a tactile] map, it's 2D, it's not 3D. So, it's really difficult to explain the buildings […] I can see the benefit of using the [3D] printer for that."

P1 (orientation and mobility specialist, group 1): "[elevation changes are] a particularity of the environment that can be represented with [3D printing]. So, I think we can use 3D printing to represent different environments."*

In short, participants perceived 3D printing as beneficial for individuals who struggle with traditional visual or tactile learning methods as 3D printed material can be easier to understand compared to 2D line drawings or verbal descriptions.

Subtheme 1.b. Facilitating communication

Participants also highlighted the potential of 3D printing to bridge communication gaps between them and their clients. 3D printing might help professionals provide their clients with tactile learning support material for their lessons. For example, having something the client can touch could enable the professional to ensure that what they say is understood and that they are not falsely answering.

P8 (vision rehabilitation therapist, group 2): "we can explain it in all different ways, but we don't know how they're interpreting it, […] unless they're actually touching it."

P5 (clinical activity specialist, group 1): "sometimes with people who are deafblind and who communicate with sign language, they have limited vocabulary […] so, to [have] such models […] it would be very appreciated"*

Furthermore, participants P1 and P5 emphasized that 3D printing have the potential to create symbolic objects for communication tables to aid their clients in communicating with others or for tactile schedules to help them organize their day.

P1 (orientation & mobility specialist, group 1) : "with deaf-blind children, they'll often use symbolic objects to communicate, to have a tactile schedule or a communication board... but sometimes they don't have the object they'd like. So, they could make it in 3D... this would impact communication with deaf-blind children."*

Subtheme 1.c. Manipulating objects for daily living

The adaptability of 3D printing was further highlighted through the creation of functional objects (i.e., check guides, labeled containers for hearing aids, geometry kits, labels for food and clothing) and adaptations (i.e., a cane holder for a walker, tactile markers, and other adaptations for frequently used tools and appliances with digital screens, or elevator control panels), to help cater to specific needs and improve quality of life through small, but meaningful, adjustments. Some of these (check guides, geometry kits, tagging system for food, and digital screen adaptations) were already produced and used in group 1.

P8 (vision rehabilitation therapist, group 2): "A tactile 3D image could assist [as a] labeling tool for identifying and organizing clothing and food… and using proper [touchscreen] appliances… dealing with safety issues…"

P2 (audiologist, group 1): "Sometimes, with remote controls for hearing aids and implants, it's complicated to find the right buttons, so by having bigger, or more protruding, buttons made with a 3D printer […] I think that could be an avenue."*

Audiologists also expressed enthusiasm to teach how to properly manipulate small objects such as hearing aids, especially for clients with spatial awareness issues. For example, a scale model of a client's hearing aids (and even of an ear or a whole human head) could help them understand their different components (i.e., button layout), how they fit in the ears, and how to change the batteries. Participants argued that such models could help make manipulating the "real thing" easier for their clients.

P2 (audiologist, group 1): "[…] because [hearing aids are] really small, changing a battery is a bit complicated for our clients. So, by having a bigger model, we can at least explain where the battery compartment is, how to open it [...] so they can […] transpose it to the smaller one."*

P9 (audiologist, group 2): "[We could create] something that they can use to [keep] their hearing aids from falling off."

Theme 2. Presentation of 3D printed objects (Q2)

Professionals argued on the nuances of presenting 3D printed objects and emphasized key factors contributing to their effective use by individuals with deafblindness. The discussion first revolved around the main perceived advantage of 3D printing over other fabrication methods: faithfulness to reality. Participants agreed that 3D printed models could accurately represent real-world objects and that this fidelity is crucial for individuals to build accurate mental images and associations.

P1 (orientation and mobility specialist, group 1): "Pretending to or presenting an object that represents something, without necessarily being that, often is not concrete enough, [...] it's going to take a long time to get [the client] to understand. [...] I'd say it must be as real as possible. [...] that's the advantage of 3D printing […]"*

However, they also highlighted considerable forms of adaptation to make these more easily accessible to their clients. Magnification, discriminable textures, braille annotations, tactile indicators, and legends emerged as critical components of effective tactile objects. At the same time, high contrast, the use of colors, and a non-reflective surface finish were considered for clients with residual vision.

P4 (clinical activity specialist, group 1): "Making it generally bigger than what you can find in the market because often the object is going to be too small, tactile discrimination is going to be difficult."*

Participants also emphasized the importance of providing additional information beyond the tactile and visual features to provide the context and meaning of the objects. For example, providing a training procedure with the 3D printed object could optimize usability and enhance the overall user experience.

P11 (braille technician, group 2): "A lot of these things would need a little bit of instruction."

