An Auditory Interface to Workspace Awareness Elements Accessible for the Blind in Diagrams' Collaborative Modeling

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***Abstract*—This Research Full Paper presents the design and evaluation of an auditory interface that allows blind people to perceive workspace awareness elements in a shared environment for modeling diagrams. Approximately 36 million Brazilians are visually impaired, where half a million are blind, and the enrollment of the blind at Brazilian higher public education institutions has been increasing. However, accessible tools for diagram authoring are scarce, despite their necessity on STEM courses. There are studies and new developments regarding the perception and authoring of diagrammatic information, but they do not consider collaborative features. Therefore, this study proposes the sonification of workspace awareness elements as a solution to enable accessible groupware features for the blind. It was designed auditory cues for three awareness categories (who, what, and where) using abstract sounds and favoring suitable metaphors for an intuitive mapping. The designed auditory cues were implemented in a prototype application for collaborative diagram modeling and evaluated through an objective usability test. The results demonstrated that participants could reasonably distinguish who made what and where. Besides, it was possible to identify the awareness categories which need more work.**

***Index Terms*—blind people, accessibility, auditory interfaces, diagrams, workspace awareness**

I. Introduction

It is estimated that more than 285 million people had some form of vision impairment, and at least 39 million were blind, according to the global data on visual impairment released by the World Health Organization in 2010 [1]. In the same year, there were 500 thousand blind people in Brazil, according to the 2010 Census [2]. The right to education for the blind and visually impaired are treated in the UN Convention on the Rights of Persons with Disabilities, where the article 24 declares that States Parties recognize the right of persons with disabilities to education by equal opportunity, and shall ensure it at all levels and lifelong learning [3].

In Brazil, there are affirmative actions to ensure the access and permanence of People with Disabilities (PwD) to public educational institutions. Due to Federal Law no. 12,711/2012 and 13,409/2016, which provide quotes in courses offered in federal vocational education institutes and universities, there was an increase in PwD students enrollment.

Despite these improvements, there are still challenges to BVI education [4]–[8]. For instance, after the entry of blind students into the informatics technician course at the vocational institution where the primary author works, it was noticed the scarcity of accessible tools for diagram design. Diagrams are hugely employed in science, technology, engineering, and mathematics fields [9], especially in the computing field. Other studies have related the same difficulty, e.g., for UML modeling [10], [11], molecular structures [12], database design [13], and statistics charts [14].

There are known studies regarding the accessibility of diagrams. They are primarily focused on perception [15], but also navigation and authoring features [16]. However, few studies handle collaboration issues on modeling diagrammatic content along with other blind or sighted people simultaneously [17].

The educational effects of collaborative activities are studied in the collaborative learning field. There is evidence that group learning activities improve engagement, grading, and self-esteem [18]–[21]. Thus, the learning process could be jeopardized by curtailing blind and visually impaired students from working together.

The design and implementation of applications that support collaboration are studied in the groupware field, and the way

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how people perceive others' interactions, specifically, is a groupware topic known as workspace awareness. That being said, an inclusive groupware application with an accessible workspace awareness should allow blind users to be aware of their colleagues' actions through interfaces alternative to vision-based.

Therefore, the goal of this study was to use an auditory interface for signaling workspace awareness elements and allow blind people to perceive other people's actions in a diagrams editor tool. It was designed an Earcon-based interface that uses abstract sounds to signaling three basic categories of awareness: who is doing what and where. In other words, it was intended that the blind could be aware of who is authoring, what action is being made, and in which location, so one can track and follow the workspace changes.

It was developed a minimal prototype as a desktop web application and based on the designed sonification techniques. Then, it was conducted a user testing session, evaluating the interface through the success rate per task method. Five participants listened to the auditory cues and answered what they have perceived, which was compared to signals actual emitted.

