# Comparing Tactile, Auditory, and Visual Assembly Error-Feedback for Workers with Cognitive Impairments

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## ABSTRACT

More and more industrial manufacturing companies are outsourcing assembly tasks to sheltered work organizations where cognitively impaired workers are employed. To facilitate these assembly tasks assistive systems have been introduced to provide cognitive assistance. While previous work found that these assistive systems have a great impact on the workers' performance in giving assembly instructions, these systems are further capable of detecting errors and notifying the worker of an assembly error. However, the topic of how assembly errors are presented to cognitively impaired workers has not been analyzed scientifically. In this paper, we close this gap by comparing tactile, auditory, and visual error feedback in a user study with 16 cognitively impaired workers. The results reveal that visual error feedback leads to a significantly faster assembly time compared to tactile error feedback. Further, we discuss design implications for providing error feedback for workers with cognitive impairments.

## CCS Concepts

**•Human-centered computing → Human computer interaction (HCI); Empirical studies in accessibility;** *Haptic devices; Auditory feedback;* **•Computing methodologies → Mixed / augmented reality;**

## Keywords

Multimodal Interfaces; Error Feedback; Assistive Systems; Cognitively Impaired Workers; Augmented Reality

## 1. INTRODUCTION

Sheltered work organizations are employing workers with cognitive disabilities for working on assembly tasks. Usually these assembly tasks can be broken down to very little complexity in order to fit the skill of cognitively impaired workers. Depending on the skill of the worker, this number of assembly steps is very little. To provide cognitive assistance

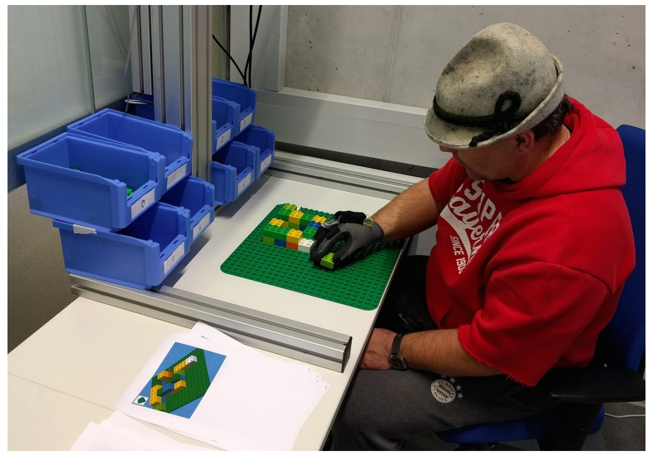

**Figure 1: A participant is wearing an augmented glove providing tactile error feedback during assembly tasks.**

for workers with cognitive disabilities during work tasks, assistive systems for the workplace have been proposed in the last years [15]. These systems usually use in-situ projection to provide information directly in the worker's field of view. Assistive systems can be used to continuously support workers and provide steady quality feedback, or they can be used to train workers to learn and adapt new assembly instructions very quickly.

The "United Nations Convention on the Rights of Persons with Disabilities" [1] describes how to ensure and protect fundamental rights of people with disabilities. This comprises of the inclusion in daily life tasks, such as work and public leisure activities. Cognitively impaired workers that are employed for conducting manual assembly tasks usually need a human instructor, who supports them during assembly tasks. The instructor is often responsible for multiple workers, which makes it difficult to check each assembly step of each worker for errors. Assistive systems providing assembly instructions can be used to reduce the number of assembly errors while decreasing assembly times [13]. However, errors can not be completely avoided. Therefore, assistive systems can be used to detect assembly errors and to provide appropriate error feedback if an assembly error occurs. Usually this error feedback shows the worker that the last assembly step has to be corrected in order to assemble the part correctly. Possible error feedback modalities delivered to the worker can be manifold but perceived diverse in terms



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of intrusiveness, comfortableness, and privacy aspects [11]. Related approaches conclude that a combination of haptic and visual feedback might be a suitable way of presenting error messages on assistive systems. As these results were collected with non-disabled participants, it is unclear if this error feedback is also suitable for cognitively impaired workers [11].