Conversely, participants highlighted that ease of manipulation and portability are also essential characteristics of 3D-printed objects. The tactile nature of these objects must be complemented by practical considerations to enable individuals to interact with and carry the models conveniently. Finally, the discussion touched upon the significance of customization in 3D-printed models. Professionals highlighted that each client's needs are unique and thus emphasized that customization is a key element in ensuring the relevance and effectiveness of the models. In a counterpoint, a participant highlighted the versatility of *computer-aided design* (CAD) 3D models with the possibility to anticipate the diversity in clients' needs and abilities in the design process itself:

P4 (clinical activity specialist, group 1): "[…] there are a lot of objects that the way you design them meets a lot of needs. [...] you must think about students who are totally blind, students who have residual vision, [...] It's about playing with everything you can; that's what 3D printing is; that's what is fun about it."*

Theme 3. Barriers to 3D printing adoption (Q4)

Recurring challenges for integrating 3D printing into rehabilitation practices were brought up throughout the discussion. Those were categorized into four inter-connected barriers: dissemination of knowledge, time, budget, and required training.

Subtheme 3.a. Barrier 1: Dissemination of knowledge

As 3D printing is a novelty for most participants, the initial barrier was the noticeable need for more consideration for 3D printing as an available and viable solution. Participants acknowledged their limited awareness regarding the possibilities offered by 3D printing and its availability within their workplace. One participant encapsulated the sentiment of the group by expressing:

P1 (orientation and mobility specialist, group 1): "The obstacles are intrinsic to ourselves. I don't necessarily think of calling on 3D printing, on [3D printing experts], […] I haven't developed that reflex yet..."*

Participants highlighted a lack of communication between the different departments of rehabilitation centers. While this was mostly associated with the repercussions of the global COVID pandemic, professionals agreed this was a significant factor contributing to their inability to ask about 3D printing, get inspired for 3D projects, or ensure the transposability of their ideas into 3D printed objects. Indeed, most participants were interrogative about the feasibility time and monetary costs of such projects, keeping them from further investigating the topic. *

Subtheme 3.b. Barrier 2: Time

Time constraints within rehabilitation episodes were a significant concern expressed by rehabilitation professionals during the discussion. This was clear when informed of the extended time required for both design and printing of objects by participants with 3D printing experience (P3, P4, and P11). Time significantly impacted the perceived feasibility of integrating 3D printing into professionals' daily practice. This concern did not only consider the workload of each professional but also the impact on the waiting time required for the client to get the 3D printed object (P1, P2, P5, and P6).

P7 (orientation and mobility specialist, group 2): "[we must] find a way to make [3D printed objects] fast. [We cannot] wait weeks, [because then] we are already working on something else. […] too bad too late, I won't use it…"

P10 (audiologist, group 2): "Something that we really don't have a lot of, as intervenors within the center, is time and I know that I [can't] go and spend a lot of time printing something [or] explaining to somebody [how to make it]."

Subtheme 3.c. Barrier 3: Required training.

Related to the novelty of 3D printing in rehabilitation settings, one significant challenge that transpired in the discussions was the lack of 3D printing training for professionals. The knowledge and training required to operate a 3D printer and design 3D models seemed overwhelming to professionals, leading to questions about the feasibility of 3D printing projects. For example, the work going into the 3D printing process was viewed as disproportionate compared to the potential use of the object, especially when it is customized to an individual's needs.

P10 (audiologist, group 2): "[…] someone would have to be in charge of this. […] if I have to take that on, it's just not going to happen."

P9 (audiologist, group 2): "[…] resource-wise, I think we're going to need a little bit more support."

Subtheme 3.d. Barrier 4: Budget

Budget constraints also emerged as a complex barrier, with some professionals expressing concerns that these could hinder the exploration of potentially beneficial 3D printing projects. The high cost of 3D printing resources outside rehabilitation centers and the demand for individualized products contributed to these budget considerations. These financial concerns were felt as potential roadblocks to the broader adoption of 3D printing in rehabilitation.

> *P6 (vision rehabilitation therapist, group 1)*: " I wonder, among other things, about the cost of 3D printing, is it affordable enough that we can afford to make models [...] for a small explanation, to maybe only one client, […] do I really […] put time, money, to create [such objects], that's the consideration I have…."*

> *P7 (orientation and mobility specialist, group 2): "[I am] not sure if it's feasible because I'm not the one who decides and the one who controls the budget."*

Then, participants agreed that a shift in mindset is required to recognize 3D printing as a go-to tool within the rehabilitation toolkit. This was particularly true for professionals in the center with notable 3D printing infrastructure, who recognized that they were not using the infrastructure at its full potential due to implicit worries about budget.