II. Background

Blind people typically perceive the world by either audible or haptic resources. As audible ones, there are verbal and nonverbal options, i.e., these solutions either use speech to communicate or other sounds that are not recognized as a discourse. As haptic assets, there are touch and kinesthetic solutions, where the former is perceived through fingertip sensation of texture, pressure, temperature, and vibration, and the later is sensed in muscles and articulations, being recognized as weight and resistance.

A. *Sonification*

Sonification is the transformation of data relations into auditory signals that can be communicated and interpreted, where sounds are not recognizable as a discourse [22]. The sonification study field is multidisciplinary and encompasses linguistic, acoustics, audio engineering, and psychoacoustics. Sonification applications are in numerous daily elements, such as vehicles, electronics, and other devices, which use abstract sounds to deliver messages to users [23]. Various sonification techniques can be employed to convert and represent information. As Auditory Icons and Earcons are the most common options, they are detailed in the following.

Auditory Icons have the intention to mimic the real-world sounds, therefore, facilitating users' comprehension as they represent direct mappings. For instance, in a chat application, it would be possible to play a typewriter sound to represent that the user on the other side is typing something. As their name suggests, they are icon-like sounds, supposing users catch the meaning as the same form as visual icons, through the relationship between a signifier and signified [24].

Earcons are message-like sounds distinct enough to represent specific events or convey information. They differ from Auditory Icons as they represent abstract relationships between signifier and signified, i.e., users are required to learn the meaning of each sound as there is no direct mapping [25].. On the other hand, they offer more flexibility to the representations, which can be assigned to almost any object, item, or process on user interfaces [26]. Without direct correspondence to the real world, Earcons rely upon the acoustic design to convey and communicate different parts of information, for instance, varying timbre, pitch, frequency, loudness, and amplitude of the audible signal [25].

B. *Workspace Awareness*

The term Workspace Awareness (WA) was coined by Gutwin and Greenberg [27] as *"the collection up-to-the-minute knowledge a person uses to capture another's interaction with the workspace."* WA is a key-feature, essential to design applications that support collaborative work [28]–[30].

WA aids coordination of tasks and resources when people are working in shared activities, and happens naturally and spontaneously in face-to-face environments. However, it is not so simple in real-time groupware systems where people cannot see the entire workspace or the same part as other members are viewing and resources they are working [31].

There are two common issues to tackle when designing workspace awareness support: (1) which information about others' interaction should be collected? (2) how to present such information to other participants? Gutwin and Greenberg handled both questions. They designed a framework to address the former and discussed common mechanisms that could be used to manage the latter.

The conceptual framework [27] handles common groupware design issues related to what information should be gathered and presented to users in real-time distributed applications. They classified this information as elements that should answer the following categorized questions: Who? What? Where? How? And when? The first three questions belong to the present time while the last two ("how?" and "when?") are related to events that took place in the past, as can be seen in Table I.

TABLE I
ELEMENTS OF WORKSPACE AWARENESS

Category	Element	Specific questions
Who	Presence	Is anyone in the workspace?
	Identity	Who is participating? Who is that?
	Authorship	Who is doing that?
What	Action	What are they doing?
	Intention	What goal is that action part of?
	Artifact	What object are they working on?
Where	Location	Where are they working?
	Gaze	Where are they looking?
	View	Where can they see?
	Reach	Where can they reach?
How	Action History	How did that operation happen?
	Artifact history	How did it come to be in this state?
When	Event history	When did that event happen?

Regarding how to present awareness information to users, Gutwin and Greenberg [27] gathered commonly employed mechanisms through a literature review, and organized them as follow:

- *Direct communication*: users explicitly communicate their actions through speech or gesture.
- *Indirect productions*: utterances, expressions, or actions that are not directed at others, but are intentionally public.
- *Consequential communication*: users observe or listen to signs of others' interaction within a workspace.
- *Feedthrough*: users notice the effects of others' actions through artifacts' updates.
- *Environmental feedback*: users notice the indirect effects of others' actions in the workspace.

Those mechanisms provide a natural mapping, which groupware designers could consider to create techniques and widgets to convey awareness information in shared virtual environments. Besides, this conceptual framework can provide a vocabulary that can be used as a starting point for thinking about awareness requirements while designing collaborative applications [27].