With this paper, we aim to close this gap by presenting a study with 16 cognitively impaired workers comparing the three most common modalities for providing error feedback: tactile, auditory, and visual. The contribution of this paper is twofold: (1) we present results of our user study favoring a visual presentation of errors and (2) we provide design implications for designing error feedback for cognitively impaired workers.

## 2. RELATED WORK

Over the last few years different approaches for providing context-aware information have been proposed. In the following, we provide an overview of different feedback approaches and introduce assistive systems for providing instructions at workplaces.

### 2.1 Feedback modalities

Different feedback modalities have been used for providing information in different scenarios. The most important categories are tactile, auditory, and visual feedback. Tactile feedback is for example used by Bial et al. [5] by using a glove that is equipped with vibrating motors. Results show that tactile feedback can be used for navigation tasks. They use the tactile feedback to provide information for motorcyclists during driving tasks. Considering auditory feedback, Rauterberg and Styger [20] proposed adding additional auditory feedback to traditional visual feedback for assembly tasks. Visual and auditory feedback has been provided at the same time while managing computer-numeric-controlled centres. Their study suggests that combining auditory and visual feedback leads to a more positive mood and improves the participants performance. However, the study was conducted with non-impaired participants. The multimodal representation of feedback could lead to a high mental demand for cognitive impaired participants. Plain visual feedback is for example used by Funk et al. [10] when comparing different visual approaches for providing feedback for workers with cognitive impairments at manual assembly workplaces. In their study, they compare video-based, pictorial and contour instructions. The results of the study suggest that visual contour instructions are perceived well among all Performance Index (PI) groups of cognitively impaired workers. Moreover, Cuvo et al. [9] use textual feedback while instructing persons with mild cognitive impairments. In their study, they found that performance feedback is crucial.

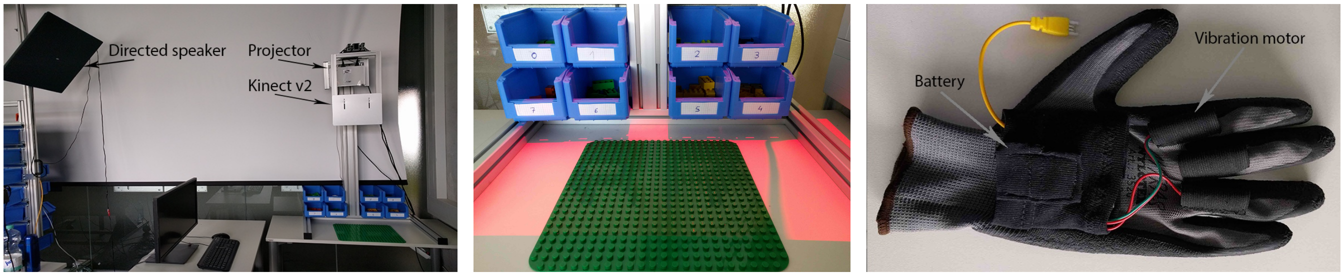
Other fields already experimented with combinations of haptic, auditory, and visual feedback. Akamatsu et al. [2] compared the three feedback types in a mouse pointing task. Their study revealed interesting design implications although no difference in Task Completion Time (TCT) was found. Further, Richard et al. [21] and Petzold et al. [18] compared the three feedback types when manipulating objects and assembling in virtual environments. Visual feedback was delivered on a screen, auditory feedback was provided by headphones and tactile feedback was triggered using pneumatic micro-cylinders, which applied pressure on the fingertips in a glove. Richard et al. found that both haptic and auditory feedback improve the workers' performance in manipulating virtual objects while Petzold et al. found that the performance is increased using additional haptic feedback.