> *P4 (clinical activity specialist, group 1)*: "[…] you don't have to think about costs, you have to think about the needs and legitimacy of your rehabilitation activities."*

> *P5 (clinical activity specialist, group 1)*: "In the end, what's important is for our clients to succeed. […] if it's an object that allows them to succeed, to maintain or acquire a new skill, well I mean, you have to do it, it's available."*

Theme 4. Facilitators to 3D printing adoption (Q5)

Professionals also engaged in an exchange regarding the main facilitators to integrate this technology into their practice. Those were about providing training and collaborations, 3D printing infrastructure within centers, the affordability of 3D printing, online resources, and an engaging community.

Subtheme 4.a. Facilitator 1: Provision of training for collaboration

In addressing the facilitators for the usability of 3D printing, most participants agreed that they, and other professionals, could benefit from minimal training and, therefore, base knowledge about the 3D printing process, including time, cost, and design principles. Most participants expressed that the presentation from the research team made them more aware of the necessities of 3D printing and inspired some ideas. However, because of the barriers regarding time constraints and required training, they agreed that closely collaborating with 3D printing experts who design and print the objects would greatly facilitate their practice. Thus, minimal training could help them better communicate their ideas to their collaborators and allow a seamless co-design process to provide their clients with quality products.

P10 (audiologist, group 2): "I would imagine if we had [3D printing services], it would be a job in itself."

P1 (orientation and mobility specialist, group 1): " […] what's interesting is not necessarily training, but an exchange [...] on what's possible, what's already been done [...] That we feed off each other; that we [then exchange with 3D printing experts on what is feasible]"*

Subtheme 4.b. Facilitator 2: 3D printing infrastructure within rehabilitation centers

Professionals painted a picture of an ideal environment where infrastructure and expertise seamlessly support the integration of 3D printing into their practices. A well-equipped facility, including printers and 3D printing experts with knowledge in vision rehabilitation, was a fundamental facilitator. Furthermore, they emphasized the importance of these experts being easily accessible, as they would need to communicate directly with them to grasp the feasibility of their ideas and the time to concretize them.

P5 (clinical activity specialist, group 1): "That's certainly a big help when you can speak directly with the person [...] access to the person, in this simple way, to make a request […]"*

As discussed by participants, this system could greatly facilitate and accelerate the process of providing customized products for clients. Some were even positively surprised by the short delays that this system could enable.

P5 (clinical activity specialist, group 1): "[…] a short waiting time, […] for a personalized adaptation. I mean, it makes the whole intervention fluid afterward."*

Subtheme 4.c. Facilitator 3: Affordability

Despite their initial budget concerns, rehabilitation professionals were reassured by braille technicians with 3D printing knowledge that 3D printing was not as expensive as they originally thought. Those also confirmed that, even if 3D printing comes with an initial investment, the required production material (i.e., filament for *Fused Deposition Modeling* [FDM] 3D printing technology) is inexpensive and that the long-term benefits can outweigh short-term financial considerations.

P3 (braille technician, group 1): "The costs, as such, are mostly my time, because plastic costs next to nothing."*

P11 (braille technician, group 2): "[Adapted products] do exist but at a price. They tend to be very costly compared to what we could produce [with 3D printing]."

As a result, 3D printing projects seem to be encouraged and sought by those working in the braille department with 3D printing infrastructure:

P3 (braille technician, group 1): "[...] we have all the equipment and expertise to do all that. All I need is your projects, your ideas, and your cases to solve because [...] you know what [your clients] need"*

According to them, they needed to develop a mentality of prioritizing clients' needs over costs as, otherwise, they may worry too easily about the budget. They also added that validating the usefulness of 3D printing to clients could further garner support from their organization, a recognition that could lead to increased funding for 3D printing.

P4 (clinical activity specialist, group 1): "[…] any adaptation is [worth producing], I think, if it can improve a person's quality of life […] we have to use [the 3D printing equipment] and promote it"*

P11 (braille technician, group 2): "[we] need the input from the client. […] if [a 3D model is] an important product that is useful to our clients, then [3D printing equipment is] something that [the rehabilitation center] should be [investing] into."

Subtheme 4.d. Facilitator 4: Online resources and community

Additionally, online communities and resources such as 3D model repositories were potential facilitators that could accelerate the integration of this technology into rehabilitation practices. Notably, 3D printing online repositories could accelerate the work of 3D printing staff to create 3D printed objects for rehabilitation needs or provide rehabilitation professionals with ready-to-print models.