III. Workspace Awareness Sonification

Taking an application for diagrams' collaborative modeling. It would be possible to turn others' actions perceptible to the blind through an auditory interface and sonification of essential workspace awareness elements. This way, blind users could get access to collaborative resources in order to follow workspace updates.

Collaborative applications usually present awareness information through graphical interfaces, i.e., using widgets and other visual cues to signaling workspace updates. For example, online writing applications, like Google Docs or Microsoft Word, represent and differ simultaneous participants by colored text cursors, allowing collaborators to be aware of what and where others are authoring.

It was designed a solution based on Gutwin and Greenberg's conceptual framework. At this point, it was specified how a blind user would perceive a subset of the workspace awareness elements, one per category, as follows:

- *Authorship*: signaling which user made an action. It belongs to the "Who" category.
- *Action*: signaling which action was made by a user. It belongs to the "What" category.
- *Location*: signaling where a user committed an action. It belongs to the "Where" category.

In this first approach, the goal was to gather essential information about the actions that could take place in the workspace. Then, this information is sonified according to the rules and techniques explained in the following topics. Each one was built using a mechanism that aims an intuitive mapping.

A. Awareness of "Who/Authoring"

A solution was designed to turn the awareness of "Who," accessible to the blind. At first, the entry and exit of collaborators in the workspace could be enunciated to the user using speech resources. These techniques are based on the mechanism of indirect production and are suitable for signaling who is participating and one's presence. However, it was needed a different strategy for signaling authorship, i.e., who is acting.

The idea was to signaling the consequence of the actions being made by the coparticipants. The mechanism of consequential communication seemed suitable for signaling this awareness element (authorship). The next design decision was how to map an abstract sound to a specific user or, in other words, how a nonverbal sound could represent a specific agent within a workspace?

The solution was inspired by how online collaborative writing works, representing each user by a colored cursor and avatar. Thus, the design was based on the tone color or timbre, which is the perceived sound quality. The timbre allows us to distinguish sound with the same frequency, i.e., note or pitch. Consequently, sounds produced by different instruments have different colors.

The workspace sketch in Figure 1 illustrates the intended design. For instance, consider four users, including the local one. Each remote user has an instrument assigned in a way their actions trigger sounds that are played with their associated instrument. The local user knows the instruments as they are played along with the announcement of collaborators' entry.

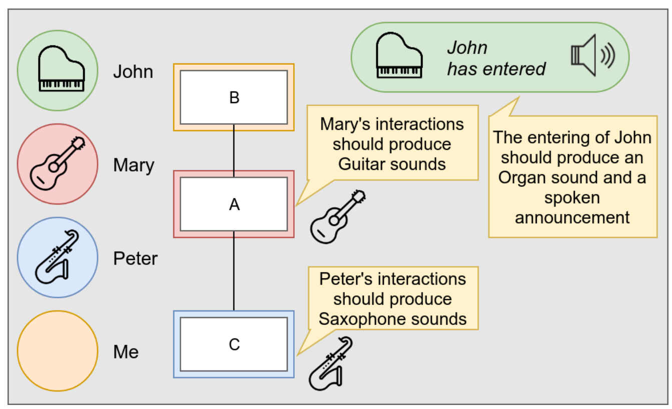

Fig. 1. Workspace sketch: awareness of "who is authoring".

B. Awareness of "What/Action"

A workspace artifact can be the target of numerous actions. For instance, a node in a graph diagram can be added or removed, and a table in an entity-relationship diagram can be renamed. Although these actions could be verbally announced, in this study, it was designed a nonverbal technique for signaling them.

It was necessary to simplify the model in order to reach a feasible generic solution based on Earcons, i.e., independent of the domain being modeled. Thus, it was considered three vital types of actions: addition, removal, and alteration.