### 2.2 Assistive systems for workplaces

In 1991, Pierre Wellner [25] suggested to use a camera-projector system to provide additional digital information for regular physical objects. In his prototype Wellner combined a digital and a physical workspace for enabling to use the best features of both spaces in one physical workspace. Later Pinhanez [19] was using a camera-projector system combined with a mirror for turning arbitrary surfaces into digital displays. Using Pinhanez's system, nearly every surface can become a display that shows information. Since then, systems using camera projector systems were deployed in different scenarios to provide cognitive assistance. E.g. Rüther et al. [22] provide assistance in sterile environments, Löchtefeld et al. [17] augment a shopping scenario, and Butz et al. [8] used it to support searching tasks. In 2008, Bannat et al. [3] used a similar setup for providing assembly instructions at manual assembly workplaces. Their system uses a camera to detect the position of picking bins and a projector, to provide pictorial instruction for the assembly process. Similarly, Büttner et al. [7] uses in-situ projection at manual assembly workplaces by providing pictorial instructions. They found that using in-situ projection is faster and leads to less errors compared to displaying instructions on smart glasses [6]. Further, Korn et al. [14, 16] used in-situ projection in combination with gamification approaches for motivating and instructing workers with cognitive impairments during assembly tasks. Their study with cognitively impaired workers revealed great potential for using gamification and in-situ instructions for instructing and motivating cognitively impaired workers at assembly workplaces. However, they did not find a statistically significant difference. Further, a comprehensive summary of assistive systems for supporting cognitively impaired workers at the workplace is provided by Korn et al. [15].

Recently, Funk et al. [13] used in-situ projection to provide instructions during assembly task at the workplace. Their results show that with increasing complexity, using in-situ instructions is leading to significantly less assembly errors and a significantly faster assembly time compared to pictorial instructions. In their system, they were providing red error feedback that illuminates the current picking bin when picking a wrong part. However, no scientific analysis of the error feedback was conducted. Therefore, Funk et al. [11] further investigated the effects of haptic error feedback, auditory error feedback, and visual error feedback by conducting a study with students. Their results reveal that a combination of haptic and visual feedback might be the best way to communicate errors while performing assembly tasks. However, this was only tested with students in a lab study.

As previous work suggests, adding haptic feedback for communicating errors during assembly tasks might be a privacy-presuming way of communicating errors at workplaces [11, 18]. Assistive systems will have a great impact on the inclusion of cognitively impaired workers in the work life [4, 23]. Thus, we are interested in whether the concepts of multimodal error feedback is also applicable to workers with cognitive impairments. This paper addresses this question.




(a) (b) (c)

**Figure 2: (a) The system uses a projector and a directed speaker for providing visual and auditory error feedback. Further, a Kinect_v2 observes the picking of items from bins. (b) Red light providing visual error feedback. In case of an error, the whole working area is highlighted. (c) A glove equipped with vibration motors is further used to provide tactile error feedback.**

# 3. SYSTEM

To incorporate the use of tactile, auditory, and visual error feedback in an assistive system for workplaces, we extended the system presented by Funk et al. [13]. The system consists of modular components that are designed for providing different modalities of error feedback. The main system, which tracks assembly steps and provides feedback to the assembly area, is constructed out of multiple aluminum profiles. The profiles can be used to mount different hardware on top of the workplace. The system uses a top-mounted Kinect_v2 to detect picking steps. Therefore, the system can distinguish between correct and incorrect picks.

We placed the system on a table, and placed a height-adjustable chair in front of it. Therefore the workers can work while sitting at a comfortable height. The system is constructed in a way that the assembly area is $70\,cm$ wide and $49\,cm$ high. This is enough space for placing instructions and assembling Lego Duplo constructions. The system further features $2 \times 4$ picking bins which are filled with Lego Duplo bricks. Each picking bin is filled with one type of Lego Duplo bricks that is unique in either color or shape. In the middle of the system there is a Lego Duplo plate firmly taped to the work area (see Figure 2b). The system triggers an error when either a picking error was made, or an assembly error was made by the participants. Picking errors are detected automatically by the Kinect_v2 if the user places his or her hand in a wrong bin. For detecting assembly errors, the system uses a wizard of oz approach where a study assistant observes the assembly process and uses a wireless presenter for triggering an error. In a case of an assembly error or picking error, an error message is triggered. Depending on the condition, our system is capable of presenting error feedback using the following three modalities:

**Visual** error feedback is provided using a projector (see Figure 2a), which is mounted at the top of the assistive system. If an error occurs, a red light illuminates the whole work area (see Figure 2b). While previous approaches only highlight the incorrect picking bin or the incorrect assembly position if an error was made, we decided to illuminate the entire work area. Therefore, the error message is harder to miss.

| Stimulus | Feedback Design | Duration in ms |
|---|---|---|
| Visual | Projecting red light | 2500 |
| Auditory | Playing deep error sound | 2000 |
| Haptic | Vibration in worker gloves | 1200 |

**Table 1: Feedback design and duration of each stimulus used in the study.**

**Auditory** error feedback is provided using the Holosonics Audio Spotlight 24i[1] (AS24i) speaker. The speaker uses ultrasonic waves to prevent the sound from diffusing. Therefore, it is only noticeable by the person sitting at the workplace and therefore retains the user's privacy. As an error sound, we are using a deep error tone exactly as used by Funk et al. [11]. In case an error is made, the error sound is played by the speaker (see Figure 2a).

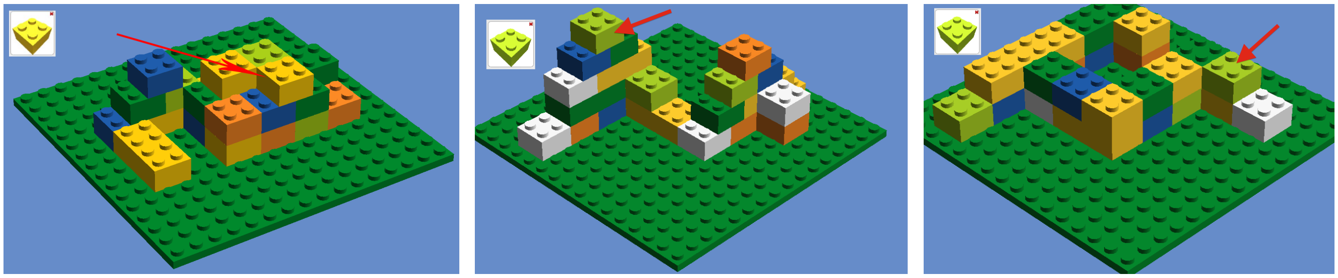
**Tactile** error feedback is provided using a glove equipped with two vibration motors (see Figure 2c). We decided to choose standard safety gloves, which are mostly used by workers while performing assembly tasks. The motors are placed on the index finger and the ring finger. Our glove uses an ESP8266 micro controller and a battery to receive the error trigger messages via WiFi. In comparison to Funk et al. [11], our glove can therefore be used without using a wire connection to a computer. This wireless feature makes the glove less obstructive while performing assembly tasks. In case an error is made, the glove uses an alternating vibration pattern that activates each motor twice directly after each other for 0.3 seconds each. This results in a vibration time of 1.2 seconds per error.

A summary of the design and duration of every error feedback modality can be found in Table 1.

# 4. EVALUATION

We conducted a user study with cognitively impaired workers to evaluate the usefulness and impact of different error feedback modalities. This section describes the used setup for the study, explains the procedure, and reports results of the quantitative measures. Ethical approval for this study

[1]www.holosonics.com/15-products - last access 08-08-2016



(a) (b) (c)

**Figure 3: The assembly tasks used in the study. We used three different assembly tasks with equal complexity. The images depict the final step of the pictorial instructions.**

was given by the employee organization of our partner sheltered work organization and by the German Federal Ministry for Economic Affairs and Energy.

