ABSTRACT

Title of thesis: SHOW AND TELL: EXPLORING HOW AUDIO NARRATIVES CAN COMPLEMENT VISUALIZATIONS OF STROKE SURVIVORS' PERSONAL HEALTH DATA

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Wearable technology in healthcare could give individuals awareness and independence in rehabilitation. In this qualitative work, I investigate how using speech-based, audio narrative summaries alongside graphical visualizations affect users' understanding of their personal data. I conducted this work in the context of stroke recovery, where stroke survivors experiencing hemiparesis can monitor their physical progress using a wearable ring sensor. Using a co-design approach, I engaged with stroke survivors and their caregivers to elicit recommendations for multimodal (speech/visual) feedback of the wearable ring data. Reflexive thematic analysis of the sessions showed that multimodal feedback can potentially lend therapeutic support for stroke survivors. Audio narratives helped to reinforce the visual feedback, and positively framed narrative content that was reflective, motivational, and suggestive was able to support stroke survivors as they navigate their independent recovery journeys.

SHOW AND TELL: EXPLORING HOW AUDIO NARRATIVES CAN COMPLEMENT VISUALIZATIONS OF STROKE SURVIVORS' PERSONAL HEALTH DATA

by

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Chapter 1: Introduction

1.1 Overview

The use of wearable technology in healthcare settings enables patients to have awareness of, and control over their recovery. In this thesis, I explore how *data output*—feedback from wearable sensing technology—can be presented to support recovery goals. Specifically, I investigate how speech-based, **audio narratives**, used alongside traditional data visualizations, can affect understanding or utilization of personal health data. An "audio narrative," in this work, is a speech output modality that includes words, phrases, and sentences. The content of audio narratives can include descriptions of an accompanying visualization, descriptions of trends or patterns, prompts for reflection, suggestions, encouragement, and motivation.

I conducted this research in the context of a wearable ring sensor device for **stroke survivors** in long-term recovery. Many stroke survivors experience a condition called **hemiparesis** (one-sided upper limb weakness) as a result of the location and impact of their particular stroke [59]. A major recovery goal for people who experience hemiparesis is to regain the function and capability of their **affected limb**: the half of their body that was impacted by the stroke. This is especially important for patients who experienced the loss of function of their dominant hand.

The wearable ring sensor enables stroke survivors to monitor how they use their affected limb and possibly incorporate this awareness into their recovery and treatment [41, 35]. The wearable ring sensor has been validated for its ability to capture fine-grain data about how users move each upper limb (shoulder, arm, and hands). However, the question remains of how to best represent this feedback to the stroke survivor such that they are motivated to incorporate the use of the affected limb in their everyday living.

Along with hemiparesis, stroke survivors may experience a variety of cognitive, mental, emotional, and physical issues, including aphasia, visuospatial disorders, and depression [59, 72]. Every stroke survivor's recovery is also unique, as no two strokes are the same. Therefore, addressing perceptual limitations and personalization are two key requirements to consider when developing technology for this population. I explore multimodal interaction as a potential solution to address these requirements and to further understand best practices when representing the wearable ring sensor feedback to stroke survivors.

Visual and audio modalities have intrinsic characteristics that can provide different benefits, as well as obstacles, depending on who is receiving the feedback. Therefore, I explore how combining the beneficial features of both modalities improves the experience of receiving feedback. This work fits into a larger context of multimodal interaction by isolating the relationship between visual and audio modalities as a potential output combination.

I am also interested in exploring the optimal content of each of these modalities, and how this content may be similar or different between visualization and audio narratives due to each modality's intrinsic characteristics. For example, audio narratives can potentially convey context-dependent information more effectively than visualizations, while visualizations may deliver content more efficiently than audio narratives.

Using a mixed approach of semi-structured interview and co-design methodologies, I directly engaged with stroke survivors and their caregivers to investigate and collaboratively design a multimodal, audio/visual interface that can represent feedback from their wearable device.

1.2 Research Questions

Using a collaborative approach, I am interested in better understanding how multimodal feedback could be designed to fit into the contexts of stroke survivors' daily lives. Within this larger question, I investigate the following:

- RQ 1. How can speech-based "audio narratives" complement visual representations of personal health data? (Attitudes About Multimodal Feedback)
- RQ 2. How do stroke survivors envision the content they want to hear in the audio narratives? (Audio Narrative Content Preferences)
- RQ 3. How can stroke survivors utilize the audio narratives in their daily lives? (Opportunities for Utilizing Audio Narratives)

1.3 Why Collaborative Design?

Technology for populations like the stroke survivor should be effective and considerate of the needs and challenges of the user group. Emerging technology can be developed without real user input, and for healthcare applications, this runs the risk of creating ineffective or even harmful interventions for users. In healthcare settings, the clinician-patient relationship can be characterized by the degree of collaboration. In a paternalistic model of healthcare, the clinician takes little input from the patient in their treatment, and the clinician or provider is appointed as an authoritative figure [66]. In the HCI context, technology can likewise be paternalistic when developed non-collaboratively. Technology for health and wellness can easily disregard its users' needs if not designed with user-centered approaches.

Participatory design, or co-design, is a method of user-centered design where the target population is directly involved in the design and research outcomes [2]. It is a hallmark of inclusive design and key in ensuring that the outcomes of research are effective for real users. Co-design has been used in health settings both with clinicians [44] and patients, to directly incorporate their experiences in the utilization of new services and treatments [77, 61]. The co-design method has also been used in previous studies with the stroke survivor population to design better treatment for post-stroke rehabilitation [49, 46]. Because the complex physical, functional, mental, and emotional consequences of stroke may make it challenging to involve stroke survivors in other research methods, I utilize the co-design method in order to collaborate, beyond consultation, with real stroke survivors.

The goals of this study are to design an effective interface to show data representations of upper limb activity to stroke survivors and investigate how audio narratives can complement visual representations for this population. The broader purpose of the study is to create motivational and usable technologies that aid stroke rehabilitation, alongside a stroke survivors' care team (individual, caregiver, clinician, etc.) to increase their at-home independence, and support their at-home recovery.

Contributions from this research can make emerging personal health technology effective for stroke survivors and other types of users with complex requirements. By including the input and ideas from real stroke survivors' perspectives, my approach represents incorporating inclusive and human-centered design in health technology research.

1.3.1 Reflexivity Statement

My approach to the framing, methodology, and analysis of this thesis is informed by who I am as a researcher and person. In this section, I acknowledge relevant personal and contextual details that contribute to my lens as a researcher.

Broadly, I identify as a woman of color and further as an Indian-American, middleclass, cisgender female. Aspects of my identify have afforded me both privileges and obstacles, which together have developed the perspective I apply in this thesis.

Health sciences has always been a part of my life, from my mother's profession as a physical therapist and my father's as a biomedical researcher. Their involvement in healthcare is a privilege that has been passed down to me, especially in increasing my awareness of health systems and processes. For example, in managing my own health I have always had informed advocates on my side, helping me to navigate jargon or providing second opinions. My mother's work as a physical therapist for patients with neurological conditions (including stroke) has especially informed this work, as her perspectives as a clinician over the years has inspired the framing of the problem statement.

My academic and professional background in biological sciences has also informed this work. As a student I was able to shadow clinicians treating patients with neurological conditions such stroke and ALS. Having some background understanding of the in-patient experience that the participants may have gone through helped me to better connect and engage with them. I nor my immediate family or friends have been personally impacted by stroke, therefore my personal experience is limited regarding family impacts or care-giving perspectives.

The personal, academic, and professional experiences in my life establish who I am as a researcher and informed the ideas and findings laid out in this thesis.

1.4 Thesis Outline

In the following chapters I will provide an overview of relevant literature, the study design rationale and methods, key findings from co-design sessions with stroke survivors and caregivers, and a discussion of findings in the larger context of multimodal interaction, stroke recovery, and wearable sensor feedback.

Chapter 2 will cover work related to the research questions, including an overview of the stroke recovery context, multimodal feedback, and persuasive messaging for supporting health.

Chapter 3 provides an overview of the method, covering the development of the co-design probes, recruitment and participants, and study procedures.

Chapter 4 organizes the findings of the co-design sessions into two levels of themes that help to answer the research questions.

Chapter 5 discusses the study findings as guidelines for the design of multimodal feedback for stroke survivors. I also discuss the thesis' limitations and opportunities for future work.

Chapter 6 will conclude the thesis by tying together the related work context and the present findings.

Appendices include study logistics materials (recruitment copy, screening questionnaire, consent forms), co-design activity materials, and co-design artifacts (results generated during the collaborative sessions).

Chapter 2: Related Work

To ground the research questions in previous findings, I lay out relevant literature related to stroke recovery and technology (including the wearable ring sensor), multimodal interaction and output, and feedback messages for healthcare contexts.

2.1 Stroke Recovery and Technology

Stroke has a major impact on communities and individuals. In the United States, close to 800,000 people suffer a stroke every year. It is considered the leading factor in the development of long-term disability, which has great consequences for individuals and their families, communities, and our whole society [69]. For example, the severity of stroke consequences can cause stroke survivors to leave the workforce, be unable to provide care for their children, and overall lead to a diminished quality of life [47]. Long-term stroke recovery and post-acute physical, cognitive, and emotional rehabilitation can also be very costly and burdensome to individuals in the U.S., especially when navigating private and public insurance [20].

2.1.1 Hemiparesis

One of the main long-term results of having a stroke is experiencing hemiparesis. Hemiparesis is the loss of function, weakness, or feeling that occurs on one side of the patient's body, contralateral to the location of the stroke in their brain (patients that have a stroke in the left side of their brain will experience hemiparesis on the right side of the body). The condition can affect both the lower and upper limbs, including the shoulder, arms, hands, and fingers [3, 59]. The degree to which the affected side is limited is dependent on the patient's stroke severity, quality of rehabilitation, and long-term recovery [58]. Through exercise and incorporating affected side use in the Activities of Daily Living (ADLs), patients can potentially reduce the effect of hemiparesis over time [59, 24, 40].

2.1.2 Other Consequences

The complex combination of the clinical consequences of stroke presents challenges for designing accessible and effective technology. For example, patients with a particular type of aphasia, such as Broca's or expressive aphasia, may be able to comprehend speech, while patients with another type, such as global aphasia, will not be able to understand speech at all [30, 59]. If a patient presents with a visuospatial disorder such as spatial neglect, they may not have the ability to perceive visual or auditory stimuli on their affected side [15, 33]. Patients may also present with acquired learning disorders such as acalulia, which causes them to lose their ability to comprehend numerical concepts or perform arithmetic calculations [21, 4]. All of these stroke consequences may have detrimental effects on how stroke survivors in particular respond to and comprehend graphical visualizations, however using visual imagery in mental practice has been a useful intervention [52]. The consequences reviewed here as well emotional and mental conditions like post-stroke depression (PSD) can coincide with hemiparesis presentation [72, 74]. These unique combinations of limitations create an opportunity for wearables to deploy feedback to individual stroke survivors using multiple modalities that compensate for and amplify one another.

2.1.3 Technological Interventions: Wearable Ring Sensor

Wearable technology is a powerful solution to support rehabilitation [11, 67]. Wearables capture large amounts of detailed information about their users' physiological data (such as heart rate, blood pressure, and temperature), activity (step count, speed, stairs climbed, and calories burned), and sleep quality [12]. Different wearables to support hemiparesis rehabilitation include gloves [18, 68], bands or bracelets [56, 55], and rings [41, 36], which are differently suited to the requirements and goals of the patient and are utilized either directly by patients or by therapists. These technologies have sensing capabilities that could provide the users with valuable information about the real-time and long-term progress of their rehabilitation, which can also be utilized by clinicians to inform their treatment [11].

A finger-worn ring sensor wearable has recently been introduced and validated for use in stroke survivors that experience hemiparesis [41]. The system consists of 2 finger-worn rings worn on both the unaffected and affected sides of the stroke survivor. The combined data captured from both rings has the ability to describe the quality and quantity of each upper limb's movement, both in real-time and over long-term periods. The rings capture data about both gross, large-scale movements of the shoulder and arm, as well as fine-grain movements of the wrist, hand, and fingers. A particularly useful metric captured by the wearable ring sensor is a description of the **ratio of use** of each limb, giving stroke survivors insight into the progress of their affected limb [36]. Monitoring the ratio of the affected versus unaffected limb use can help stroke survivors and clinicians accurately understand stroke survivors' limb use outside the clinic and devise treatments for targeted recovery [6].

While the wearable ring sensor has the capability to capture powerful information, the question remains for how to deliver that information back to the user. Feedback from the ring sensor has the potential to create awareness and even produce behavior changes for the stroke survivor that can improve the function of their affected limb and overall rehabilitation [35]. The modality of feedback is one consideration in how to help users best access the therapeutic effects of the wearable ring sensor and due to the kaleidoscope of perceptual consequences that stroke survivors may face, multimodal interaction is further investigated as a potential solution.

2.2 Multimodal Feedback

Multimodal interaction in technological systems can make the most of our perceptual capabilities and deliver effective user experiences [34, 70]. The senses available in our perceptual toolbox are paired with their own set of trade-offs in certain contexts, and can be altogether inaccessible for individuals with disabilities [23, 32]. Combining modalities together therefore provides a potential way for technology to address each mode's shortcomings as well as amplify benefits [50]. Out of the long list of modalities available, I further investigate two, visual and auditory, in an output interaction context for stroke survivors.

2.2.1 Visual Modality

The visual modality uses our sense of vision to transfer information. One of the most common ways that wearables return data back to the user is through visualizations. Visual feedback of captured data can be presented to users directly on a wearable interface (such as on the Apple Watch interface) or indirectly on a companion application (such as the Fitbit app). These visualizations can be traditional graphical representations like bar charts, scatter plots, or pie charts, depending on the type of data being shown. They can be represented over various time lengths, from real-time feedback to hourly, weekly, monthly feedback, and even longer-term feedback over years [48]. On top of the simple data representation, the visual modality can also include more complex information related to users' goals, positive or negative reinforcement, and gamification as ways to motivate behavior change [31, 16]. These contextual elements can be further optimized to enhance the visual modality and maximize functionality to the user, based on their purpose for using the wearable. In other words, visualizations can be made more effective with additional layers of contextual information.