The designed solution for this issue was to play chords varying the direction. That is, to play notes with ascending or descending pitch to denote additions and removals. These chords would produce a doppler effect of distancing as if something is moving away or approaching. The intention is to provide a proper metaphorical mapping, as "adding" would be the arrival of an artifact and "removal" would be the departure of it. Artifact alterations, on the other hand, would trigger a single note.

For instance, taking the action of adding an ordinary artifact into consideration, as illustrated by Figure 2, the local user would listen to an ascending C major chord sound, played by the instrument that represents the user who made the action. When a user deletes an artifact, it should play a descending C major chord. Both techniques seek to provide auditory cues in a way the blind user can perceive whether a collaborator is adding, removing, or altering an artifact.

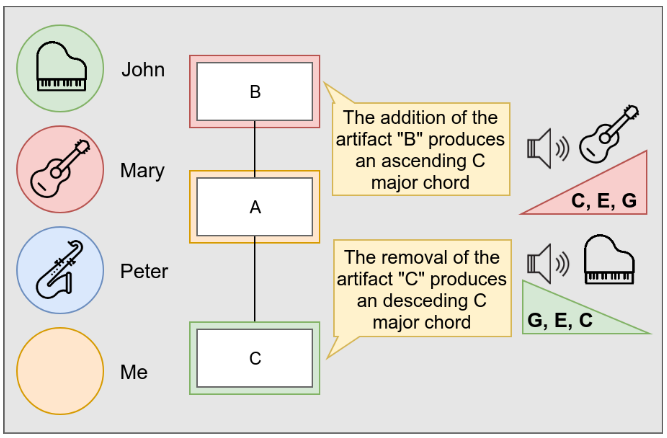

Fig. 2. Workspace sketch: awareness of "what action is being made".

C. Awareness of "Where/Location"

First, it was necessary to handle the issue of spatial layout in order to design an auditory interface that provides a proper location representation. Thus, this category required more designing thought, in order to provide a proper auditory cue representing the awareness of where other users are working on and allow a blind user to follow changes within the workspace.

Some authors [12], [32] consider that the objects' two-dimensional position could be relevant. Solutions that encompasses coordinates typically communicate them through haptic resources [33]. Studies that propose audible resources only, generally provide location cues through spatialized sound [34], [35]. Besides, there also are multimodal proposals, i.e., which combine audible and haptic resources [36], [37].

As a generic node/link solution for representing diagrams, it was required more attention to relationships between artifacts than the exact location of them within the workspace. Other studies reported the same approach [38]. For instance, Bennet [39] conducted an experiment where some blind participants had received information about artifacts' locations while others did not. It demonstrated that conveying the position information does not relevantly influence diagrams' comprehension or learning process.

Therefore, in this study, it is proposed a replacement for the two-dimensional spatial model. This replacement is based on three relative directions: left, front, and right (Fig. 3). It would be an alternative model to the blind, while sighted users would seeing the conventional spatial drawn model. This measure would permit using regular stereo headphones for signaling the direction where actions are taking place.

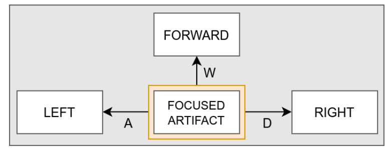

Fig. 3. Navigation using the relative directions model.

An alternative underlying layout based on relative directions was designed in order to turn positioning information accessible to the blind. As can be seen in Figure 4, while a sighted user would notice that the artifact "A" is below "B," a blind user would perceive "A" as at the left side of "B." Thus, the blind user would have to use the left key to navigate from "B" to "A" (Fig. 3), and the up key to navigate from "A" to "D."