> *P3 (braille technician, group 1)*: "There are many websites that have [pre-made] models, so all I have to do is download [, make modifications if needed, and print them]. I don't necessarily have to start a project from scratch [...] "*

Furthermore, the potential benefits of online platforms were providing inspiration and practical ways for professionals to stay informed and enhance their proficiency in creating 3D printing projects for their clients. This discussion extended into the idea of creating online repositories and diffusion platforms within the centers' infrastructure to help inspire professionals.

> *P5 (clinical activity specialist, group 1)*: " [...] Dissemination, when you introduce a new way of doing things, […] there's a bit of sharing that needs to be done between clinicians too. […]. Otherwise, it remains a little abstract, but if we see examples of how it's integrated into clinical practice…"*

> *P3 (braille technician, group 1)* "A repository that could be accessible to everyone, with all the objects that have already been made [at the center]."*

Theme 5. Logistical considerations for providing 3D Printed Objects (Q3, Q6)

The discussion brought different practical considerations for integrating 3D printing into rehabilitation practices. Professionals preferred short waiting times and emphasized the need for timely access to 3D-printed materials. The ability to swiftly incorporate 3D-printed objects into ongoing rehabilitation episodes was deemed essential for maximizing their impact.

> *P10 (audiologist, group 2): "When you need it, you need it […] these people wait a long time to see us, and then [you] don't want something to make them wait again."*

Following this, the personalized nature of rehabilitation emerged as a recurring theme: the dialogue extended to envisioning a system where models are designed, updated, and stocked based on client demands; or even kept by the rehabilitation professional to be used when necessary. Participants emphasized the importance of adaptability and responsiveness of services to individual requirements. This tailored approach, although challenging, was deemed crucial for addressing the diverse needs of individuals with deafblindness.

P2 (audiologist, group 1): "[Our intervention is] so personalized to the client […]. [The 3D model] is so personalized that it's not necessarily reusable, but let's [imagine a product for regularly taught subjects], we keep it in stock in our things, [and] we use it with clients who need it […]."*

P9 (audiologist, group 2): "[some models will] be a one-time thing. So, it shouldn't be an issue as much. But [for other products], you do it once you have the model, and you kind of replicate it for [the next] clients […], I guess that would be a little bit easier and quicker."

However, to attain this level of productivity and adaptability, collaboration with 3D printing experts was seen as an essential aspect of the process. Professionals highlighted that this collaboration should be as seamless as possible to ensure continuous and effective integration of 3D printing into rehabilitation practices. They envisioned an ideal process for obtaining 3D-printed objects that prioritized simplicity, accessibility, and speed. A simple, straightforward process is a key factor in encouraging professionals to explore and utilize 3D printing in their daily practices.

P5 (clinical activity specialist, group 1): "[...] the ideal process is [...] in terms of operation: simple, fast, accessible."*

As a result, the consensus naturally leaned towards rehabilitation centers having in-house staff with 3D printing expertise, capable of co-designing objects with professionals, and producing 3D material tailored to rehabilitation needs. To do so, they emphasized the need for, on the one hand, professionals to be minimally taught about 3D printing, enabling them to conceptualize potential projects and communicate effectively with 3D printing experts; and, on the other hand, for 3D printing experts to also be minimally trained regarding sensory impairments and rehabilitation. According to the discussions, this collaborative approach is essential for streamlining the process and ensuring that 3D printing aligns seamlessly with rehabilitation services' goals and requirements.

P7 (orientation and mobility specialist, group 2): "[…] it would be good if [the 3D printing expert] has some [rehabilitation knowledge or background]. [Otherwise, they] may not really understand how we use it, what we need."

P4 (clinical activity specialist, group 1): "[you] send us your [requests], we sit down together, we design [it], and then we print it."*

Participants also emphasized the need for a straightforward communication process to ensure this collaborative approach. Indeed, communication was a key theme as professionals advocated for upstream, constant communication between professionals and 3D printing staff in addition to streamlined request forms for traceability purposes.

P4 (clinical activity specialist, group 1): "A new request form that will help you send us requests of all kinds. [...] It's super easy […] We receive and process them. […] Then, we look into it together [and find] what would be ideal."*

P2 (audiologist, group 1): "What I'd do is call them first because I'm not sure all my ideas can be modeled [...] before filling in that form."*

Discussion

The present focus group study aimed to explore the potential applications of 3D printing in deafblindness rehabilitation from the perspective of rehabilitation practitioners. Throughout the discussion, 3D printing emerged as a potentially beneficial tool for professionals to improve their clients' quality of life. Most notably, participants identified applications to improve compensatory skills, access technology skills, orientation and mobility skills, and independent living skills. Applications included tools to aid their clients in many tasks and activities and to complement their teaching and communication abilities as professionals. Participants were also able to pinpoint the main barriers and facilitators – mainly related to training, available resources, time, and budget – that could influence the transferability of this technology into their practice. Ultimately, this discussion allowed them to brainstorm the most efficient system to produce and provide 3D-printed material to their clients.