2.2.2 Audio Modality

The audio modality makes use of our sense of hearing to transfer information. Innate characteristics of the modality include its ability to alert (and disrupt) which can have benefits with pulling attention to key information [57, 53]. Another quality of audio (and speech output) is its chronological order, where components are perceived and possibly processed by the order they were delivered [75]. These qualities can be utilized in information delivery systems such as the wearable ring sensor feedback to bring attention to important findings from the data captured in a speech narrative format.

In some cases, audio modalities can be used to replace a visual modality that is inaccessible. For example, screen readers can provide a speech-based audio description of visual elements for BLV vision users to access the content of web or mobile interfaces [64, 25]. Similar to the visual modality being inaccessible for BLV populations, the audio modality can be inaccessible to deaf or hard-of-hearing populations [22]. Accessibility considerations for both modalities are important to include when envisioning a multimodal solution, especially for stroke survivors who may have co-existing conditions related to hearing or vision loss [8, 53].

Although visual and audio modalities can compensate for each other as unimodal alternatives, their combined or complementary delivery can provide amplified benefits. I discuss existing work in multimodal interaction and feedback next.

2.2.3 Multimodal Interaction in Existing Technology

Real-world settings combine sensory modalities to provide their users with multiple sources of information, including in high-risk scenarios. For example, pedestrian walking signs in the Washington D.C. area combine the traditional 'red hand' visualization, used to signal a pedestrian to stop at a crosswalk, with an audio (speech) instruction. When the pedestrian presses a button on the crosswalk sign, the words "wait wait wait" are played repeatedly to signal that it is unsafe to cross. The audio then plays a rapid beeping noise to indicate that it is safe for a pedestrian to cross and how much time they have left before the signal changes. The feature is designed for pedestrians to have amplified awareness of pertinent traffic information by engaging both audio and visual modalities [65].

Pedestrians both with and without visual impairments use this feature to navigate traffic crossings safely. This phenomenon begs the question of how the combination of auditory and visual information alters the experience for users who can perceive both modalities. Beyond public works contexts, the walk signal scenario provides inspiration for the exploration of how visual and auditory feedback, when used together, can affect information comprehension and utilization in other interfaces. For instance, wearable technology can make effective use of multimodal interaction to deliver feedback to users [19].

Multimodal interaction not only allows one modality to compensate for the shortcomings of another, but also provides an opportunity to combine the benefits of multiple modalities as a means of reinforcement and amplified interaction [73]. Combinations of visual and auditory modalities can be found in many technological applications. In language learning technology, for example, applications such as Google Translate and Duolingo provide users with both textual (visual) and auditory input and output options to interact with the application [28, 27]. The combination of modalities gives language learners avenues for how they want to learn and reinforces that learning. Map navigation applications such as Google Maps and Apple Maps provide spoken directions in addition to visual and textual modalities to prevent distracting drivers who are primarily using their sense of vision to drive [42]).

Applications that involve users engaging with their personal data, especially in health and wellness contexts, have made effective use of both multimodal input and output offerings. The combination of speech and touch input has been utilized in self-monitoring applications to give users an amplified method of documented data. For example, the application of these modalities in *Data@Hand*, a smartphone personal health application, resulted in fast and flexible interactions that leveraged the beneficial qualities of each modality. For example, speech input would be more naturalistic in inputting commands, while touch input was useful to engage in common smartphone touch interactions or when speech input became difficult [38]. NoteWordy, a smartphone application for tracking personal task management and productivity, also utilized a complementary speech and touch input approach to improve the user experience of digital self-monitoring. Speech in this case helped ease the burden on users during data input as well as allowed for richer, higher-quality data to be capture, while touch could be used in public contexts to conduct simple interactions [45].

Literature in cognitive psychology describes how cross-modal interaction has been deployed in previous studies with stroke patients who have experienced various perceptual effects. In patients with spatial neglect, audio alerts were found to bring awareness to the affected side and potentially help patients to progress their rehabilitation [71]. On the other hand, multimodal feedback may also present some drawbacks to users, such as having to switch attention between modalities [73, 25, 51].

Audio and visual modalities complement and resemble each other in their capacity to deliver information effectively, but differ in key mechanisms of how that information can be delivered and optimized for recovery. Therefore, putting audio and visual modalities together and exploring their effects on the stroke population is important to explore further.

2.3 Feedback Messages in Health Technology

The purpose of wearables like the ring sensor that are applied in a specific health context is to support recovery. Persuasive feedback can amplify the effectiveness of wearable technology by providing users with motivation or guidance to create and maintain positive behaviors. The capability of these devices to capture information can be fueled by many motivations, ranging from monitoring purposes to intended behavior change. A common concern in self-monitoring activities is that wearable users may experience reactivity, or a heightened awareness that they are being "monitored" or "surveilled," which can cause them to deviate from their typical behavior. Although a concern in evaluative contexts, reactivity can be leveraged by these tools in independent recovery contexts to motivate positive behavior change alongside or outside the care of clinicians [54, 63]. I therefore take into account how feedback should deliver awareness to empower positive behavior change without also causing other unintended consequences, such as rumination.

Beyond the feasibility of audio modality, I am also interested in the exploring the *content* of the audio modality, or the narratives that audio modalities can create using speech. To support recovery, persuasive methods can be incorporated into a speech-based audio modality and optimize its effectiveness for stroke survivors.

Effective feedback messages have been deployed by mobile health applications to support the utilization of their technological capabilities by users [29]. Prior work explores how feedback can be used to *nudge* people to achieving goals or promote healthy behavior. During the COVID-19 pandemic text (SMS) messages were used by medical applications to alert and support citizens' awareness of the pandemic and encourage vaccination [60].*Narratives*, which include information beyond facts, such as personal stories or testimonials, have also been shown to be persuasive and effective in contexts such as disease prevention [62]. Feedback content that positively frames personal health data was found to improve behavior by influencing the self-efficacy of users [17]. Considerations of the content of audio narratives is therefore extremely important when applied to support rehabilitation for stroke survivors.

Accessible technology also provides guidance on how to build the content of effective messages, especially when creating messages that involve describing data. Constructing alternate text of visualizations, for example, can include a hierarchy of different information. Descriptions of charts can include identification of chart elements at the very lowest level, with explanations of statistics and complex trends added. At the highest level, alt text can provide users with contextual, domain-specific information that goes beyond the information provided in the visualization [43]. Audio narratives can also include these different levels of information, however the auditory modality presents new affordances and drawbacks than text-only.

Creating audio narratives that apply the principles of effective health messaging is important to ensure that the modality is optimally utilized. In the next section, I discuss how audio narratives were generated and deployed to participants during the semi-structured interview and co-design sessions.

Chapter 3: Methods

In this study, I used the co-design method combined with semi-structured interviews to gain further insights about participants' stroke rehabilitation journey and discover how wearable sensor feedback can fit into their daily life contexts.

3.1 Co-Design Artifacts

The co-design session began with presenting participants with the visual modality first, which helped to introduce them to the ratio of arm use metric captured by the wearable ring sensor. After, the audio modality was added on top of the visualization using our audio narrative probes. Here, I describe how I designed the visual and audio narrative probes and used them during the co-design sessions to elicit participants' reactions. The study was reviewed and approved by the University of Maryland College Park's Institutional Review Board under #1977290-1 (IRB Approval Letter can be found in appendix A).

3.1.1 Visual Probes

Visual probes were designed to introduce stroke survivors to the wearable ring sensors' key data metric, **ratio of use**, using a visual modality.

The ratio of use metric captures the duration and quality of movement on both the unaffected and affected upper limb, from gross movement of the shoulder, arm, and wrist to fine movement of the hands and fingers. The ratio metric presents the activity of the unaffected and affected limbs [41]. To present this metric, I chose a horizontal bar chart that is spatially mapped to true left and right (for example, the left bar represents the activity of the left upper limb and vice versa). The bar representation of the affected side was also filled in a blue color for emphasis, while the bar representation of the unaffected side was not filled in. This design choice was motivated by previous work which has utilized the horizontal bar colors as indicators of goal achievement [17] Each visual probe was customized to the individual's actual affected side in order to make the procedure more relatable, so both left-affected and right-affected templates of the probes were generated (fig. 3.1).

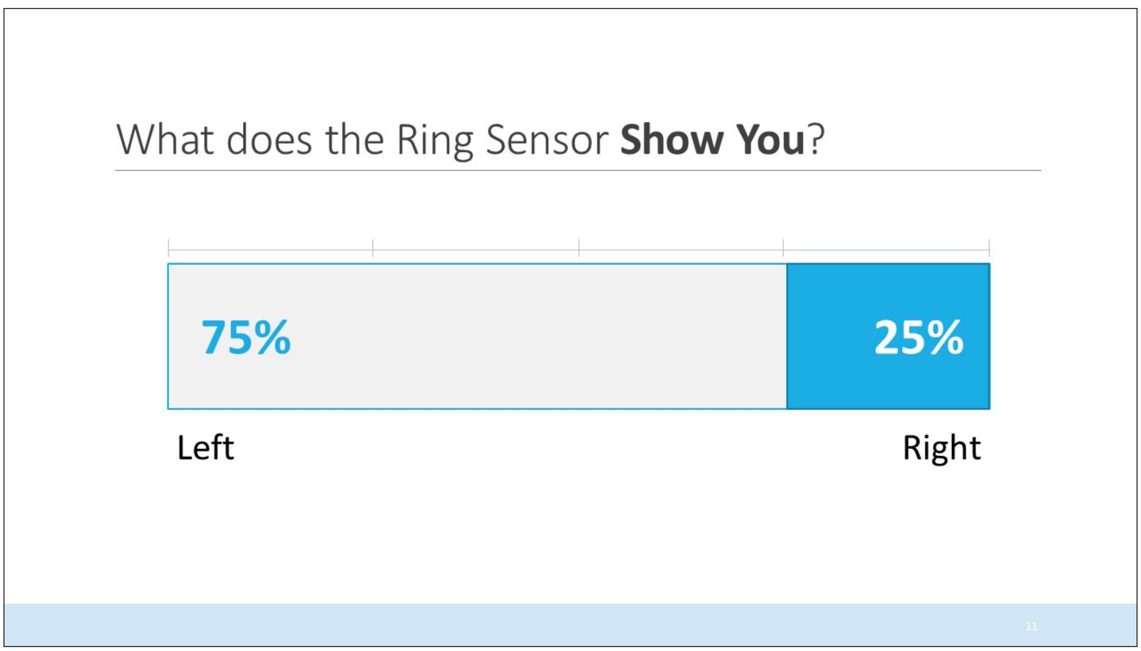

Figure 3.1: Presentation of the ratio of use' metric and visual modality to participants.

Participants were encouraged to share their initial reactions to the visualization and demonstrate their understanding of the ratio metric. They were prompted to provide ideas for how they would change the visualization to help the visualization be more effective to them. In order to facilitate idea generation, I made the visualizations ”device-agnostic” and asked participants which devices they would prefer to receive the feedback from the ring sensor (e.g. tablet or smartphone). If participants had difficulty coming up with new ideas, I provided a toolbox of visual changes for them to consider, shown in fig. 3.2.

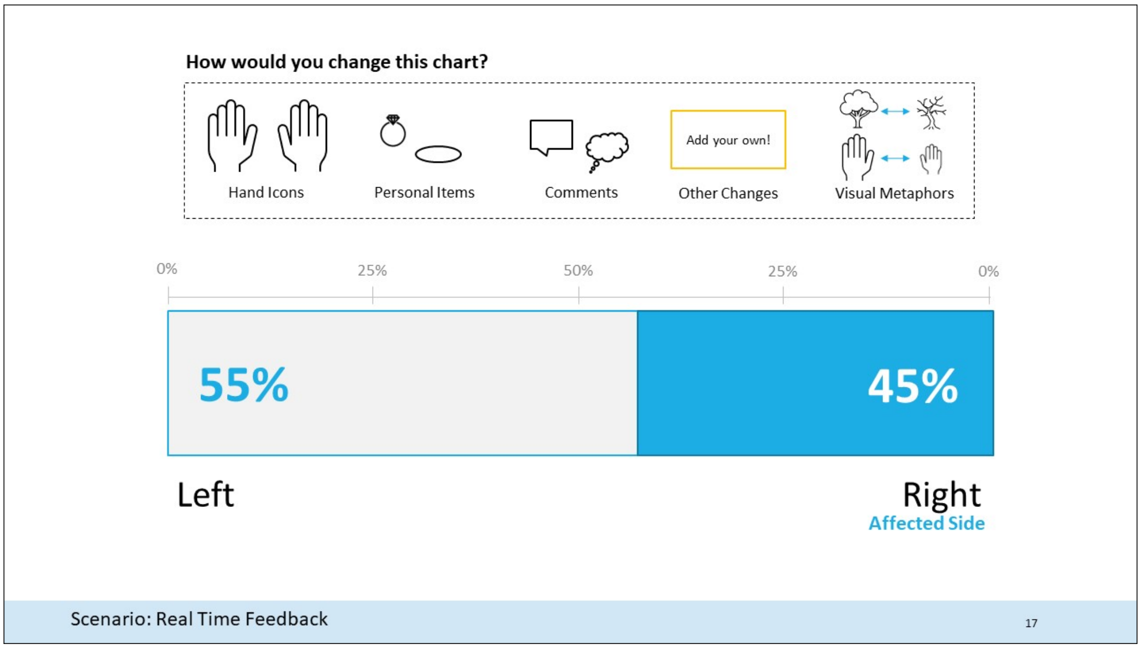

Figure 3.2: Toolkit of visual changes to help participants consider ways they could add contextual information to the basic visualization provided.