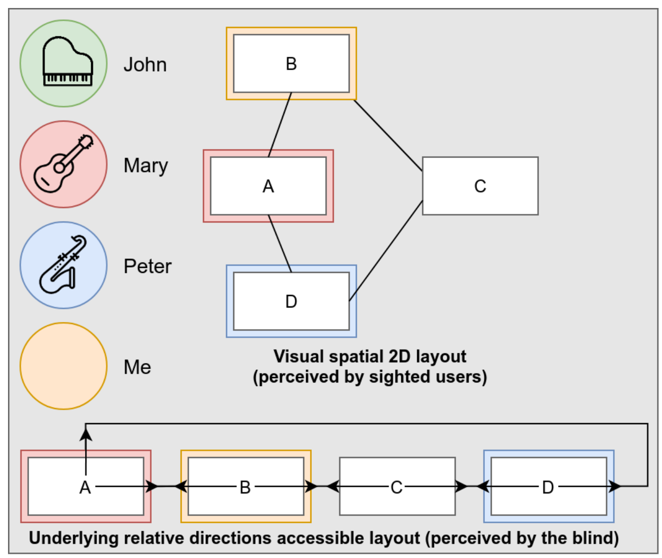

Fig. 4. Alternative underlying layout based on relative directions.

The alternative positioning model was designed not only to facilitate navigation but also for signaling the actions according to the relative direction where they are taking place. For instance, actions occurring at the left would trigger sound on the left channel of the headphone. The auditory cues were designed upon stereophonic effects, the same as a blind user would perceive events in the real world, i.e., listen to other people working in the surroundings. A similar metaphor was employed to communicate distance, always looking for an intuitive mapping.

The signaling of distance would provide cues to the blind on how much navigation effort he or she would need to reach artifacts being modified. As can be seen in Figure 5, it would depend on how far, by counting the links between the artifact focused and the target artifact. This auditory cue was designed based on loudness property in a way that updates being made right next to the user should play louder sounds, while farthest updates should play softly. The proposed loudness decrease strategy starts from one link at 100%, two links at 80% of volume, and keeps decreasing loudness by 20% for each additional link. Thus, it was designed to communicate up to five levels of distance: 100, 80, 60, 40, and 20 percent, where 100% represents an event happening at the adjacent artifact, and 20% percent represents an event taking place at the artifact located at the far end of the diagram.

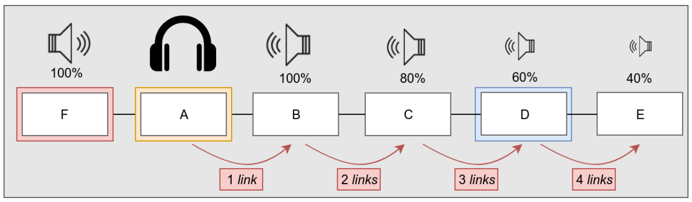

Fig. 5. Sound loudness according computed distance.

IV. Evaluation

A web-based prototype for diagrams' collaborative modeling was designed and implemented in order to evaluate the designed auditory interface. Subsequently, five participants were recruited for a usability test that is described as follows.

A. Prototype

The proposed auditory interface was implemented in a prototype for diagrams' modeling using web technologies such as HTML, CSS, JS, SVG, Vue.JS, SoundJS, and ToneJS. It resulted in a web application suitable for desktop computers.

As a prototype, a real multi-user environment was not implemented. However, it was designed to simulate multiple user activity, considering three users, previously registered and logged, namely: (1) "me" as local user, (2) Jane (represented by an Organ), and (3) Peter (represented by a Guitar), as can be seen in Figure 6.

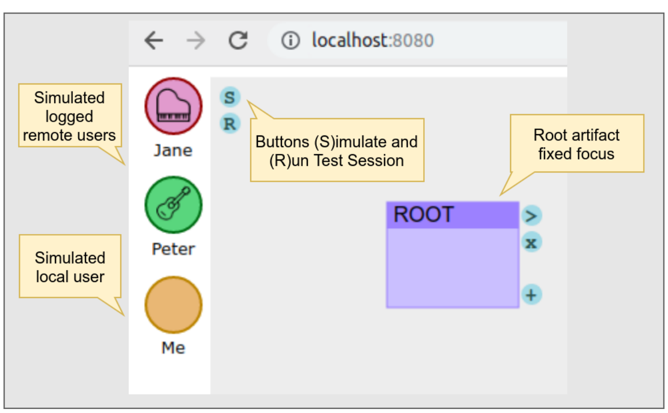

Fig. 6. Prototyped workspace and testing resourcess.