Current and potential 3D printing applications (theme 1)

Deafblindness can affect several aspects of functioning across the nine domains of the Activity and Participation component of the International Classification of Functioning, Disability and Health (ICF) framework (see Table 3). As part of the development of ICF Core Sets for deafblindness, these effects have been examined through a systematic literature review (33) as well as from the perspective of experts in the field of deafblindness (34) and individuals with lived experience (35). For example, a more detailed exploration of these effects of deafblindness in the context of communication using the ICF framework has been presented elsewhere (36). Similarly to a recent literature review (14), the discussions underlined notable applications to support individuals with deafblindness in domains such as *learning and applying knowledge (d1)*, *mobility (d4)*, and *communication (d3)*. Furthermore, the study also highlights additional functional adaptations that can improve independent living skills, therefore improving ICF domains such as *major life areas (d8), self-care (d5), domestic life (d6), and general tasks and demands (d2)*; some of which were already successfully used by professionals and their clients. Figure 1 displays these 3D printing applications, combining those found in the literature review (pink) and those discussed in the present focus group study (green).

Mainly, the discussion emphasized the utility of 3D printing for learning and education (see theme 1, subtheme a). Indeed, deafblindness, characterized by the challenge of compensating for two impaired senses (5), leads to diverse learning abilities among individuals (37). Consistent with existing literature, participants agreed that 3D printing can harness a third sense, touch, by creating tangible products to enable greater learning potential. Mainly, 3D models can enhance general knowledge acquisition in STEM and health domains, thus increasing the accessibility of all levels of education (16, 19, 38-41). 3D printed products can provide customized learning opportunities (42, 43), a promising avenue echoed by participants who highlighted the flexibility of 3D printing to produce more tactile experiences and broaden the accessibility of various concepts (30, 44, 45). As seen in previous work (42), 3D models facilitate comprehension and learning by addressing challenges related to size (e.g., too large or too small), distance (e.g., animals in distant countries), or abstractness (e.g., trees, clouds, internal organs). Anatomic models (i.e., eye models) could also improve awareness of certain health conditions, their symptoms and evolution, therefore helping clients in monitoring their health and knowing when to seek support.

Participants emphasized the potential for creating adaptive solutions to enhance independent living skills (see theme 1, subtheme c) with examples that, comparably to prior studies (46, 47), had proven beneficial for their clients (tagging systems for food, check guides, adaptations for touchscreen appliances).

Additionally, discussions revolved around expanding the available library of printable 3D models by designing adaptations to help handle, identify, and store smaller devices like hearing aids and remote controls. Participants also explored adaptations to improve general organization skills (i.e., tactile schedules) and access to mainstream technologies (i.e., models to learn how to navigate computers and smartphones) that have the potential to increase employment, a priority in the community (3, 13, 45).

As for orientation and mobility, 3D printing is an interesting avenue to produce tactile maps (see theme 1, subtheme a) while using handmade materials is time-consuming and limited for the representation of essential aspects of the environment. Consistently, previous work has shown the potential of 3D printing to automatically create tactile maps with CAD design and open satellite data (48, 49), and even decrease exhaustion in professionals (23-25). Furthermore, 3D information can also improve the ability to develop a general mental understanding of an environment, and thus, improve memorization of routes, orientation, and general independence (50, 51). This notable advantage stems from the possibility to expose clients to essential concepts previously inaccessible with traditional 2D graphics, particularly those related to depth, such as occlusion, building dimensions, and land elevation (24, 50, 52, 53). Therefore, 3D tactile maps could enable professionals to represent more types of environments and adapt more easily to the needs of their clients.

Finally, this study highlights the potential of 3D printing applications to decrease communication barriers for individuals with deafblindness (see theme 1, subtheme b), which aligns with previous research and development in affordable communication devices, notable examples include tactile boards and devices like the *Hapticomm* (27, 28, 54, 55). Most notably, 3D printing can become a tool to enhance professionals' communication strategies when working with clients who use tactile sign language (TSL), have limited vocabulary, or have difficulties understanding concepts, a challenging aspect even with many years of experience (56). As expressed by participants, tangible support material that enriches teaching methods and ensures better comprehension, motivation, and engagement among clients (23) can facilitate and speed up lessons. As a result, reducing communication barriers between individuals with deafblindness and rehabilitation professionals or caregivers with 3D printed material could, in turn, positively impact various aspects of individuals' lives targeted in rehabilitation.