3.1.2 Audio Narrative Probes

Audio narrative probes provided the context for the investigation into the effectiveness of the speech feedback modality. The probes were designed with the consultation of physical and occupational therapists who work with stroke survivors on a regular basis. Working with the therapists enabled us to gain a better idea of the important elements to include in an audio narrative from the clinical perspective. I provided therapists with several scenarios of the ring sensor wearable feedback context, including real-time feedback, daily feedback, weekly feedback, and long-term feedback. I asked therapists to describe the visual representations of the feedback in their own words, as if they were talking to a real stroke survivor.

From the therapists' feedback, I learned of four semantic content categories that could be used as audio narrative probes. These included: 1) *Descriptions of the data and context*, 2) *Self-reflection questions*, 3) *Suggestions for improving performance*, and 4) *Encouragement and/or motivation*.

Data descriptions consisted of phrases that described the visualization of the ratio of use metric (e.g. which side was used more or less, percentage of each upper limb's use) with some additional time passage indicators that described when the metric was captured (e.g. "during the activity" or "over the past week"). This content category conveys the same information as the visualization.

Self-reflection questions were phrases that could prompt the stroke survivor to consider the data captured. Therapists stated that these questions are used during therapy to help patients better engage with their care. In clinical practice, questions like these are part of a larger conversation between the therapist and the patient. In the audio narrative use case, I do not have a back-and-forth dialogue between the ring sensor feedback and the stroke survivor. This content category conveys information beyond what is provided by the visualization.

Suggestions for improving performance provide stroke survivors with guidance for how to improve their affected limb performance. Therapists provided detailed and customized guidance when they discussed what they might want the feedback to say to stroke survivors (e.g. telling stroke survivors to use their affected hand in more stabilizing actions). The audio narrative probes I generated provided more broad guidance and did not include specific methods of improvement. This content category conveys information beyond what is provided by the visualization.

Encouragements were phrases that therapists typically included in the beginning or end of their complete narratives that could reinforce the other content in a positive manner. The therapists gave different examples of encouragement they use with their patients like "keep up the good work," or "you're almost there," which were to be used when patient goals were met or almost met. This content category conveys information beyond what is provided by the visualization.

I generated variations of the phrases in each category from therapists' quotes by manipulating the sentiment and wording of each phrase. Examples of the audio narratives generated can be found in Table 3.1.

Category	Examples of Audio Narrative Phrase
Data Description	You used your affected hand more than your unaffected hand during the activity.
Data Description	You used your affected hand 45% and your unaffected hand 55% during the activity.
Reflection	How can you use your affected limb more during this activity?
Reflection	Why did you use your unaffected side more during this activity?
Suggestions	Try to think of ways that your affected hand can help your unaffected hand during the activity next time.
Suggestions	Next time, use your affected left hand in places where your unaffected right hand does the activity.
Encouragement	You're almost there, keep going!
Encouragement	You can do better next time.
Encouragement	Keep up the good work!

Table 3.1: Categories of the audio narratives and examples that occupational therapists created.

I used the text-to-speech software Natural Reader to generate audio clips of narratives in each of the categories. These clips were embedded into the co-design activity for stroke survivors [1].

3.1.3 Powerpoint as the Co-Design Interface

Microsoft PowerPoint was used as the digital medium to facilitate each co-design session. Although it is used primarily as a presentation tool, the software has numerous features that can facilitate a virtual co-design session. In this work, I used PowerPoint to both present background information and tutorials about the wearable ring sensor, and conduct the interactive design prompts. I used the following features from the PowerPoint toolbox:

- Text-box tool and square shape tool as virtual sticky notes
- Icons for emoji coding (eg. 'star' for a good feature)
- Draw tool to circle features or create organic shapes (like a whiteboard marker)
- Low fidelity charts using rectangle shape tool
- Embedded audio clips to hold audio narrative probes
- Sequential slides to build up components of the co-design activity, instead of presenting all at once (such as on Miro or other whiteboard tools)

Through Zoom, I screen-shared the PowerPoint deck, which was not provided directly to the participant(s), so that they could view the changes being made. Using this method also made use of real-time "member checking" because participants could see what the researcher was noting from the think-aloud response to a probe or question [10]. If something was captured incorrectly by the researchers, participants were encouraged to speak up and correct me. Participants would be able to view my enlarged cursor to follow along on their screen during the sharing fig. 3.3.

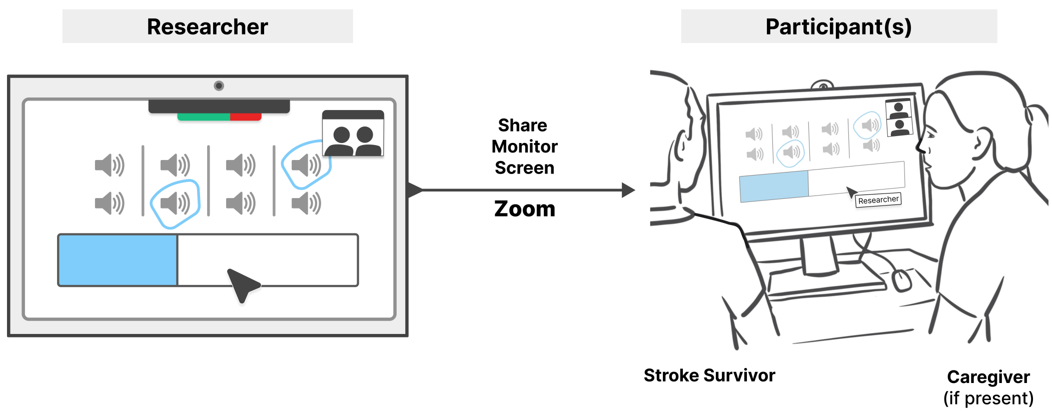

Figure 3.3: Remote Session Set-up. Left: researcher's point-of-view, showing screen share of PowerPoint slide with visual and audio probes. Right: Participant(s)' point-of-view watching the screen shared by the researcher. If a caregiver was present for the session, they could either be in-person with the stroke survivor or using an alternate Zoom account.

Each session was tailored to the participant's background. For example, if the participant experienced a stroke that resulted in right-sided consequences, all of the co-design scenarios (visualizations and audio narrative probes) were adapted to show right-affected results, and vice versa for left-affected participants. Artifacts generated from the co-design sessions can be found in appendix F.

3.2 Recruitment

Participants were recruited through local support groups, clinicians, and snowball sampling from other stroke survivors who completed the study sessions. The recruitment language and flyer can be found in appendix B

I mainly aimed to recruit stroke survivors, and encouraged their primary caregivers to participate along with if they were available. The caregiver's perspective is also important to consider in addition to the stroke survivor's experience because they are involved in helping the survivor manage their recovery [7]. I was interested in capturing how caregivers are involved in helping stroke survivors track and motivate recovery, which could inspire improvements to the audio narratives. In addition, caregivers could also help facilitate the conversation with stroke survivors by providing additional context. During recruitment, potential participants were prompted to complete a screening survey with information about their stroke. If the respondent was a stroke survivor, they were prompted to forward the survey to their primary caregiver (if they had one), and vice versa if the respondent was the primary caregiver.

Survey respondents that fit the initial screening requirements were then screened for inclusion criteria over a 15-minute phone or video call. The full screening script can be found in appendix C. Criteria for the stroke survivor participants included:

- Above the age of 18
- Stroke occurred at least 6 months before the start of study (patients are in the chronic stage of stroke recovery [26, 9, 39]
- Experienced one-sided upper limb weakness (hemiparesis) as a result of their stroke (specify which side was affected and which side was originally dominant)
- Ability to carry out the co-design protocol (self-reported)

    Answer questions in a yes/no and open-ended format

    View visual objects on a screen

    "Think aloud" their thought processes

    Hear audio recordings played through screen

- Ability to access study virtually (through Zoom) or in-person (at the University of Maryland, College Park)

- Comfortable with audio and video recording capture

The screening questions related to participants' ability to carry out the co-design protocol relied on the recruit's self-reported answers. I subjectively evaluated participants' ability to communicate during the screening as a practical test for the real session. For example, recruits who were able to carry out conversations during the screening and answer in a non yes/no format were accepted, while recruits who were not able to answer the questions on their own were not accepted.

After respondents were screened, a 90-minute session was scheduled in the next 1-2 weeks. Prior to the session, all participants signed a consent form acknowledging the session procedures, comfort with recording, compensation ($80 for stroke survivors and $50 for caregivers through Tango e-giftcard), and other study logistics. Consent forms provided to participants can be found in appendix D and appendix E. The compensation was funded using through an NIH grant, NIBIB 5R01EB027777 "Achieving Optimal Motor Function in Stroke Survivors via a Human-Centered Approach to Design an mHealth Platform."

3.3 Participants

Recruitment and screening were conducted on a rolling basis from late December 2022 to March 2023. During the recruitment, 19 people responded to the Qualtrics survey or directly emailed the researcher to conduct a screening session. After conducting screening sessions, 10 participants fit the inclusion criteria and were scheduled for study sessions. Recruits were primarily excluded because of the recency of their stroke (less than 6 months ago), lack of interest in the study, and lack of ability to do the tasks of the session (such as speak in a conversation/open-ended format, primarily due to severe aphasia). Participants' demographics can be found in Table 3.2.

	Sex	Age	Years Since Stroke	Aphasia	Caregiver Dyad
P1	M	58	8	—	—
P2	F	43	11	—	—
P3	F	41	3	Expressive	CG-P3
P4	F	45	12	Expressive	CG-P4
P5	M	62	20	—	—
P6	M	61	5	Expressive	—
P7	F	76	5	—	CG-P7
P8	F	72	2	—	—
P9	M	55	4	Expressive	CG-P9
P10	F	60	4	Expressive	—

Table 3.2: Participant demographic information including sex, age, time since stroke occurred (years), presence of aphasia (if so, type), and if the caregiver was present for the session.

During the screening I also captured how the stroke affected the participants' handedness as a result of hemiparesis. I was interested in which side of their body was affected by the stroke (right or left), and whether the stroke forced them to switch their dominant hand (if their dominant hand was affected and non-dominant hand was unaffected). Participant information can be found in table 3.3.

	Affected Side	Dominant (Pre)	Dominant (Post)	Effect on Handedness
P1	L	L	R	Handedness Switch
P2	R	R	L	Handedness Switch
P3	R	R	L	Handedness Switch
P4	R	R	L	Handedness Switch
P5	L	R	R	No Effect
P6	R	R	L	Handedness Switch
P7	L	R	R	No Effect
P8	L	R	R	No Effect
P9	R	R	L	Handedness Switch
P10	R	R	L	Handedness Switch

Table 3.3: Information about the participants' hemiparesis effects, including affected side, original dominant side, current dominant side, and whether they had to switch handedness

3.4 Procedure

Each study session consisted of the following sub-sections: Introductions, Semi-Structured Interview, Technology Tutorial/Background, Co-Design Activity, and Closing Questions. Following the completion of the early sessions, the protocol for the next session was slightly altered (e.g., sections were rearranged or abbreviated to save time). However, the general sections and layout were consistent for every participant.

3.4.1 Session Part 1: Introduction to Study

The study sessions began with a technology and logistics check to ensure that participants had their webcam and microphones enabled, and were in clear view to the researcher. I also ensured that the participants could see and hear through Zoom clearly. I performed a screen share check to ensure that visuals and sound were being properly transmitted via the screen share. Lastly, I ensured that participants were in a comfortable, distraction-free zone.

All participants were asked to introduce themselves before the session began, and participants were asked if they had any initial questions. I then introduced the overview of the project, the goals of today's sessions, and provided instructions for what to do if participants felt uncomfortable or wanted to skip a question and take a break. After this introduction, I began the semi-structured interview portion.

3.4.2 Session Part 2: Semi-structured interview

Prior to the co-design activity, I asked the participant and caregiver (if present) semi-structured questions about their background, life, and post-stroke experiences to gain better context. I also inquired about how the stroke survivor uses technology, specifically any wearable or personal monitoring technology, in their daily life.

If the caregiver was present for the session, I asked them questions about their experiences providing care, what type of tasks they assist the stroke survivor with, and if they accompany the stroke survivor to appointments with therapists. I also asked whether they would be interested in the ring sensor feedback and what type of role that data may play in their lives.

3.4.3 Session Part 3: Technology Tutorial / Background

Following the end of the semi-structured interview, I switched from the Zoom gallery (face-to-face) view to screen share PowerPoint materials. I first introduced the co-design concept and how it would work using PowerPoint, using a demonstration slide with the question: “What activities do you do with your hand during the day?” and ‘post-it notes’ (fig. 3.4).

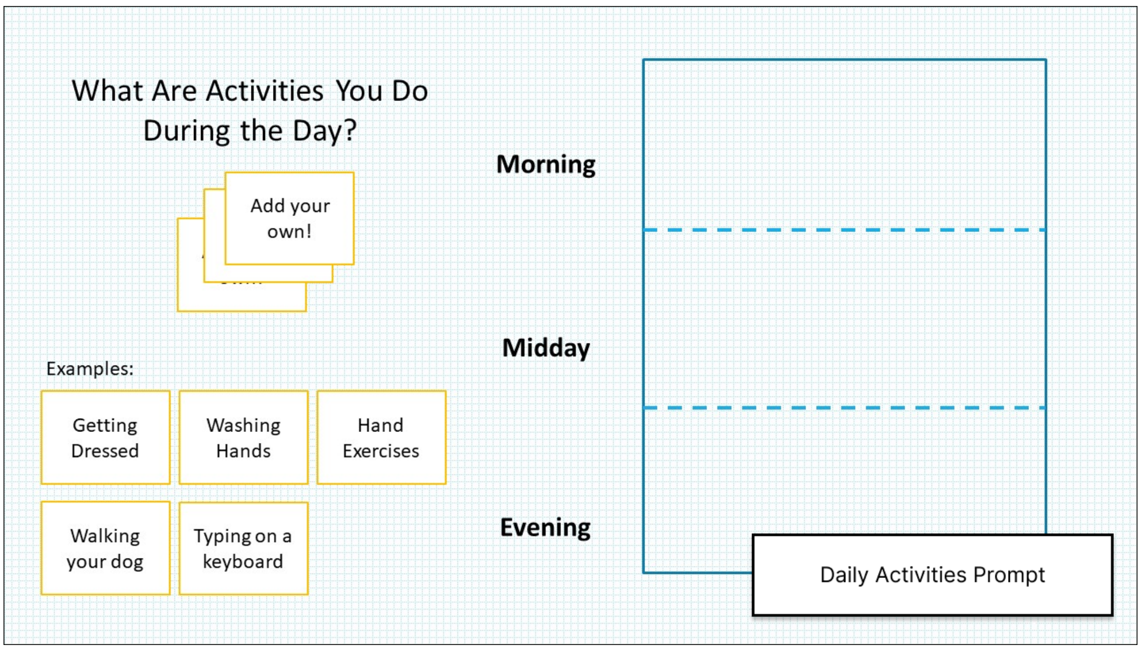

Figure 3.4: Slide used to demonstration co-design procedure using PowerPoint and document the participant’s daily activities to reference later in the co-design activity.