## 4.1 Design

To find the most suitable error feedback modality for communicating errors to workers with cognitive impairments, we designed our experiment following a repeated measures design with the used error feedback modality as only independent variable. As dependent variables, we measure the TCT, the number of assembly errors, and the number of picking errors. We counterbalanced the order of the feedback modalities according to the Balanced Latin Square. Additionally, we collect qualitative feedback through semi-structured interviews and observations. We decided not to use a baseline condition that measures the time and errors without any error feedback as related approaches showed that error feedback is beneficial for workers with cognitive impairments. They usually ask their socio-educational instructors for feedback about the assembly [10, 13].

## 4.2 Apparatus

For our experiment, we use the system providing tactile, auditory, and visual error feedback described in the previous section. We configured it that only one feedback modality is active per condition. As previous work suggested, using Lego Duplo tasks provides a good abstraction of assembly tasks, which enables changing the complexity of tasks without changing the task itself [24, 13, 12]. Therefore we decided to use a Lego Duplo assembly task. As we designed the experiment to have three conditions, we created three unique Lego Duplo assembly tasks consisting of 24 bricks per task[2]. The tasks are mainly inspired by the tasks that were used by Funk et al. [13]. Therefore, we used their 24 bricks task, increased their 12 bricks task by 12 more bricks, and used their 48 brick task and stopped at 24 bricks. The instructions in their final assembly state are depicted in Figure 3. We printed the instructions on a single-sided A4 sheet of paper in a way that one assembly step is printed at one sheet of paper. The upper left corner of the instruction depicts the brick that has to be picked from one of the 8 picking bins. The assembly position is depicted in a way that the brick to assemble is shown in its final position. Further, a red arrow highlights the assembly position that it can be found immediately. Further, the instructions were designed in a way that the same brick does not have to be picked twice directly after the first occurrence.

[2]We provide the created assembly instructions to other researchers for reproducing the study.
Link: www.hcilab.org/assets16instructions

## 4.3 Procedure

In preparation of the study, we asked for a written consent from either the participants or their legal guardian before the study. As the study was conducted in our laboratory, which was a new environment for every participant, we initially made all participants familiar with our laboratory environment. Accompanied by their regular socio-educational instructors, we initially explained the assistive system and the three modalities that are used in the study. At first, we informed the participants that their participation in this study is voluntarily. We told them that they should inform us whenever they felt unwell or uncomfortable, as we would immediately abort the study in this case. Afterwards, we explained the intention of the study and why the tasks they perform are relevant. After explaining the course of the study, we made the participants familiar with the paper assembly instructions, i.e. which part to pick and where to assemble it. Once the participants felt confident using the paper assembly instructions, we introduced the error feedback modality for the current condition and explained what we count as an error and what the system will do if an error occurs. As the participants felt that they understood both error feedback and the paper assembly instructions, we began with the study and started measuring the TCT. During the study, 3 researchers were present at the scene. The first researcher triggered the assembly error feedback in case an assembly error was made as a wizard of oz. Picking errors were detected using a Kinect_v2, which triggered the error feedback automatically. The second researcher was measuring the TCT and counted the picking errors and assembly errors that were made for each condition. The third researcher was observing the worker reacting to the error feedback and taking subjective notes based on the observation. The error feedback was displayed immediately while performing the assembly, when an assembly or picking error was triggered. After the assembly was completed, we asked the participant for their opinion about the used error feedback. Then we repeated the procedure for the other two remaining conditions. At the end of the third condition, we asked each participant for a subjective rating which error feedback was perceived the best by her or him and we asked them why they preferred or disliked the feedback.