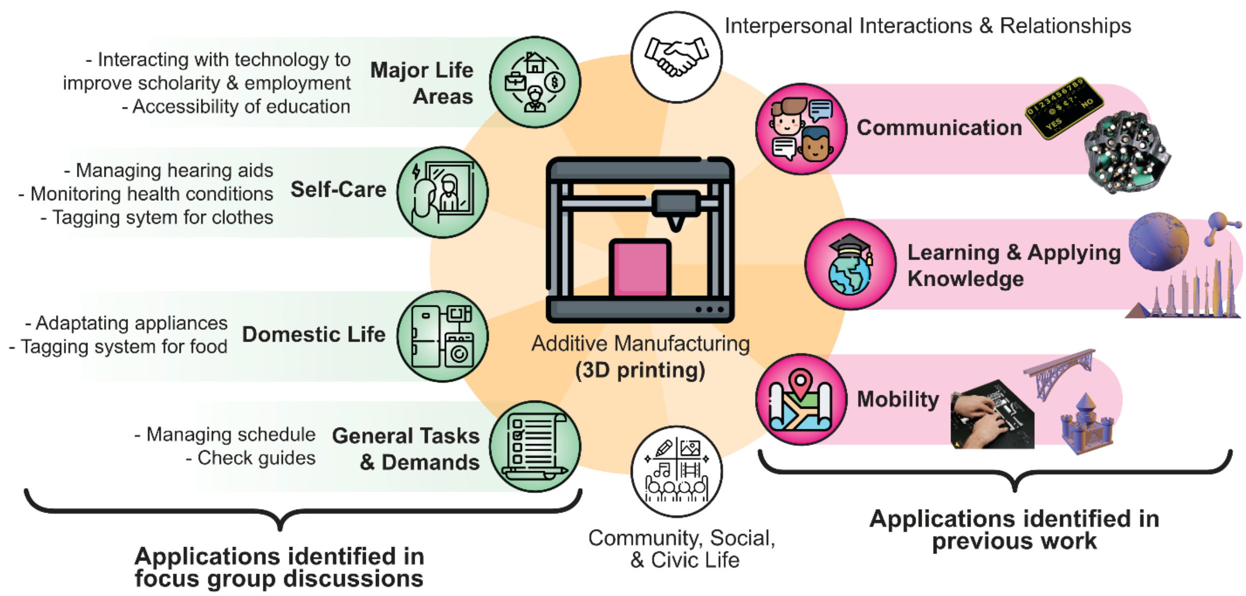

Figure 1. Current and potential applications of 3D printing in rehabilitation according to the nine ICF activity and participation domains (modified from (14)). Current applications (in magenta) were previously identified in three domains: *communication, learning and applying knowledge,* and *mobility*. Potential applications (in green) were identified in four other domains (*major life areas, domestic life, self-care,* and *general tasks & demands*) and emerged throughout the discussions. However, applications in *interpersonal interactions & relationships,* and *community, social, & civic life* (in white) were not identified. This figure was created using resources from Flaticon.com and thingiverse.com (3D models by minicityart, XtrudeLAB, bld, wolverineboat, and guiosca).

While the present study did not bring forward applications to improve domains such as interpersonal interactions & relationships, and community, social & civic life, one can speculate that 3D printed products could in fact impact these areas, whether it is by using devices to improve communication and, therefore, facilitating relationships (57); by enabling individuals with deafblindness to access the same knowledge as their peers (58); by creating tactile objects that can be jointly explored, therefore creating shared experiences (59); or by increasing accessibility of leisure and civic activities with tactile adaptations. Indeed, recent applications of 3D printing in vision rehabilitation include leisure activities such as puzzles and board games (60), means to increase accessibility of art, cultural or natural sites, and children's artbooks (42, 58, 61-65), all of which can foster interpersonal connections between deafblind individuals and their family, friends, and communities. Furthermore, the 3D printing community can help with the creation and distribution of 3D printed models (45), a factor that can further foster a sense of community.

Table 3. 3D printing applications to support in challenges related to deafblindness and each ICF Activity and participation domains.