I then introduced several concepts to provide background information: wearables, the ring sensor and its capabilities, and feedback from the ring sensor. I showed participants videos and images of the ring sensor in use by models and gave them an opportunity to ask further questions about the technology.

To ensure that participants understood the capability of the ring sensor wearable and the data metrics it produces, I administered two tasks where participants had to construct a ratio graphic of the wearable feedback after watching a video of it in use. If participants were able to accurately describe the sample visualizations, these tasks were skipped to save time (see fig. 3.5).

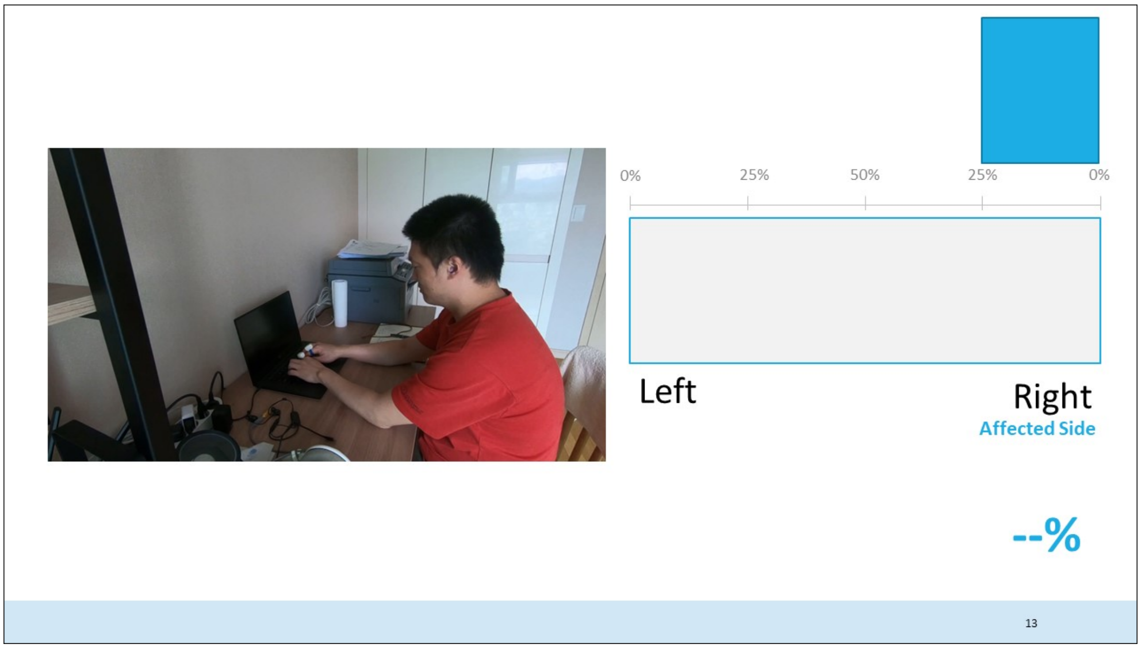

Figure 3.5: Slide used to test if participants can comprehend the visualization and ratio metric before moving on to the next co-design activity.

3.4.4 Session Part 4: Co-Design Activity

After sufficient background tutorial images were provided, I began the co-design activity. In the first part of the activity, I showed participants the visual representation of a sample real-time feedback scenario. Some light background was provided about the scenario, pulling examples from the previous question about the participant's daily activities to personalize the scenario. I asked the participants their interpretation of the visualization, how they could apply their interpretation in daily life, and if they would want to change anything about the visualization. If participants could not think of changes unprompted, I provided a toolbox of visual contextual information they could add.

I then introduced an open-ended prompt to participants and proposed that if the feedback could "speak" to them, what they would want it to say. After participants gave a free response, I introduced the audio narrative probes created in collaboration with occupational therapists. The audio clips were played one-by-one, with participants providing their initial reactions to each clip after it was played (fig. 3.6). After all the clips were played, participants were asked which ones they would want to hear in a complete audio narrative of their data. They were also asked how hearing the audio narratives while viewing the visualizations impacted their understanding and potential utilization of the information.

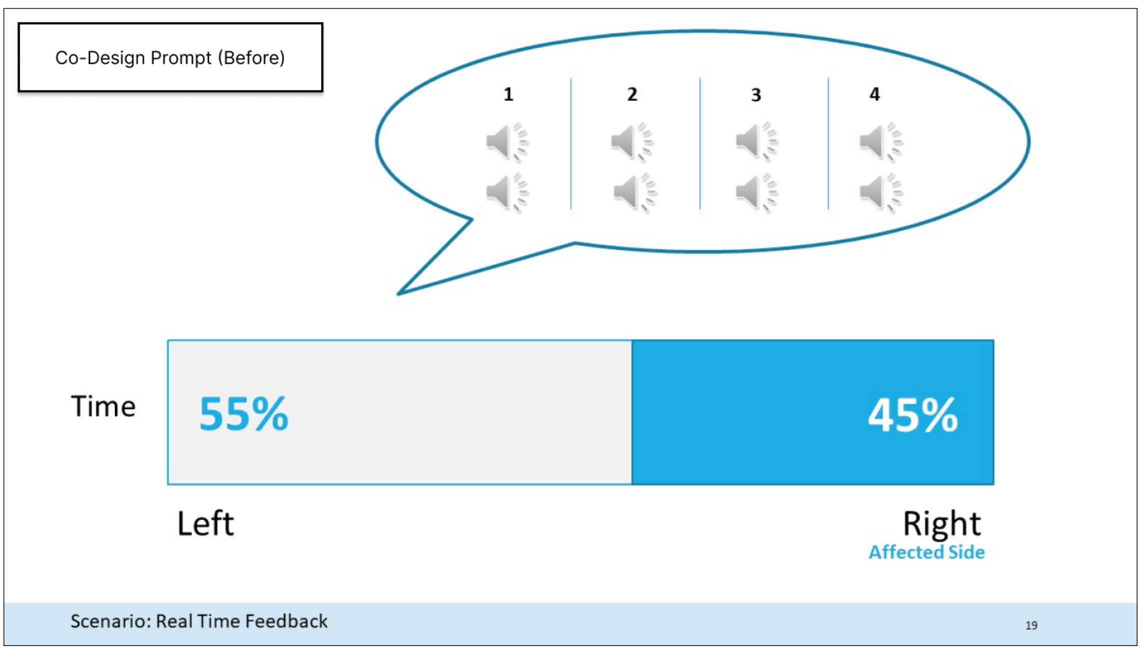

Figure 3.6: Slide for participants to hear the audio narrative probes while simultaneously viewing the visualization. Audio clips were played one-by-one, giving participants time to react and respond between each clip.

The final step in the co-design activity was to have participants generate their own audio narratives, with the question "If you were to say this feedback to yourself, what would you want to hear?" as a prompt. Participants could provide aesthetic preferences for the voice of the narrative (e.g., male/female, US/UK) and the speed of speaking. A real-time text-to-speech tool (NaturalReader) was used to play the participant's audio narrative back to them. After hearing their version, participants were asked the same set of probative questions about the effectiveness of the narrative. The co-design activity slide can be viewed in fig. 3.7

If time permitted, the previous steps were repeated for other scenarios of wearable sensor feedback, including a daily report scenario and a 6-months report scenario.

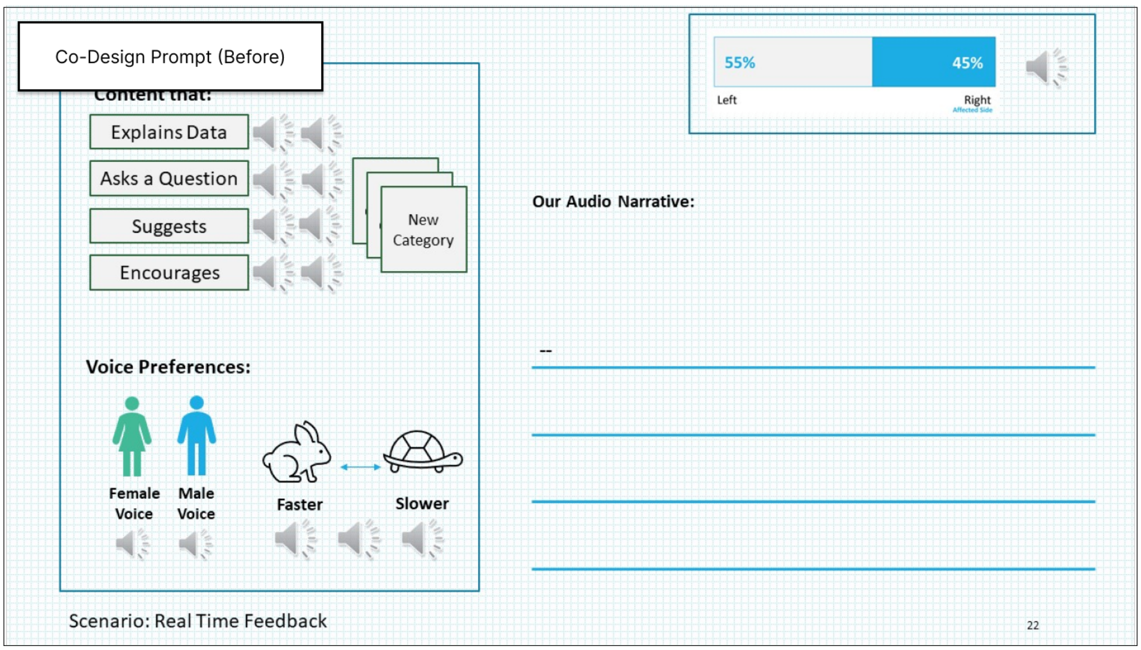

Figure 3.7: Slide for the co-design activity to allow participants to create their own audio narrative. On the left side of the slide is a toolbox of audio elements they could add, such as content by category, voice preferences, and speed preferences. On the right side is a free text area to create their own narrative text, which was later audio-played in real time using Natural Reader.

3.4.5 Session Part 5: Closing Questions

After completing the co-design activity, I stopped screen-sharing the PowerPoint and moved on to closing procedures with the participant. This included asking questions about how they envisioned using the ring sensor wearable in their daily life and contexts where feedback from the ring would be helpful (if not already covered in the session).

Participants were then given instructions for how to redeem compensation via Tango e-gift card in their email, and instructed to complete a post-study questionnaire to capture their demographics and any feedback to improve the session.

All study sessions' audio/video recordings, co-design artifacts (PowerPoint decks) and transcripts were stored securely on UMD Box.

3.5 Analysis

Transcripts from the study sessions were generated using the closed captioning function of Zoom's recording software. The transcripts were manually cleaned to de-identify participant names, correct captioning errors, and delete other erroneous information.

Cleaned transcripts were then imported into Taguette for initial reflexive coding passes. Codes were then exported and organized by two layers of themes in Miro, with the top layer mapped to the research questions [13]. I utilized reflexive thematic analysis in the qualitative data to gain more flexible insights related to a multitude of topics including multimodal interaction, daily experiences and contexts of stroke survivors, and the utility of wearable feedback [14]. The reflexive coding process and theme conceptualization was informed by my background, which is expanded more in section 1.3.1. In the next section, I present key findings from the analysis.

Chapter 4: Results

Analysis of the semi-structured interview and co-design activity sections of the study revealed findings related to the daily contexts of stroke survivors, as well as their attitudes towards the use of an audio modality in the multimodal feedback, content and aesthetic preferences of the audio modality, and opportunities to use the multimodal feedback in daily life. I first provide insights from the participants' stroke recovery journey to establish the research setting and then organize the findings according to the three research questions: (1) attitudes about multimodal feedback, (2) audio narrative content preference, and (3) opportunities for utilizing multimodal feedback.

4.1 Establishing Setting: Daily Contexts of Stroke Survivors

The semi-structured interview portion of the study session garnered insights into how the lives of participants have changed since their stroke, and provided the setting for the co-design activity to be applied to their real life. Key findings are included below, as they inform the greater context of findings related to the multimodal feedback.

4.1.1 Consequences of Stroke

The stroke survivor participants experienced different combinations of consequences from their conditions based on the severity of their stroke, their stage of recovery, and the quality of rehabilitation or treatment they received. These consequences provided a contextualized set of requirements that were addressed later in the co-design activity as potential opportunities or limitations for the wearable ring sensor feedback and its utilization.

Hemiparesis

P1, P2, P3, P4, P6, P9, and P10 experienced hemiparesis on their original dominant side (for example, the stroke affected the left side of their body and they were left-handed). In the early stage of their rehabilitation, participants were prescribed treatment that forced their non-dominant hand to switch and become their new dominant hand, as it was easier for the non-dominant hand to learn new activities than the original dominant hand affected by the stroke. In subsequent stages of rehabilitation, the participants who were forced to switch handedness were encouraged by their therapists to begin re-learning how to use their originally dominant hand that was affected, either to prevent further loss of function and regain lost function.