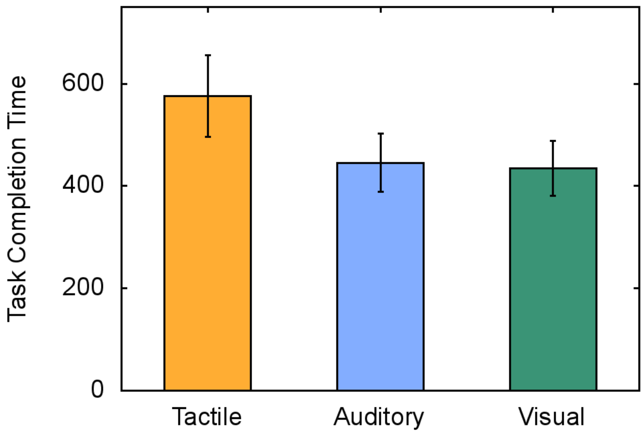



**Figure 4: An overview of the average Task Completion Time to assemble the Lego Duplo construction using the different error feedback modalities. The error bars depict the standard error.**

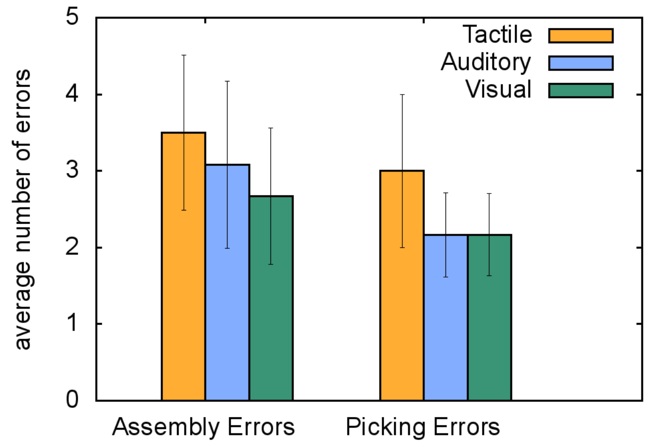



**Figure 5: The average number of errors that were made using the different error feedback modalities for both assembly errors and picking errors. The error bars depict the standard error.**

## 4.4 Participants

We invited 16 participants for our user study. The participants were aged from 34 to 53 years ($M = 40.33$, $SD = 6.36$) and were employees of a sheltered work organization working in manual manufacturing. All participants worked on manual assembly tasks on a daily basis. None of the participants were familiar with our system, the used task, or the error feedback modalities used in our study. We invited the participants according to their PI in a way that they represent the population of the sheltered work organization. Therefore, we used the PI of the sheltered work organization to categorize their capabilities. The PI is a percentage ranging from 0% to 100%, which indicates how capable a worker with cognitive impairments is of performing a work task. Inspired by previous work [10, 13], we divided the population to belong to one of three PI groups: 5-15%, 20-35% and above 40%. Accordingly, we invited 5 participants belonging to each of the three PI groups. The study took approximately 40 minutes per participant.

## 4.5 Results

During our study, 4 participants belonging to the 5-15% PI group aborted the study as they did not want to wear the glove anymore. Therefore, we excluded these 4 participants from the quantitative evaluation.

We statistically compared the TCT, the number of assembly errors, and the number of picking errors, between the error feedback modalities using a one-way repeated measures ANOVA. Mauchly's test showed that the sphericity assumption was violated for the number of assembly errors ($\chi^2(2)$=6.852, p=.033) and the number of picking errors ($\chi^2(2)$=9.201, p=.010). Therefore, we used the Greenhouse-Geisser correction to adjust the degrees of freedom ($\epsilon$=.668 for the number of assembly errors and $\epsilon$=.624 for the number of picking errors). Further, we used a Bonferroni correction for all the post-hoc tests.

Considering the TCT, the participants assembled the Lego Duplo construction fastest using the visual error feedback ($M = 434.42$ sec, $SD = 185.27$ sec), followed by the auditory error feedback ($M = 445.08$ sec, $SD = 197.40$ sec), and the tactile error feedback ($M = 575.42$ sec, $SD = 276.71$ sec). As the shapiro-wilk test did not show a non-normal distribution, we use a parametric one-way ANOVA. The one-way repeated measures ANOVA showed a statistically significant difference in the TCT between the feedback modalities $F(2, 22) = 4.634$, $p = .021$. The post-hoc tests reveal a significant difference between the visual and tactile feedback. The effect size estimate shows a large effect ($\eta^2 = .296$). Figure 4 shows a graphical overview of the results.