ICF Activity and participation domains	ICF Code example & definition	Challenges for individuals with lived experience of deafblindess	3D printing applications/solutions
d1: Learning and applying knowledge	d1200 Mouthing: Exploring objects using **mouth** or lips. d1201 Touching: Exploring objects using **hands**, **fingers** or other limbs or body parts.	Understanding the shape of objects that are too large to explore manually, or are inaccessible for tactile exploration (e.g., the shape of an elephant or an airplane)	Potential applications: Educational models like those used with blind individuals (19). Support material for professionals during their interventions (theme 1, subthemes a and b). Such 3D models could be explored by hands and mouth (66). Evidence of 3D printing benefits: Evidence by blind individuals using 3D printed models to access otherwise inaccessible concepts (42, 67).
d2: General tasks and demands	d2100 Undertaking a simple task Preparing, initiating and arranging the **time and space** required for a simple task	Teaching and demonstrating abstract concepts like time, sequence, routine, or cause & effect	Current applications: Check guides (used by participants in focus group 1, theme 1, subtheme c) Potential applications: Tactile calendars to manage schedule and other tools to learn routines of every day life (68). Evidence of 3D printing benefits: x
d3: Communication	d3152 Communicating with - receiving - drawings and photographs: Comprehending the meaning represented by drawings (e.g. line drawings, graphic designs, paintings, **three-dimensional representations**, pictograms), graphs, charts and photographs, such as understanding that an upward line on a height chart indicates that a child is growing.	Personalizing communication tools that address individuals communication needs.	Current applications: 3D printed communication cards (22), letters and tokens (theme 1, subtheme b). Potential applications: Communication devices for clients (55) and supporting material for professionals (24). Evidence of 3D printing benefits: Anecdotal evidence from one deafblind individual and a team of professionals using a 3D printed communication system (57).
d4: Mobility	d440 Fine hand use: Performing the coordinated actions of handling objects, picking up, manipulating and releasing them using one's hand, fingers and thumb, such as required to lift coins off a table or turn a dial or knob.	Personalizing training and teaching tools that facilitate mobility by exploring tactile maps	Current applications: 3D models (buildings, street intersections) are used by some O&M specialists, rehabilitation centers and museums (69), as evidenced by P1 and P3 (theme 1, subtheme a). Potential applications: Publicly displayed, affordable, tactile maps (70).

			Evidence of 3D printing benefits: 3D printed tactile maps offer greater range of environmental representation and improve cognitive mapping abilities (50, 51).
d5: Self-care	d5404 Choosing appropriate clothing: Following implicit or explicit dress codes and conventions of one's society or culture and dressing in keeping with climatic conditions.	Creating individualized tools that facilitate daily activities related to grooming	Current applications: tagging system for clothes (47). Potential applications: Supporting tool to learn how to use and maintain hearing aids Evidence of 3D printing benefits: x
d6: Domestic life	d6403 Using household appliances Using all kinds of household appliances, such as washing machines, driers, irons, vacuum cleaners, dishwashers.	Using appliances with touch screen interfaces that do not provide tactile information	Current applications: tagging system for food, tactile adaptations for touchscreen appliances (46) like those used by participants in group 1 (theme 1, subtheme c). Potential applications: individualised interfaces that facilitate touchscreen interaction Evidence of 3D printing benefits: x
d7: Interpersonal interactions & relationships	d750 Informal social relationships: Entering into relationships with others, such as casual relationships with people living in the same community or residence, or with co-workers, **students**, playmates, people with similar backgrounds or professions.	Building relationships with individual that are unfamiliar with deafblindness and the necessary accommodations for communication	Potential applications: Fostering relations by facilitating communication and shared experiences, or by supporting the development of social skills (43). Evidence of 3D printing benefits: 3D printed models can increase collaboration between students in a classroom for children with vision impairments (23).
d8: Major life areas	d820 School education: Gaining admission to school, education, engaging in all school-related responsibilities	Providing personalized tools that can facilitate accessibility	Current applications: 3D models are used by some professionals to teach how to use technology (i.e., smartphones and computers according to P6, theme 1, subtheme a). Evidence of 3D printing benefits: educative models can enhance the accessibility to educational programs and jobs (19, 71, 72).
d9: Community, Social and civic life	d9202 Arts and culture: Engaging in, or appreciating, fine arts or cultural events, such as going to the theatre, cinema, **museum or art gallery**, or acting in a play, reading, being read to,	Accessibility of 2-dimensional art	Current applications: Creation of 3D models to represent art (paintings, sculptures, historical artifacts) according to the interest of the individual (73, 74); or access cultural sites (61).

	dancing, singing or playing a musical instrument for enjoyment.		Evidence of 3D printing benefits: Evidence by blind individuals accessing museums expositions with the support of 3D printed recreations (75).

2

Characteristics of 3D printed products (theme 2).

According to the discussions, the main advantage of 3D printing, compared to other traditional methods, resides in the possibility of producing faithful representations of real-world objects (30, 42, 61, 76), facilitating comprehension to those who may struggle with more abstract symbols and shapes (76). However, professionals emphasized that requirements and guidelines regarding adapted tactile or visual material (77-79) must apply to 3D printed products. These include 1) contrast, either visual (using discriminable colors or luminosity levels) or tactile (easily discriminable textures and embossing levels); 2) scaling that allow easy discrimination between elements (i.e., space between lines, different textures and symbols); 3) magnification to access all essential details; 4) comprehensible labeling, legends, or instructions, which can be helpful for novel 3D printed objects (53, 80, 81). Other design aspects brought by participants regarded the ergonomics of more utility-oriented tools, such as ease of manipulation and durability. This aligned with development guidelines of physical and electronic aids (82-84), and thus with the overarching goal of enhancing clients' autonomy by enabling them to interact safely and autonomously with 3D printed objects (30, 81). Finally, professionals also emphasized the need for 3D printed material to be a pleasurable experience for users, which echoes the importance of eliminating 3D printing artifacts (i.e., stringing, pointy edges, lines, and rough surfaces) that can hinder the tactile experience (23, 80).