> "The occupational therapist told me to use the left side because the right side was weak. Now they're telling me to use the right side, you know." (P6, right-side affected and originally right-hand dominant)

P10 expressed that even though she is learning how to use her non-dominant unaffected hand, she eventually wants her affected hand to regain dominance. To support this goal she reported trying to do daily activities consistently with her affected hand, which she characterized as being "50 or 60%" of what it used to be. P1 also reiterated the importance of constantly using his affected hand, stating "I'm sitting here talking to you, but I have my hands here and I'm constantly rubbing them and trying to stretch them and keep them keep active, and that's something I do all day long."

P5, P7, and P8 experienced stroke effects on their non-dominant hand and had a marked difference in their affected hand rehabilitation than the participants who were forced to switch handedness. Although they reported being not as motivated to recover the function of the affected hand, these participants still reported doing exercises and setting broad goals for improvement to prevent any further loss of function to the hand. P07 reported, “since I’m right hand dominant, the left hand didn’t use to do a lot of these jobs, anyway. Sometimes I try to make it do things that it never did before.” P7 stated that even though she didn’t need to use her non-dominant hand that was affected, it has been an obstacle during fall prevention because her affected side won’t catch her fall, due to the left neglect effect.

P5 also reported trying to engage his affected hand more to maintain its function, even though it is his non-dominant hand.

> “I always put my keys in my left hand and use my left hand to open the door, even though using the right would be easier, I’m right-hand dominant. So that would be natural. **But I figure the more I use the left hand, the less chance of it getting worse.** You know, if I had put it in my pocket and just left it alone 20 years ago, it wouldn’t be of any use.” (P5)

For stroke survivors with more severe hemiparesis or even paralysis, affected hand or limb usage was primarily limited to stabilizing types of activities. P4 utilized the combination of her affected hand and elbow to grasp objects if her unaffected hand was in use, such as holding on to the railing of a staircase. P7 and P8 referred to their affected, non-dominant hand as the “helper hand,” that would only be used for gross, stabilizing motions such as holding down a piece of paper while writing.

> “I really try to remember to use my left, but I think more of my left hand as ‘my helper hand.’ It’s not like my dominant hand. It’ll never be my dominant hand.” (P8)

P8 also went on to say that if her stroke had affected her dominant hand, she would attempt more aggressive regimens to bring back the use of the dominant hand. However, because her stroke affected her non-dominant hand, she is mostly focused on two-handed activities that would be inefficient or difficult to do with only one hand (for example, putting on socks).

The differences in recovery perspectives between participants who did and did not experience a handedness switch are important to consider because they have differing goals and expectations for recovery.

Aphasia

Aphasia-related consequences played a large role in many participants' lives (P3, P4, P6, P9, P10), with different manifestations and effects. P4 reported an aphasia-related condition that led to difficulty with understanding numbers and mathematical activities, such as measuring ingredients for a recipe, understanding time, or calculating ratios (highly relevant to the data metric captured by the wearable ring sensor).

Some participants (P4, P6, P9, P10) reported that overcoming their aphasia is their highest priority in recovery, more so than hemiparesis or other consequences. P9 stated that for him, "it's been a pretty big change, and talking, it's big. The biggest thing, even bigger than arm and leg, is talking because when I worked, I always talked to people. And now it's difficult." P9 and P10 both reported feeling self-conscious about their aphasia in social settings, where they were mocked for the way they spoke.

4.1.2 Perspectives On Recovery

All participants shared their perspectives about the future of their recovery and what they imagine rehabilitation looks like for them. P9 provided an optimistic perspective saying that he knows that if he “keeps working at it, the [right hand] will get a bit better.”

> “So I’ve always been an overachiever. But now with the stroke? My memory, retention, comprehension, are so far below normal. That word, “normal.” I don’t like it, you know. I don’t like where I’m at right now.” (P6)

P4 provided a less optimistic perspective about her expectations for the affected side’s recovery, stating that she is not focused on improving the hand’s function but is focused on preventing pain that results from non-use.

> “Her trajectory has become less about improving the use of the arm than it is about keeping it listed, because that causes all kinds of other pain and discomfort. You know, because she does have feeling in her shoulder, and the tighter that arm is, you know, it causes problems into her, you know, neck and her shoulders, and so she’s constantly, you know, like trying to stretch it out and relax it so it’s sort of like, you know. Her goals are different than they were in the beginning.” (CG-P4 speaking for P4)

P5 expressed a similar perspective about the recovery of his affected side, saying “I don’t wanna be over the hill and slide down the hill. I wanna take as long as I can going down. I’m getting older. I’m not getting younger. So it’s really about trying to maintain as much functionality.” His sentiment highlighted time as a foe against his recovery, and punctuated the importance of maintenance over improvement.

The individual pieces of the stroke survivor’s life post-stroke, especially their perspectives on recovery, help to inform the next set of findings on how to deliver feedback through multimodal output channels.

4.2 **RQ 1**. Attitudes About Multimodal Feedback

During the co-design activity, I introduced the idea of an audio narrative along-side visualizations to participants with the question and asked if they would want their personal data to speak to them, in addition to being shown to them. This initial question, along with the audio narrative probes, revealed stroke survivors' and their caregivers' attitudes toward the inclusion of a speech-based narrative of their data alongside the visualizations I had shown previously in the session.

4.2.1 Apprehension towards multimodality

Some participants reacted with apprehension to idea of multiple feedback modalities during the co-design activity, either initially when the idea was introduced or in the closing portion of the activity. Apprehension was mainly targeted towards the audio modality, with P2, P3, P4, P7, and P8 expressing that the speech-based output would be unnecessary for them when the visualization provides the same or enough information. Participants provided different justifications for they felt apprehension towards needing both modalities.

P2, P4, P7, P8, and P9 cited that the visualization of their physical activity data was enough, and another modality would not be needed. P7 stated "I would be just happy with 2 charts and words on the charts. But that's me," and further expressed that with multiple visualizations showing her activity over time, she could draw her own conclusions. P8 relayed her initial rejection toward technology that has audio components, stating "the data kind of speaks for itself. So I don't need it to tell me if I'm on an upward trend."

P7 and CG-P7 both justified their perspective by talking about their education and background working in highly technical jobs, stating they "are used to using data, looking at it, and making [their] own conclusions." P2 and P4 also made references to their technical backgrounds as reasons for why they did not need an audio narrative to explain the visual data to them, but expressed that other stroke survivors may benefit from it.

> "Well, my background is data management. My particular thing is the statistics. It's visualization. I can read what the graph is showing me. It's helpful to me." (P4)

P9 stated that everyday audio feedback would become redundant and repetitious to him, and that he would rather look at the visualizations of feedback more consistently than listening to the audio feedback. He justified his preference by stating that he doesn't expect to see major changes on a smaller scale, and that his recovery is expected to be "small changes over longer time." Therefore, the audio narrative content would probably say the same thing if he checked it every day.

When probed further about the audio modality, some participants expressed ways they thought it could be helpful for them if the audio modality was included. P3 stated "I don't think it needs audio, but if it had audio, then it should say motivational things to me," which was further explored when I showed the audio narrative probes related to positive reinforcement. P3 also expressed that she did not want the audio narrative feature, but would want a gamification feature like badges.

Although participants had varying reactions and attitudes towards the audio narrative modality, they were all shown audio narrative probes in the next part of the co-design activity to further understand the capability, content preferences, and aesthetics of the audio narrative.

Audio modality as a hindrance in daily life

While participants provided examples of daily life scenarios where the audio narrative modality would be useful, they also provided concerns about the modality in other types of scenarios.

Participants who supported the use of the audio modality still expressed concerns about its use in particular contexts. P6 stated that in social contexts, such as having family over to his house, he would not play the audio narrative. He stated that, in those cases, he would prefer the option of having a textual description of the audio narrative, "like closed captioning." P7 expressed her disdain for others using audio outputs in public settings saying, "it bugs me when somebody else around me is on the phone with a voice you can hear it. I find I think it's interruptive to the other person, to that person it's rude."

P1 talked about situations where he would feel rushed by others, leading to frustration and abandoning using his affected hand. P2 also expressed feeling a pressure in social scenarios such as eating to use the easier option of her unaffected hand. Although these are compelling scenarios to provide feedback to use the affected hand, the audio modality may not be best due to its disruptive nature. For P1, P2, and P6, social pressure heightened their awareness of how they are using their affected side. P4 reported that she is always aware of her affected side's activity because of her low expectations for its progress.

While not expressed explicitly by the participants, I observed that some participants had difficulty remembering all of the components of the audio narrative probe due to their long sentence-length, or they requested to hear certain probes again because they did not understand them the first time.

4.2.2 Support for multimodality

Many participants expressed their support for the audio modality with the initial open-ended question about spoken data. P1, P5, P6, P9, and P10 provided their justifications for their approval of the modality and ways that it could be beneficial for their understanding of their personal data.

P9 talked about the idea of multimodality as reinforcement, stating that "hearing it, in addition to seeing it, it reinforces it. It's really giving good feedback. I hear and see it, and boom! I got it." He discussed "seeing" and "hearing" as two different experiences, comparing the feeling to when he's driving a car and can see out the windshield while also hearing things around him, both of which are helpful. CG-P09 disagreed with P09 during the discussion, stating that for her, seeing the feedback would be enough and she didn't need the audio narrative.

P5 talked about how audio output in other apps helps him focus on the content. He brought up how he used the read-aloud function in apps like Word, stating "if something's more than a couple of pages long, I find hearing it causes me to stay focused. If it's reading it, I'm hearing it. Every now and then it will mispronounce things, and that's not really wrong. It just helps keep me focused." P6 also discussed how he uses often prefers to use the speech input function in other apps, such as his phone's Messages and Notes apps, so he would be open to a speech output from the ring sensor.

P10 expressed that the audio narrative could even help with her aphasia recovery as well as provide support for her hemiparesis recovery. She stated that "when you get a stroke, initially it's hard to speak. The audio is helpful because you can hear but you can't speak. And then you do therapy and you can learn to speak more clearly. And it helps you speak clear." She went on to say that hearing speech during aphasia therapy is helpful because it provides examples to practice with as she works with the Speech Language Pathologist. Using the audio modality in this context would have dual benefits.

Different types of content within the audio modality were more or less beneficial when paired alongside the visualizations of the ring sensor data. In the next set of results, I will discuss different content preferences for the audio narratives if they were to be implemented in a multimodal format.

4.3 **RQ 2.** Audio Narrative Content Preferences

Despite differing attitudes about the utility of the audio narrative modality alongside the visualization, all participants responded to prompted questions regarding the content and preferences of a hypothetical audio narrative, especially when listening to the audio narrative probes. Participants provided perspectives about what types of speech content would be helpful or harmful for their recovery, and provided ideas for how insights should be delivered to them about their personal data.

4.3.1 Data description should be context-rich and non-redundant

Audio narrative probes that fell under the category of *Data Description* (table 3.1) had mixed reactions from participants. Some participants felt that pure descriptions of the visualization would not be helpful to them because they could read the content of the chart themselves. P4, P5, P7, and P9 stated that descriptions restated what they already knew about their activity, and would be "redundant." P4 even stated that readouts of the quantity of her activity would be completely ineffective due to the nature of her acalculia (an acquired loss of the ability to understand numerical concepts) , saying that percentages "would not connect at all." P5 also echoed that spoken percentages would be "unnecessary" to him if there was already a visual, and the spoken version would be more confusing.

Instead, some participants desired more context about the quality of their movement beyond what a chart could tell them. P2 wanted to annotate her data with identifiers such as what activity she was doing or the amount of time it took her to complete the activity to be able to use it more effectively. P3 also wanted to know the quality of her movement, not just the quantity, to understand how "active" she actually was. P10 wanted to know which activities she did that led to the best ratio of her affected to unaffected hand use. Knowing the context would guide her to doing more of those activities so can she optimize her affected hand's rehabilitation.

> "I want to know what activity lead up to my 45%. Slower, faster. Cooking and washing and stuff. What activity will lead up to 45%? What activity is equal to that? 45%. Because I said I want to increase that number." (P10)

Participants also wanted to enrich the descriptions of their data using comparisons. In a broad sense, P2 stated that seeing where she started and how she has improved would be important feedback to her in her recovery. P2, P3, and P8 wanted to hear comparisons of their activity between weeks, while P9 wanted to see between months. P7 expressed wanting to compare her activity over a longer period, such as 6 months. For other participants, they desired feedback that was provided only when an upward trend was recorded, not feedback on a consistent timescale that could possibly show no improvement. P9 stated "if it said if I did something on the affected side, and it let me know, that would be kinda neat." P8 and P10 both wanted to see their accomplishments and data that highlighted an upward trend, and P10 even stated that seeing feedback that her affected side was not improving would be "discouraging." Similarly, P5 expressed concerns over audio readouts that called out downward trends, saying that it was "highlighting failure, highlighting inability."

For some participants, self-awareness did not lead to reflection but instead to negative rumination. P7 expressed that she would not be interested in data and prefers not to know, stating it "just make me worried. I don't want to be stressed. Maybe I'm lazy" as justification. However, CG-P7 reported tracking P7's personal data manually for her, such as her daily blood pressure. He stated "I'm just the bookkeeper," suggesting that he would be more interested in monitoring P7's data for her instead of doing it herself.

Not all participants disagreed with wanting to hear descriptive spoken data. Alternatively, speech output that was purely descriptive actually appealed to some participants. P6 expressed a desire for straightforward descriptions, stating he wants to know "the truth" and that the description should not "cut any corners." He went on to say "no improvement has been made using the left [unaffected] side" as the rationale for why the descriptions should be direct and honest. Although P2 desired speech that was tagged for context, she also stated that the output could be very short. For example, "right 45, left 55," to describe the percentages of how each side was active. She stated that she did not need extra descriptors like "affected," "unaffected," or even the percentage symbol because it would become repetitive over a long period of time. P1 said that descriptive data output would be helpful to people like him who are "goal-oriented" because the quantified data would "keep him on pace." P8 went back and forth about whether percentages were necessary but punctuated her desire for brevity, stating "I don't know if it needs to say the percentage. Well, maybe it does. Yeah, I liked that. It was short and sweet."