Analyzing the number of assembly errors that were made by the participants using the different error feedback modalities, the visual error feedback resulted in the fewest assembly errors ($M = 2.67$, $SD = 3.09$), followed by the auditory error feedback ($M = 3.08$, $SD = 3.77$), and the tactile error feedback ($M = 3.5$, $SD = 3.5$). As a shapiro-wilk test showed a non-normal distribution for all three modalities (all $p < .05$), we use a non-parametric Friedman test. Accordingly the Friedman test did not reveal a significant difference between the error feedback modalities ($p > .05$). The results are depicted in Figure 5.

For the number of picking errors that were made using the different error feedback modalities, the visual error feedback ($M = 2.17$, $SD = 1.85$) and the auditory error feedback ($M = 2.17$, $SD = 1.89$) lead to the same number of picking errors. Using the tactile error feedback, the participants made the most picking errors ($M = 3.0$, $SD = 3.46$). As a shapiro-wilk test showed a non-normal distribution for all three modalities (all $p < .05$), we use a non-parametric Friedman test. However, the Friedman test could not reveal a significant difference ($p > .05$). The results are depicted in Figure 5.

# 5. QUALITATIVE OBSERVATION

Considering the qualitative observational feedback that was collected during the user study, two researchers continuously observed the participants during the study. The first researcher observed the interaction of the participants with different error feedback modalities and asked questions after the condition was finished in a semi-structured way. The second researcher was performing an observational study for subjectively analyzing the effect of the different error feedback modalities on the participants.

When asked about the Lego Duplo task itself, a participant stated that *"with increasing number of steps the task gets more complicated"* (P1). Another participant pointed out that the used task has several error sources as *"[he] had difficulties in distinguishing between the two different types of green bricks"* (P2). During the study, we subjectively observed that 10 of our 12 participants had difficulties to recognize bricks, whereas most of them stated that they did not have problems differentiating between the different colors.

We also asked the participants about how easy it was to perceive the different feedback modalities. One participant liked the visual feedback as it is *"directly in the field of view"* (P2), others said that the visual feedback is *"easy to see"* (P4). The participants were unsure about the tactile feedback as *"the vibration is rather unpleasant during the work task"* (P2) and *"[it] distracted me in my workflow"* (P4). Some participants (P3, P8) also did not feel or pay attention to the tactile stimulus. Further, four participants had to abort the study after the tactile feedback condition. Two of these participants stated that they did not feel well wearing a glove, the other two were uncomfortable or scared of the tactile vibration. Considering the auditory feedback a participant stated that the *"sound was very easy to perceive"* (P2). On the other hand, three participants (P3, P8, P14) stated that they was distracted by the auditory error feedback as it *"scared [them] when it triggered"*.

Considering the privacy implications of the different error feedback modalities, some participants stated that auditory feedback would be *"not that good because others can hear when [I] made an error"* (P2, P13). On the other hand considering the visual error feedback many participants told us that *"[they] don't care if others could see that they made an error"* (P2, P4, P5, P12, P14). When we asked why, the participants responded that *"usually the supervisors are watching the work steps as a quality control and are telling us when an error occurred"*. (P4) One participant was concerned that his supervisor would not be able to see anymore when an error was made as only he could perceive the tactile feedback (P16).

One participant (P7) stated after the study that he perceived working with the system using any error feedback as very easy as he could completely relax and rely on the system because it would tell him when he makes an error. Two other participants stated that they *"could imagine using the visual feedback on a daily basis"* (P4, P5).

At the end of the semi-structured interview, we asked the participants to rank the feedback modalities according to which modality they liked best and to also consider which error feedback they would use on a daily basis. One of our 12 participants who finished the study did not want to rank the error feedback modalities. The results reveal that participants' subjective impression of the visual error feedback was best (5× first, 4× second, and 2× third) followed by the auditory feedback (4× first, 4× second, and 3× third). The tactile feedback was perceived the worst (2× first, 3× second, and 6× third). The results are also depicted in Figure 6.