Integrating 3D printing in rehabilitation (themes 3, 4, and 5)

The discussions, consistent with prior work, reaffirmed the potential of 3D printing to improve the affordability and availability of assistive technology by enabling production within rehabilitation centers (23-25, 44). Professionals who already use this technology within their practice agreed that it offers more intervention possibilities while braille technicians argued that it can offer time-saving benefits through automation and access to online repositories of adaptable 3D models (45, 85). However, our study unveils that limited 3D printing awareness among professionals hinders its consideration, especially given their worries about the diverse needs of clients and concerns about budget. Importantly, in a context where professionals are already using time-consuming methods to address shortages of adapted material (23-25, 86) combined with tight timelines of rehabilitation episodes, introducing 3D printing should not exacerbate exhaustion or increase client waiting times. Furthermore, the adoption of 3D printing by professionals may also prove challenging due to the considerable training it requires (15, 25, 86). According to the focus groups, the optimal approach to introduce the technology is to have full-time staff with 3D printing expertise who receive requests from professionals and clients, resembling how centers already produce other adapted materials such as braille books. These employees should also possess minimal rehabilitation training to engage in the co-design process with the team.

Interestingly, the two focus groups differed in terms of their concerns regarding this implementation approach to 3D printing. While group 2 could only speculate and, therefore, worried about printing times and the needed budget to acquire 3D printers and trained personnel, group 1 was actively implementing this logistical approach, and their exchanges fostered new creative ideas, diminished the perceived access barriers to specialized material, and shed light on additional challenges. Despite easy access to 3D printing, they underscored the importance of accessible resources and efficient interdisciplinary communication, as they felt that communication barriers between the different departments limited the knowledgeability of this fabrication technology. Consistent with previous literature, they emphasized that exposure to success stories and online repositories could continually inspire professionals to benefit from 3D printing resources (45, 85), and that these repositories could potentially be internal to the rehabilitation center or internationally shared between centers to increase the number of possible applications. Indeed, promoting international collaborations and sharing 3D printing models for rehabilitation could not only accelerate 3D printing adoption (85), but also streamline assistive technology production, particularly in regions with limited financial resources (44, 87).

Limitations of the study

While this study brings insights into the potential rehabilitation products offered by increasingly accessible 3D printing technology, it is essential to acknowledge its limitations. On the one hand, this study involved a relatively small sample size of rehabilitation professionals working in Quebec, Canada, during the circumstances of the COVID-19 pandemic. Therefore, regional variations in rehabilitation practices and access to resources may influence the applicability of the study's findings. On the other hand, this study relies on discussions without practical testing, which emphasize the need for additional validation of the identified applications and challenges linked to the adoption of 3D printing as a rehabilitation tool. Indeed, no available research has explored the extent to which 3D printing can positively impact the life and rehabilitation process of individuals with deafblindness. As a result, the perspectives of people with deafblindness on the benefits of 3D printing are still poorly understood. Future research should explicitly involve people with deafblindness to determine their opinions on the benefits and practical applications 3D printing. Furthermore, discussions in the context of this research have emphasized the importance of the co-design process between rehabilitation professionals and 3D printing experts, but the involvement of clients with deafblindness in this process may prove essential in developing the best 3D printing practices and insuring its adoption by clients (88). Due to these reasons, the team is interested in conducting a follow-up study in collaboration with rehabilitation centers and their clients to address this gap. This endeavor would aim to accumulate evidence on the evolving integration of 3D printing within the practices of rehabilitation professionals and its reception by clients with hearing and vision impairments.

Conclusion

This focus group study highlights the potential applications of 3D printing in deafblindness rehabilitation. Rehabilitation professionals explicitly agreed that its versatility as a fabrication technology can help improve the adaptability of their interventions and enable the production of more concrete material that can positively impact learning, mobility, communication, and independent living. However, this study also emphasizes the need for validation and enhanced knowledge dissemination within rehabilitation centers to integrate 3D printing seamlessly into deafblindness rehabilitation. Local and global collaborations, co-design approaches and online repositories were deemed essential to achieve this goal.

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