4.3.2 Self-reflection should appropriately utilize self-awareness

P8 reported that one of the *Self-Reflection Questions* I played (i.e., How can you use your left side more during this activity?) reminded her of cues or phrases that her husband says to her to remind her to move the affected side more. She stated that hearing the technology say something similar would be motivating and encouraging in the same way.

However, alternate versions of the reflection that were more probative ("Why did you use your unaffected side more during this activity?") were perceived as "bossy," "not encouraging," and "questioning." P8 reported that if she were to answer the prompt honestly she would say it's because she was "lazy, which wouldn't help accomplish anything." P4, P7, and P9 responded to this version of the self-reflection prompt with matter-of-fact answers like "because I had a stroke" or "because I can't move my arm." In these scenarios they bypassed the specificity of what the reflection prompt was asking for and answered more broadly. P4 further stated, "What's the point?" and expressed wanting to hear solutions from the feedback, not questions. Some participants did not react as negatively to this version of the narrative, however. P6 expressed that he would be likely to respond to the question because he would want to be truthful, and stated that he'll entertain "anything that makes me conscious of what makes me better." However, he stated that the reflection questions "left him wanting more details," and more specific guidance.

P5 spoke about how other stroke survivors may react, saying "that value judgment causes a defensive reaction to [the self-reflection question]. But that's based on where the person is, what they're ready for." He expressed that stroke survivors who are at more vulnerable stages of their recovery should not be presented with doubts about their recovery progress, which is what the reflection questions could do.

4.3.3 Suggestions should provide guidance in real-time

Audio narrative content that included suggestions or guidance to help stroke survivors use the wearable ring sensor data more directly were received with acceptance.

Some participants expressed that suggestive or guided content was similar to "cues" or reminders that they had heard from real people in their lives, such as caregivers or therapists. After listening to the one of the *suggestion* audio narrative probes table 3.1, P8 stated that her husband had said the exact same phrase to her before, and that hearing the phrase would encourage her to follow the suggestion. Participants who were farther in their recovery, such as P5 (20 years post-stroke), stated that stroke survivors such as P8 (2 years post-stroke) who were still early in their recovery–yet already settled into chronic rehabilitation–would benefit more from the suggestive content. He stated that stroke survivors in this stage have experienced both successes and failures by now, and would therefore be receptive to guidance, whereas stroke survivors in very early phases may not have experienced any successes on their own yet and may not believe that following the wearable's suggestions will lead to progress.

Other attitudes toward this content category were related to the timing of the feedback delivery. For example P4, P7, and P8 desired feedback that would suggest ways to improve their activity be delivered at the specific times they are doing that activity, not at random intervals. These participants stated that this type of feedback content would be more useful as *reminders* rather than after-the-fact suggestions because they could be utilized in real-time. P3 referred to her FitBit's hourly haptic notification that reminds her to stand up at least once every hour as an example. Some participants mentioned that suggestions could be useful as reminders for the next day's activities rather than real-time, such as suggestions for improvement on a daily report card (P6).

4.3.4 Encouragement should motivate and maintain behavior

All participants expressed that *Encouragement* audio narrative content should be used for motivational feedback. Positive tones of feedback were preferred. Between the two encouragement narratives, "You're almost there, keep going", and "You can do better next time," all participants preferred the first version and reacted very negatively to the second.

Motivational content was discussed in contexts of both desirable feedback (upward trends, goal maintenance, general improvement) and undesirable feedback (downward trends, no improvement or change). P1 expressed that motivation is necessary in both contexts, firstly to celebrate goals that were met and secondly to provide an extra push to motivate. He also expressed that positive reinforcement should not be overused and stated "every once in a while it would be nice to hear something encouraging that said, 'hey you're doing all right.' I think that works. So not every time."

While participants were largely supportive of motivational content being included in the audio narrative, they also expressed their concerns about how and when it is used. P5 stated that “overly saccharine” content would be detrimental or meaningless rather than supportive. P8 talked about motivation being occasionally “bothersome” to her, stating “while I think it’s something cool, I don’t necessarily think that it’s something necessary. Sometimes it can actually be bothersome. Like if it spoke to you and said, ‘Hey, great job today,’ or it gave you some kind of encouragement. Those are all nice, but I don’t know. I kind of find them bothersome.”

4.3.5 Narrative qualities should be customizable

Participants also provided their preferences for the aesthetic qualities of the audio narrative. The main aesthetic characteristics I prompted were voice gender preference and talking speed preference.

Some participants preferred a female voice for their audio narratives but provided different justifications. P1, P6, and P9 both stated that they prefer a female voice due to its “calm” tone. P6 expressed that the voice should be “not as loud as the lady on the Amber Alert but a calming, motherly voice.”

P8 expressed that she preferred the female voice because she was used to hearing it in other technology such as Alexa or Siri, and so the ring sensor application would also fit into this norm.

P10 also wanted to hear a female voice, and justified her choice by comparing the voice to other aspects of her recovery journey, specifically therapists. She stated that “most female therapists is sympathetic with what I am going through,” however, she reiterated that she did not want the *content* of the audio narrative to sound like a therapist.

P4 and P2 stated that they had no preference between a male and female voice, but expressed that it could a personalized feature to account for different peoples’ preferences.

None of the participants expressed specifically wanting to hear a male voice for the

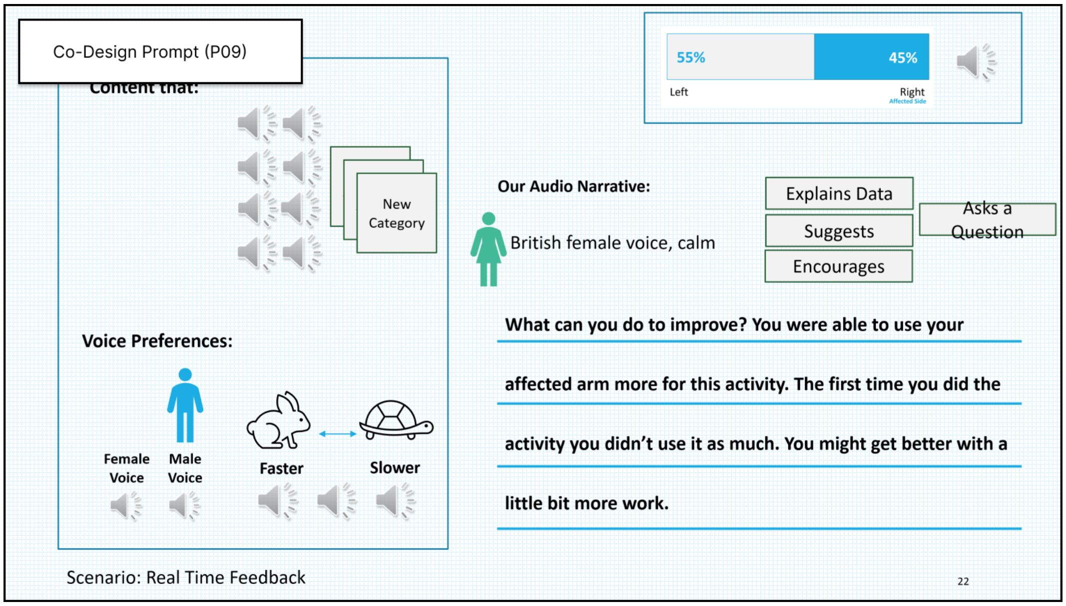

Figure 4.1: P9 and CG-P9's co-design artifact from the unprompted activity. They preferred the audio narrative to be voiced by a woman with a British accent.

audio narrative. P9 and CG-P9 both mentioned that the voice of the audio narrative reminded them of a humorous TV show character, which while funny "probably wouldn't be appropriate."

All participants except P10 preferred the audio narrative's talking speed to be around 160-175 wpm. P10 preferred a slower talking speed to better understand the content. P2 did not have a preference for slower or faster talking speed than the default speed of the audio narratives, but expressed a desire for the option to personalize for both her and other stroke survivors using this system. She stated "if you could, I prefer to toggle in between. To me that doesn't make or break the app or the feedback. I'm a big fan of bunny to turtle."

Content and aesthetic preferences about the audio narrative modality were not static, but rather fluctuated by how stroke survivors envisioned using the modality in their daily lives. Not all content categories would be useful if deployed all at once, and rather have optimal contexts where the stroke survivor could best utilize the audio narrative with the visualization.

4.4 **RQ 3**. Opportunities for Utilizing Multimodal Ring Sensor Feedback

4.4.1 Different occurrences/intervals to utilize multimodal feedback

Daily events in stroke survivors' lives were reported as potential opportunities for when the audio narrative would be effective. For example, in situations of frustration, such as performing a difficult task, the stroke survivor is tempted to stop using their affected hand and switch to using their unaffected hand. P1 reported "forgetting" to use his affected hand in situations where he is able to and P8 reported a similar feeling of needing to be reminded to use her affected side. She stated that because her affected side is her non-dominant hand, remembering to use it "doesn't happen automatically." In these situations, some participants expressed wanting a strong intervention of feedback that could call out the non-use of the affected hand and tell them to use it.

> "I told you when I get stressed out or tired, that I switch from my right [affected] to left [unaffected] hand. That alert will tell me to switch back to the right [affected] hand." (P6)

Different times of the day or events were also more optimal **better** for different stroke survivors to receive feedback from the ring sensor. P2 and P8 both suggested pairing their ring sensor usage with specific activities for their affected arm rehabilitation, so that the ring sensor feedback would be contextualized to the particular activity. P3 spoke of hourly feedback as prompts for activity, comparing how her Fitbit sends her haptic feedback hourly to stand up and move around.

P6 reported engaging with other health applications like Constant Therapy at nighttime alongside his prayer routine, in a way to align or "bundle" his daily reflective rituals. When prompted, P6 stated he might be open to also receiving feedback from the ring sensor at the same time in a "daily report" to also engage with during prayer and other reflection.

However, he only wanted a summary “report card,” and not too many notifications. P5 also wanted a daily report provided at “bedtime” so he could reflect on the day’s activities and P8 said that a daily report would be helpful for her to “match up her daily activities.” P10 also wanted daily feedback but in the middle of the day when she would still be able to utilize it within the day.

4.4.2 Content should match to stage of recovery

The participants fell into different stages of recovery depending on the severity of their stroke-related consequences and the amount of time passed since their stroke. Participants with 10–20 years of recovery experience provided insights into where the audio modality would have been more or less helpful.

P2, whose stroke was 12 years ago, stated that the audio narratives reminded her of the language used by occupational therapists early in her recovery process. For people like her who are “farther out in their recovery,” content like the audio narrative probes would not be helpful because it has been given to them repeatedly over their recovery. Instead, P2 expressed that self-reflection prompts and suggestions would be more beneficial to people who are in earlier stages of their recovery who have not become desensitized to the language yet. P1 also stated that stroke survivors at the earlier stages would benefit, stating “at the beginning stages, I think that would work perfect,” because they are still setting their goals and aspirations for what they would like to achieve.

P5, who experienced his stroke almost 20 years ago, gave insight into how internal phenomena such as post-stroke depression can intermingle with external sources of feedback. P5 stated that for stroke survivors in the early stages of recovery dealing with the denial of their condition and depression, the audio modality would reinforce internal negative feelings.

> "'You could do better.' That's a perception of value judgment for a stroke survivor. I was beating myself up so much that that would just push me to be even more negative. That negative past. A very common side effect is depression, and that unwillingness to accept what you've become. It would reinforce that you're not as good as you used to be. 'You're not as good.'" (P5)

Based on this account, P5 suggested that the audio modality would be helpful for stroke survivors who have moved past this stage of denial and accepted that they will not return to their old normal, stating there will be a time when the stroke survivor is "ready for it."

I discuss the takeaways from the key findings next in the Discussion.

Chapter 5: Discussion

Findings from the combined semi-structured interviews and co-design activities garnered key insights into how stroke survivors envision multimodal interfaces being used in their daily lives. In this section, I discuss key takeaways from our findings as implications for design, as well as highlight interesting aspects of the methods and procedure, limitations, and future work.

5.1 Complementary Relationship Between Visualizations and Audio Narratives

A multimodal output approach to deliver feedback from the wearable ring sensor can be applied effectively with the stroke survivor population. The two output modalities, visual and audio, amplified each other when providing stroke survivors with differing content. For example, purely descriptive audio narratives that repeated the information provided by the visualization were redundant and unnecessary. However, audio that provided additional contextual cues, recommendations, and positively framed encouragement–not provided by the visualization–was well-accepted by participants. In this scenario the visualization can provide a baseline of usable information, and the added audio narrative can provide an extra push to stroke survivors to act on the information.

The audio narrative revealed an unexpected benefit for some stroke survivors with aphasia, who may be able to use the audio as practice material in their speech rehabilitation along with a way to access information about their hemiparesis progress. With additional studies it will be possible to explore what other aspects of multimodal interaction can also be equipped with secondary therapy functions, such as speech or cognitive therapy.

5.2 Recommendations for Implementation

Although audio and visual modalities can work together to create an effective experience for stroke survivors, several recommendations for implementation should be mentioned to maximize the benefit of multimodality.

5.2.1 Deploy Feedback in Situations of Low Awareness

Throughout their day, stroke survivors experienced different levels of awareness of how much they are using their affected side. For example, social situations heightened their awareness. Therefore in situations where a stroke survivor is already highly aware of the low use of their affected limb, the wearable ring sensor feedback may not be as useful. Feedback, either visual or auditory, would reinforce their internal awareness, and may add on to negative feelings of disappointment or frustration. Audio feedback may contribute more so than visual to this effect due to its more anthropomorphic quality and perceived as blaming or overly critical.