In addition to the interviews, 5 participants made comments on their performance or formulated their thoughts during the assembly task. In most cases these participants showed a higher TCT than other participants. Another 4 participants needed to be guided verbally during their tasks and reacted positively to the verbal help.

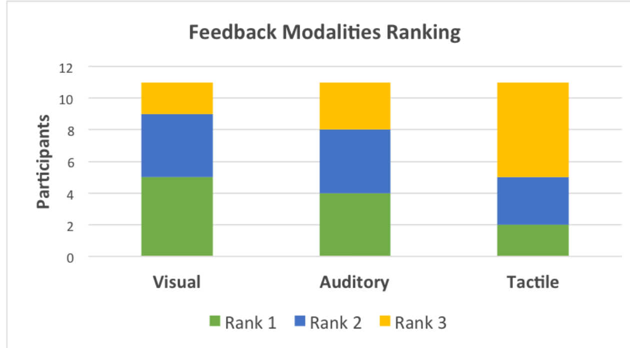



**Figure 6: The subjective ranking of the feedback modalities ranked by the participants.**

# 6. DISCUSSION AND IMPLICATIONS

The results of our study reveal that both the number of assembly errors and the number of picking errors are not significantly different between the error feedback modalities. We argue, that the number of errors is not different between the error feedback modalities as the error feedback occurs after the participant made the error. Thus, we could not measure that the used feedback modality is influencing the participant in the way they are working, e.g. paying more attention to a correct picking or to a correct assembly of the Lego Duplo construction or being insecure and making more errors due to an error feedback modality. However, the TCT is statistically different between tactile error feedback and visual error feedback. We assume that this difference in the TCT is caused by a faster error recovery after an error was made. The visual error feedback was perceived significantly faster than the error feedback provided by the tactile glove.

The qualitative observations and the answers we got from the participants through semi-structured interviews after using the different error feedback modalities tend towards using visual error feedback. Although some participants did not care about using error feedback that preserves their privacy at the workplace, an auditory error feedback was perceived as distracting. Considering the tactile feedback using the vibrating glove, some participants were able to perceive the tactile feedback while others did not react to the tactile feedback at all.

While using privacy presuming error feedback mechanisms might be a good decision in general [11], the implications for using these error feedback mechanisms for cognitively impaired workers are different. Through interviews we found that errors that are made at the assembly workplace are considered a non-private information, which is acceptable to communicate to supervisors. Compared to related work [11], which analyzed the error feedback for non-disabled workers the design implications are different as error privacy has a higher priority.

# 7. CONCLUSION

In this paper, we compared auditory, tactile, and visual error-feedback for cognitively impaired workers at manual assembly workplaces. In this user study, we obtained data from 12 participants to estimate the best feedback modality in terms of task completion time, measured errors, and qualitative feedback. We found a significant difference between visual and tactile error feedback regarding the task completion time, but could not find a significant effect between picking errors and assembly errors between each error feedback modality. We did not observe that altering the error feedback modality had an impact on the way the participants worked on assembly tasks. Therefore, the number of assembly errors throughout all error feedback modalities were not significantly different. However, we measured a significantly faster task completion time using visual error feedback compared to using tactile error feedback. Using visual error feedback, the participants were able to recover faster from errors than using tactile error feedback.

In future work, we want to perform a study, which addresses the limitations of working memory during assembly tasks. Assembly instructions will be provided as visual, auditory, and tactile representation to evaluate changes regarding performance and user acceptance of the error feedback modalities. Additionally we want to conduct a long term study in an industrial context to evaluate the user acceptance, performance, and learning effects of the proposed error feedback modalities, especially when used over a longer period of time. Furthermore, the presented vibration glove will be improved by reducing the size of electronic components within the glove for observing changes regarding the assembly and pick performance.

# 8. ACKNOWLEDGMENTS

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