The prototype also considers that the local user ("me") has the focus on a pre-existing artifact named "root", which is fixed (Fig. 6), i.e., unable to navigate. Thus, the participant hears the sound cues from this "root" artifact perspective, i.e., as the diagram grows around this fixed point.

B. Usability Test

It was conducted a usability test to check whether the sound cues and awareness signals could be adequately perceived and distinguishable. Usability tests are empirical methods suitable to evaluate applications in the Human-Computer Interaction field. It was selected as a quantitative test, known as the success rate per task, which measures whether a user could safely accomplish particularly designed tasks [40].

During the recruitment, it was noticed the low population representation. However, even small user groups are suitable for this kind of usability test [41], [42]. Thus, there were recruited five sighted participants for the usability test. All participants had a computer science-related background. Besides, as researchers, they were acquainted with usability and accessibility issues.

The test environment was set up at the facilities of the Center of Computational Sciences. A laptop computer was positioned in a way the participants could not see the graphical interface nor access input devices. It was provided a stereo over-the-ear headphone with 20Hz 20Khz response. The volume was adjusted to 50%, observing the limit of 55dB recommended by the [43].

Previously to the test session, each participant had approximately 10 minutes to get acquainted with the auditory interface. The basic concepts were explained, e.g., the relative directions model and sound effects for each awareness signaling. The test session only initiated after all doubts have been settled.

During the test session, participants were asked to accomplish 20 tasks, referenced from now on as Test Cases (TC). In each TC, a simulated random user (Jane or Peter - same probability) acts (addition or removal - 60% / 40% probability) in a random direction (left, right, or front - same probability). The "addition" action was favored to avoid ending up with a null diagram. Only the nodes at the far end were updated. Each iteration triggered a sound carrying three awareness information: (1) who/user (as a musical instrument), (2) what/action (by playing a chord) and (3) where/direction/distance (by switching stereo channels and fading the sound volume). Participants listening to the sound cues were asked about what they perceived according to Table II. There was no time limit, so the test session was suspended until a participant answer the question.

V. Results

The comparative chart in Figure 7 demonstrates the success rate of each participant and the average result for each awareness category. Overall, the signaling of which user, action, and direction obtained at least 75% of correct perceptions on average. The exception was regarding distance signaling,

TABLE II
QUESTIONS SUBMITTED TO PARTICIPANTS.

Question	Awareness Category	Possible answers
Who made the action?	*"who/user"*	Jane/Organ or Peter/Guitar
What was done?	*"what/action"*	Addition or Removal
In which direction?	*"where/direction"*	Left, Right, or Front
How many links away?	*"where/distance"*	Number between 1 and 5

which achieved only 43% of exact answers on average. Each category is examined in detail in the following.

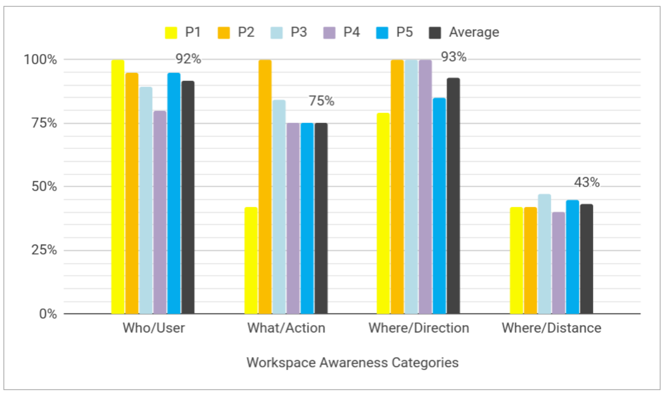

Fig. 7. Overall success rate per participant and on average.