Instead, wearable sensor feedback, especially auditory feedback, should be designed to be utilized in situations where the stroke survivor may not have awareness of their affected side's progress. Some participants wanted the feedback to specifically notify them when their affected side had done something unexpected or progressed over time, suggesting that anomalies are useful indicators. Participants often stated that noticing their affected side's function returning slowly over time indicated that their rehabilitation was working, and motivated them to keep up their regimens. Therefore supporting stroke survivors by celebrating the payoff of consistently completing their exercise or treatment could be a method for motivating future adherence. Additional work with therapists can help to define anomalies detectable by the wearable ring sensor and how treatment plans or guidance should complement these notifications.

5.2.2 Parallel Feedback to the Timescale of Recovery

Another common thread through the stroke survivors' experiences was how recovery happens on a much larger timescale than other types of disease recovery. Stroke survivors like P2, P4, or P5 who have been in recovery for 10 or more years reported that while they still observed improvements within themselves to this day, progress is happening incrementally over a very long period of time.

When applying these time-scale experiences to the design of the wearable's feedback, efforts have to be made to respect the realistic expectations of stroke recovery, and to the particular stroke survivor's stage of recovery. Even though the ring sensor wearable has the capacity and power to provide real-time, daily, weekly, or even monthly feedback to the stroke survivor, it's very likely that these shorter timescales will not show significant changes or trends in terms of the affected limb's performance or capacity. The audio narrative's reinforcing characteristic on top of a visualization showing no progress may pile on to the user, who would now be receiving multiple messages implying they are not making any progress from the days or weeks before, leading to rumination or discouragement. Stroke recovery is a chronic condition, and so the wearable feedback should reflect the nuances of chronic care. To combat potential rumination, daily feedback messaging could be focused more on activities or topics that the stroke survivor has control over. For stroke survivors who in a more chronic stage, audio narrative messaging that acknowledges the realistic progress expectations and long-term timescale of recovery may be one way to alleviate discouraging effects of seeing no improvement in the short-term.

5.2.3 Provide Text Alternatives to Audio Narratives

Two consistently reported drawbacks to the audio modality were its potential for disruption in social settings and the serial nature of its content. Participants reported that they would not play the audio narrative around other people for reasons such as protecting their privacy and not wanting to cause a disruption. However, they still expressed wanting access to its content.

Participants also had some difficulty with remembering the content of longer audio narrative probes and often wanted us to replay the recordings to listen to them again. This observation represents the second drawback of the audio modality, related to phrase length and serial processing.

To account for these drawbacks, I propose that when the audio narrative is applied, closed captioning or a text-based version of the narrative should be provided as an alternate option, very similar to how alt text is generated for charts and graphical visualizations, because similar to audio narratives, alt text is meant to be read aloud [43]. In these scenarios where the audio is a hindrance more than a benefit, stroke survivors should have the option to not use the function (either through a mute function, or touch-to-activate function) while still having access to the content. Although converting the audio narrative to a textual narrative transforms the modality from audio to visual, it can still provide additional support to the stroke survivor as they interact with and utilize their personal data.

Textual versions of the audio narrative may also be easier to translate into notifications. Notifications can be deployed at personalized times for the stroke survivors and be effective as they contain the best content for supporting recovery without being disruptive if delivered quietly.

5.2.4 Opportunities for Customization

All of the participants and their caregivers mentioned the phrase “every stroke is different,” either as a direct quote or alluded to the idea in other words. The concept is repeated throughout early treatment and later in the rehabilitation journey to help stroke survivors manage their expectations for recovery. The idea of a unique “stroke survivor experience” has bubbled up to the surface for how health technology for stroke survivors should be designed as well. The participants’ discussion of their personal preferences and their speculation that other stroke survivors may disagree with their preferences has contributed to the recommendation for personalization in the application of the ring sensor feedback.

Personalization in health technology has been realized in some other applications such as OmniTrack, where users can customize the mobile interface based on their self-tracking needs [37]. The innate customizability of paper bullet journals has also served as inspiration for designing non-rigid methods of daily tracking technology [5]. Not all features of the ring sensor and its feedback can be feasibly personalized, both due to the burden on the application development and the burden on the stroke survivor to customize settings for themselves. Customization is also difficult for people who may be facing mental illnesses or cognitive impairments (which is common for stroke survivors) [76]. Customization should therefore be deployed to maximize stroke survivors’ needs without overburdening or overwhelming them. The findings suggest several avenues of customization, from the simplest to the most complex: aesthetics of the audio narrative (e.g. voice gender, talking speed), on/off toggle, personal identifiers (e.g. the stroke survivors’ name), length of the audio narrative, feedback occurrence (e.g. hourly, daily, weekly, monthly), delivery timing, feedback modality, content sentiment, and which category of semantic content is utilized.

5.3 Session Considerations and Limitations

5.3.1 Involving Caregivers in the Stroke Study

The presence of the caregiver during the session significantly impacted the structure of the session itself. For the participants with aphasia, Many caregiver participants often rephrased or 'translated' a semi-structured interview question or co-design prompt given by the researcher into a format that was more understandable to the stroke survivor. In this way, caregivers helped us enhance the salience of the question to the stroke survivor and facilitated answers. On the other hand, caregivers would also take over answering the questions directed towards the stroke survivors and speak for them, with the stroke survivor either nodding or giving short affirmative phrases. When this occurred, I possibly lost access to the stroke survivors' true perspective on a prompt. Even if the question was then directly targeted to the stroke survivor, they tended to agree with their caregiver's assessment.

Caregivers also provided their own perspective of the recovery process, often detailing the struggles of providing care and the impact on their own lives. Caregivers often reported feeling that the stroke also happened to them as much as it did to the stroke survivor because of the new roles they had to take on, such as childcare. Some also reported feeling loneliness and feelings of abandonment by their social circles, and talked about how caregiver support groups provided an outlet for their perspective. These perspectives gave us a more holistic and authentic to the lives of stroke survivors, which helped to frame the larger context for how wearables fit into the picture.

Co-design sessions with caregivers also added a logistic obstacle because their responses took time away from the stoke survivors' responses. Future studies where there is more time allotted, or additional sessions, will help to more effectively engage with both stroke survivor and caregiver participants.

5.3.2 Time Constraints

The 90-minute time frame of the session of the study meant I had a limited amount of available time to gather both stroke survivors' existing contexts and their perspectives on the audio narrative modality. Although all participants were able to provide their perspective on the audio narrative in a real-time feedback context, I did not hear from all participants about their thoughts on other time contexts such as daily, weekly, or long-term feedback. As introducing these additional time contexts would increase the 90-minute allotted time for the session and increase the burden on participants, I cut this final portion. This missing perspective on longer-term feedback will be key to explore further in future work. The study was also conducted in one session, so I do not have access to participants' attitudes and preferences toward the audio narrative past their somewhat immediate responses during the session. Understanding their acceptance to the technology after longer exposure to the ideas is also a key missing perspective.

Sessions with participants who also had aphasia occasionally took a longer amount of time to respond to questions, however the difference was not significant as I completed all required parts of the study with all participants.

5.3.3 Lack of Participants with Additional Consequences

Out of 10 participants, 5 of the participants self-reported having expressive aphasia, which allows them to comprehend speech clearly but experience difficulties in producing it. I did not work with participants who had other types of aphasia, such as receptive or global aphasia, who would have severe difficulty with the comprehension of speech [30]. These potential participants were excluded because they would not be able to complete the co-design activity procedures. An audio modality for stroke survivors with this type of aphasia would likely not be feasible, however additional work that includes these participants is necessary.

I also had a limited number of participants who experienced visuospatial disorders. P8 self-reported experiencing hemispatial neglect on her affected side and P5 experienced vision effects early in his treatment, but had since recovered. Conducting additional sessions with participants who experience the visuospatial consequences of stroke would help to better understand how the audio modality can be utilized if the visual modality is either fully or partially inaccessible.

5.3.4 Remote Session Format

Using Zoom to conduct the sessions allowed for more accessible participation as stroke survivors would not have to physically travel to the in-person study location. However due to the remote format, participants did not have physical access to the actual wearable ring sensors and could not try them out personally. Being able to handle the system in-person may have helped stroke survivors better envision the ring sensor in their daily context. In addition I could have used the stroke survivors' real ratio of use data in lieu of fabricated data and template scenarios that would have been more realistic and relatable.

Future work that seeks to understand how the wearable system should deliver feedback can be conducted in settings where participants can interact with the rings and provide more situated responses.

5.4 Future Work

In addition to addressing the limitations of the thesis study, this research presents several avenues for future work. Additional modalities of output can be explored such as haptic or non-speech audio feedback along with visual and speech audio. These modalities can provide benefits that neither visual or speech audio possess, such as simplicity or brevity.

Multimodal input could also be explored further within the wearable ring sensor context in addition to multimodal output. Many stroke survivors desired context-rich descriptions of their limb use data, which may be difficult for the wearable to capture directly. Instead stroke survivors could provide context themselves, with easy-to-use input functions such as speech or touch modalities [45, 38]. Combining input and output functionalities, such as a chatbox or in-app dialog with the stroke survivor, is another area of future work.

Chapter 6: Conclusion

We explored how multimodal feedback in the form of visualizations combined with a new modality, audio narratives, can be used to support stroke survivors in their recovery journey. We conducted this research in the context of a wearable ring sensor capable of capturing activity metrics that can help stroke survivors improve their hemiparesis, or one-sided loss of function and weakness in their upper limb. Using the human-centered approach of co-design, we were able to collaborate with stroke survivors and their caregivers and engage ideas about multimodal feedback in three parts: attitudes towards multimodality, content and aesthetic preferences of the feedback, and how multimodal feedback could fit into their daily lives.

RQ 1. How can speech-based "audio narratives" complement visual representations of personal health data? (Attitudes About Multimodal Feedback) Audio narratives can compensate and add to information that is conveyed by visualizations to potentially nudge stroke survivors toward creating or maintaining healthy behaviors. Stroke survivors invest significant time and money in rehabilitation technology. If they were to use the wearable ring sensor to support the progression of their hemiparesis–one-sided limb weakness–they would want that tool to deliver as much context-rich information as possible to use in independent or therapist-assisted recovery. Multimodal output provide a way to maximize the capability of the wearable ring sensor by delivering its information capture effectively and efficiently.

Audio narratives can reinforce the content of visualizations and provide secondary benefits beyond information delivery, such as therapy practice. Some participants expressed apprehension towards multimodality and voiced their need for visual, unimodal feedback only. However the concerns they brought up about the audio modality, such as its redundancy, disruption, and privacy concern, can be incorporated as design recommendations for implementation.

RQ 2. How do stroke survivors envision the content they want to hear in the audio narratives? (Audio Narrative Content Preferences) Through the co-design activity, participants were able to interact with several different types of audio narrative content that were generated with the help of occupational and physical therapists. Through this activity, participants provided their preferences and apprehension for four different content probes: data descriptions, self-reflection prompts, suggestions, and motivation/encouragement (table 3.1). Descriptive content conveyed the same information in both visual and audio modalities, while self-reflective, suggestive, and motivational content conveyed information not provided by the visualization. Stroke survivors responded more positively to these types of content because they found the descriptive content redundant.

Within content categories that provided extra information beyond the visualization, participants preferred content that was more positively framed and responsive to their stage of stroke recovery. Individual differences between stroke survivors were also present in their preferences toward phrases, terminology and aesthetics, which can be opportunities to utilize customization settings. For example, participants with acalculia who had difficulty comprehending numerical relationships did not respond well to content with quantity relationships (less vs. more) or percentages.

RQ 3. How can stroke survivors utilize the audio narratives in their daily lives? (Opportunities for Utilizing Multimodal Feedback) After gathering stroke survivors' attitudes towards audio and visual modalities used in complement, as well as preferences for the audio narrative content, I collaboratively identified opportunities where multimodal feedback could be utilized successfully. For example, feedback that is deployed at specific intervals or occurrences would be matched to certain types of content. Feedback that is provided in real-time may be best suited to suggestions so that stroke survivors could utilize the visualization of their performance and recommendations for improvement immediately. On the other hand, descriptions of trends would be useful over long-term periods (over months or years) to bring attention to long-term progress.

Expectations of progress, related to self-efficacy and how multimodal output could frame feedback, is an important consideration with the stroke survivor population due to scale of recovery. For example, stroke survivors early in their recovery journey may be more receptive to some types of feedback content because they are still sensitive to the messaging. Stroke survivors who are in further phases could be desensitized to the messaging and therefore would not find it effective. On the other hand, early-stage stroke survivors could be hesitant to follow therapy recommendations or suggestions from the feedback if they had not yet experienced any rehabilitation successes.

These considerations speak to the potential effectiveness of deploying visual and audio feedback together in a multimodal interface. Additional work is needed to address limitations of this thesis, such as time constraints and limited participants, as well further explore future avenues of research in how both multimodal inputs and outputs can benefit stroke survivors using the wearable ring sensor. Finally, utilizing human-centered approaches like co-design was effective in engaging with the stroke survivor population, who can easily be disregarded or ignored in the development of novel health technology.

Appendix A: IRB Approval

UNIVERSITY OF MARYLAND
INSTITUTIONAL REVIEW BOARD

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DATE:	December 19, 2022
TO:	Eun Kyoung Choe
FROM:	University of Maryland College Park (UMCP) IRB
PROJECT TITLE:	[1977290-1] Designing Audio and Visual Representations of Upper Limb Activity Data to Aid At-Home Stroke Rehabilitation
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	December 19, 2022
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category #7.

Thank you for your submission of New Project materials for this project. The University of Maryland College Park (UMCP) IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

Prior to final approval of this project scientific review was completed by the IRB Member reviewer.

This submission has received Expedited Review based on the applicable federal regulations.

This project has been determined to be a MINIMAL RISK project.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Unless a consent waiver or alteration has been approved, Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the appropriate Amendment forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed. All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Please note that all research records must be retained for a minimum of seven years after the completion of the project.