Answering the question "who made the action?" participants had to distinguish whether sound cues were played with an organ or a guitar. Thus, particularly considering the awareness of "who," there was a minimum success rate of 80% and a maximum of 100%, with low dispersion (sd=8%). The average success rate was 92%.

To answer to the question "who made the action?", participants had to distinguish whether sound cues were been played with an organ or a guitar. Thus, in consideration to the awareness of "who", particularly, there were a minimum success rate of 80% and a maximum of 100%, with low dispersion (sd=8%). The average exact perceptions was 92%.

To perceive which action was done, participants had to distinguish whether the chords were played with ascending or descending tones. Te worst success rate was 42%, and the better was of 100%, showing a higher amplitude than other categories. The results were also more disperse (sd=21%), as can be seen in Figure 8.

Participants had to distinguish whether the sound cues were played at the left, right, or in both channels in order to answer "in which direction" an action was made. This category had an average of 93% of correct perceptions. Three of the five participants distinguished all cues and obtained a success rate of 100%. The standard deviation for this category was 10%.

In order to perceive the exact distance from where actions were taking place, participants had to distinguish five levels of loudness variations. There were only 43% of success in this

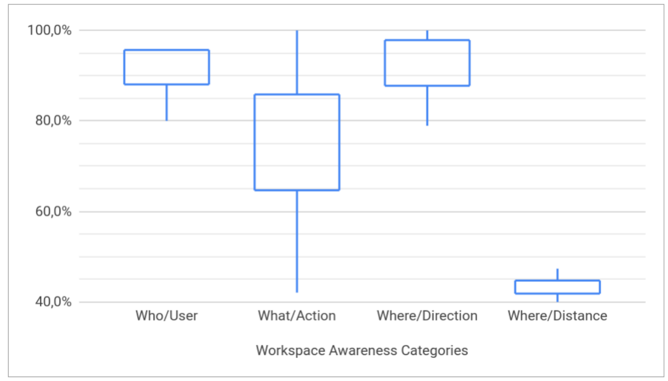

Fig. 8. Success rate dispersion per awareness category and auditory cue.

category on average, with low results dispersion (sd=3%). The misinterpreted perceptions were analyzed, and it was noticed that 36% of the responses were wrong by just one level, as can be seen in Figure 9.

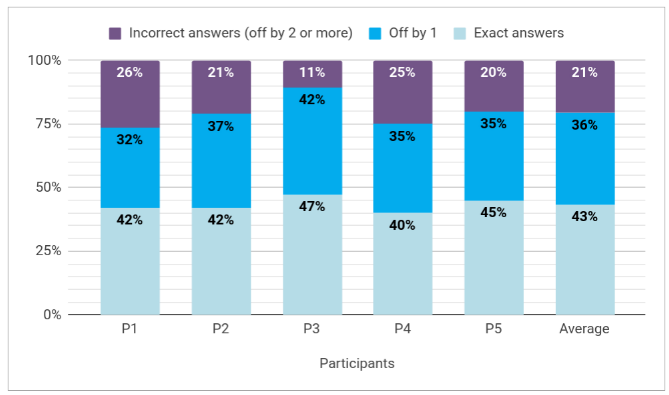

Fig. 9. Incorrect answers analysis on where/distance perception.

VI. DISCUSSION

The designed auditory interface aimed to overcome an obstacle for blind people to participate in collaborative sessions of diagrams' modeling. According to the results, it seems feasible for blind users to be aware of what others are doing in a shared workspace. In the usability test, participants could perceive who was doing what and where.

However, it is necessary to improve the awareness of "what/action." This category had a higher standard deviation, which could mean that the designed auditory interface is not suitable for everyone. In addition, the poor results in signaling "where/distance" indicate that it needs a redesign. The high number of approximate answers suggests that the success rate could improve if there were fewer levels and with a more spaced volume between them.

As future developments, there are improvements for the auditory interface, as stated before, and new features for the prototype, like the possibility of repeating the last sound cue and navigating among the artifacts. Both could improve user experience and help to obtain better results.

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