If you have any questions, please contact the IRB Office at 301-405-4212 or irb@umd.edu. Please include your project title and reference number in all correspondence with this committee.

Appendix B: Recruitment Flyer

Subject line: Invitation to Participate in a Research Study on Technologies to Support Stroke Recovery

Have you or someone you know had a stroke that led to the loss of function of one of the arms? We would like to invite you to participate in a research study at the University of Maryland, to talk about your experiences and to share your opinions about stroke technology. The study will be conducted by Dr. Eun Kyoung Choe (PI) at the University of Maryland. We are inviting both stroke survivors and caregivers for this study. If you qualify to participate in our study, you will be invited to a 90-minute study session, which will be held over Zoom/WebEx or in-person. During the study session we will conduct a short semi-structured interview about your experiences with stroke and how you use technology in your everyday life. We will also conduct an interactive design activity where you can help us directly design the technology and influence the future of stroke rehabilitation based on your goals and preferences. Stroke survivors and caregivers will participate in the session together. Note: Stroke survivors without caregivers are invited to participate. To participate in the study, you must meet all the following criteria: If you are a stroke survivor:

1. Be 18 years old or older
2. Had a stroke at least 6 months ago
3. Experience arm weakness or arm limb function loss on one side

4. Interested in participating in a research study about technologies for stroke rehabilitation

5. Able to understand and answer questions asked during an interactive design activity

6. Able to join the session virtually or in-person. For virtual access, you must have equipment capable of participating in a Zoom/WebEx video chat (computer, internet access, webcam, microphone, Zoom/Webex software), and willing to participate with video and audio recording

If you are the primary caregiver of a stroke survivor:

1. Be 18 years old or older

2. Be the primary caregiver of stroke survivor a stroke at least 6 months ago

3. Give care for a stroke survivor who has experienced arm weakness on one side

4. Interested in participating in a research study about technologies for stroke rehabilitation

5. Able to understand and answer questions asked during an interactive design activity

6. Able to join the session virtually or in-person. For virtual access, you must have equipment capable of participating in a Zoom/WebEx video chat (computer, internet access, webcam, microphone, Zoom/Webex software), and willing to participate with video and audio recording

As a thank you for completing the session, stroke survivors will receive an \$80 gift card and caregivers will receive a \$50 gift card as compensation. If you are interested, please fill out a screening questionnaire or send us an email so that we can reach out to you directly to assist with the screening process over the phone (fig. B.1).

Figure B.1: Recruitment flyer sent to stroke support groups and local clinicians to share.

Appendix C: Screening

Script: Thank you for joining me today. This should be a relatively short call, no more than 15 minutes to give us more information about how you can be involved in our study.

I'll start by going over the purpose of our study and some general things to note. Please stop me if you have any questions. Before I get started do you have any questions?

Great! So I'm part of a research group studying how to support stroke survivors in their recovery using new technology. The study we're inviting you to participate in is about how stroke survivors can use a new tool called a wearable ring sensor. This is a tool for people who have experienced one-sided upper limb weakness or hemiparesis to monitor their how their left and right sides are moving. In this study we'll ask you questions about how you would use the data that this tool brings about. You do not need previous experience with it to participate.

The next thing I'll mention is how we'll conduct the study. We're going to be using a method called co-design or participatory design. This means that you'll be able to provide your thoughts and ideas for how this technology should work for you, and the idea behind it is to involve stroke survivors as much as possible in the development of technology that is aimed for you to use. Next I'll ask you some questions. I'll be taking notes on your answers if you see me look away from the screen. If you feel uncomfortable answering or would like to skip, please let me know. Any questions before we start?

Okay, let's start:

- Are you a stroke survivor or caregiver for someone who has had a stroke?
  - Stroke Survivor (jump to section A)
  - Caregiver (jump to section B)

Section A: Questions if Stroke Survivor is Going Through Screening:

- What is your age?
  - 0-12 (reject)
  - 13-17 (reject)
  - 18-24
  - 25-40
  - 41-64
  - 65-90
  - 91+
- When did you have a stroke?
  - Less than 6 months ago (reject)
  - Greater than 6 months ago
- Have you experienced any weakness, lack of function, or paralysis in one of your arms (arm/shoulder/hand) because of your stroke?
  - No (reject)
  - Both Sides (reject)
  - Yes, Left Side

    - Yes, Right Side

- What is your dominant hand?

    - Left Side

    - Right Side

    - Ambidextrous

- Do you have a caregiver?

    - Yes

    - No

- If they said "Yes" to having a caregiver: We would like to invite both stroke survivors and their primary caregivers (if they have one) to participate in our study. If your caregiver is available to join you for the study session, can you forward these recruitment materials to them?

    - Yes

    - No

- We would like to conduct the study in a format based on your preference and capabilities. Would you prefer to participate in-person or online through a video conference?

    - In-Person

        * Can access the University of Maryland Human-Computer Interaction Lab (HCIL)

        * Cannot access the University of Maryland HCIL Lab (reject or direct to remote option)

- Remote Video Conference
  - Do you have the following equipment available to use? (check all that apply)
    * Computer (Desktop / Notebook / Laptop) or Tablet
    * Webcam
    * Microphone
    * High-speed internet access
    * Zoom or WebEx software

    (Less than 5 selected: reject)
- Our study will consist of an interactive design activity to see how stroke survivors can better access their own data about their rehabilitation and recovery. To successfully participate in the study, you will need to be able to answer questions about your rehabilitation. Do you have difficulty with any of the following:
  - Answering questions in a non-yes/no format
  - Answering questions in an open-ended format
  - Viewing images on a screen or print-out
  - Describing images
  - Listening to audio recordings
  - Other examples of study participation ability
- During the session, we will record your video and audio responses to questions. Are you comfortable with being recorded?
  - No (reject)
  - Yes

That was our final question. So for next steps, I will send you an email with a document regarding your consent to participate in the study. I will also send you options for scheduling the full session and details about joining.

Section B: Questions if Caregiver is Going Through Screening:

- What is your age?
  - 0-12 (reject)
  - 13-17 (reject)
  - 18-24
  - 25-40
  - 41-64
  - 65-90
  - 91+
- When did the person you give care for have their stroke?
  - Less than 6 months ago (reject)
  - Greater than 6 months ago
- Has this person experienced any weakness, lack of function, or paralysis in one of their arms (arm/shoulder/hand) because of their stroke?
  - No (reject)
  - Both Sides (reject)
  - Yes, Left Side
  - Yes, Right Side

- What is their dominant hand?
  - Left Side
  - Right Side
  - Ambidextrous
- We would like to conduct the study in a format based on your preference and capabilities. Would you prefer to participate in-person or online through a video conference?
  - In-Person
    * Can access the University of Maryland Human-Computer Interaction Lab (HCIL)
    * Cannot access the University of Maryland HCIL Lab (reject or direct to remote option)
- Remote Video Conference
  - Do you have the following equipment available to use? (check all that apply)
    * Computer (Desktop / Notebook / Laptop) or Tablet
    * Webcam
    * Microphone
    * High-speed internet access
    * Zoom or WebEx software

    (Less than 5 selected: reject)
- Our study will consist of an interactive design activity to see how stroke survivors and their caregivers can better access their own data about their rehabilitation and recovery. To successfully participate in the study, both you and the stroke survivor

will need to be able to answer questions about their rehabilitation. Do you or the stroke survivor have difficulty with any of the following:

  - Answering questions in a non-yes/no format
  - Answering questions in an open-ended format
  - Viewing images on a screen or print-out
  - Describing images
  - Other examples of study participation ability

- As a caregiver, what types of activities do you assist your stroke survivor with?

  - Open-ended answer

- This study will include an interactive co-design session with both you and the stroke survivor. Can you forward the recruitment materials of this study to the stroke survivor to undergo this screening process?

  - Open-ended answer

Appendix D: Consent Form (for Stroke Survivor Participant)

Consent to Participate (Stroke Survivor)

- Project Title: Designing Audio and Visual Representations of Upper Limb Activity Data to Aid At-Home Stroke Rehabilitation

- Purpose of the Study: This research is being conducted by Eun Kyoung Choe at the University of Maryland, College Park. We are inviting you to participate in this research project because you are above the age of 18, experienced a stroke at least 6 months ago, have hemiparesis/hemiplegia (one-sided arm weakness), and expressed interest in being involved in a research study on stroke rehabilitation. The purpose of this research project is to design better data representations for stroke patients in their physical and functional recovery.

- Procedures: The procedures involve a 90-minute interactive design activity where you will view data representations, provide your feedback about the representations, and tell us about how technology can play a role in your daily life and stroke recovery journey. This session will take place over a video conference app such as Zoom or WebEx, or in-person at the University of Maryland Human-Computer Interaction Lab (HCIL), based on your preference. You will be audio and video recorded for analysis, however all measures to ensure privacy will be taken. Audio and video recording will be required to participate in this study.

- Potential Risks and Discomforts: There may be some risks from participating in this research study. We will ask you questions about your stroke recovery journey and how you can use wearable technology to improve your physical and functional health. You may skip any question you do not wish to answer, take a break, or end the session at any point. To minimize the risk of a potential breach of confidentiality, we will de-identify personal information before analysis, keep all video/audio recordings and session notes in UMD Box, and only allow co-collaborators to view study materials.
- Potential Benefits: There are no direct benefits from participating in this research. However, possible benefits include having access to data about limb recovery after stroke. We hope that, in the future, other people might benefit from this study through improved understanding of how stroke patients use wearable technology to improve their recovery.
- Confidentiality: Any potential loss of confidentiality will be minimized by storing data in a secure digital location such as the University of Maryland Box. Only collaborators approved by the Institutional Review Board (IRB) will have access to this data. Any identifiable data collected will be destroyed 5 years after collection. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.
- Compensation: You will receive an $80 gift card. You will be responsible for any taxes assessed on the compensation. If you will earn $100 or more as a research participant in this study, you must provide your name, address and SSN to receive compensation. If you do not earn over $100 only your name and address will be collected to receive compensation.

- Right to Withdraw and Questions: Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator:
  - Principal Investigator: Eun Kyoung Choe (4130 Campus Dr. Hornbake Library Room 2117F University of Maryland, College Park, MD, 20742)
  - Co-Investigator: Aishwarya Shettigar
- Participant Rights: If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: University of Maryland College Park Institutional Review Board Office 1204 Marie Mount Hall College Park, Maryland, 20742; E-mail: irb@umd.edu; Telephone: 301-405-0678

  For more information regarding participant rights, please visit: This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.
- Statement of Consent: Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.
- Participant Fields: Name, Signature, and Date

Appendix E: Consent Form (for Caregiver Participant)

Consent to Participate (Caregiver)

- Project Title: Designing Audio and Visual Representations of Upper Limb Activity Data to Aid At-Home Stroke Rehabilitation
- Purpose of the Study: This research is being conducted by Eun Kyoung Choe at the University of Maryland, College Park. We are inviting you to participate in this research project because you are above the age of 18, are the caregiver of someone who experienced a stroke at least 6 months ago, are the caregiver of someone who has hemiparesis/hemiplegia (one-sided arm weakness), and expressed interest in being involved in a research study on stroke rehabilitation. The purpose of this research project is to design better data representations for stroke patients in their physical and functional recovery.
- Procedures: The procedures involve a 90-minute interactive design activity where you will tell us about how technology can play a role in your life as the caregiver of a stroke survivor. As a caregiver, we would like to hear your experiences about how you help the stroke survivor with their everyday life and how our technology could play a role in assisting that care. This session will take place over a video conference app such as Zoom or WebEx, or in-person at the University of Maryland Human-Computer Interaction Lab (HCIL), based on your preference. You will be audio and video recorded for analysis, however all measures to ensure privacy will be taken.

Audio and video recording will be required to participate in this study.

- Potential Risks and Discomforts: There may be some risks from participating in this research study. We will ask you questions about your experience providing care for someone who has had a stroke, their recovery process, and how they use wearable technology to improve their physical and function health. You may skip any question you do not wish to answer, take a break, or end the session at any point. To minimize the risk of a potential breach of confidentiality, we will de-identify personal information before analysis, keep all video/audio recordings and session notes in UMD Box, and only allow co-collaborators to view study materials.

- Potential Benefits: There are no direct benefits from participating in this research. However, possible benefits include having access to data about limb recovery after stroke. We hope that, in the future, other people might benefit from this study through improved understanding of how stroke patients use wearable technology to improve their recovery.

- Confidentiality: Any potential loss of confidentiality will be minimized by storing data in a secure digital location such as the University of Maryland Box. Only collaborators approved by the Institutional Review Board (IRB) will have access to this data. Any identifiable data collected will be destroyed 5 years after collection. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

- Compensation: You will receive an $50 gift card. You will be responsible for any taxes assessed on the compensation. If you will earn $100 or more as a research participant in this study, you must provide your name, address and SSN to receive compensation. If you do not earn over $100 only your name and address will be collected to receive compensation.

- Right to Withdraw and Questions: Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify. If you decide to stop taking part in the study, if you have questions, concerns, or complaints, or if you need to report an injury related to the research, please contact the investigator:
  - Principal Investigator: Eun Kyoung Choe (4130 Campus Dr. Hornbake Library Room 2117F University of Maryland, College Park, MD, 20742)
  - Co-Investigator: Aishwarya Shettigar
- Participant Rights: If you have questions about your rights as a research participant or wish to report a research-related injury, please contact: University of Maryland College Park Institutional Review Board Office 1204 Marie Mount Hall College Park, Maryland, 20742; E-mail: irb@umd.edu; Telephone: 301-405-0678

  For more information regarding participant rights, please visit: This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.
- Statement of Consent: Your signature indicates that you are at least 18 years of age; you have read this consent form or have had it read to you; your questions have been answered to your satisfaction and you voluntarily agree to participate in this research

study. You will receive a copy of this signed consent form. If you agree to participate, please sign your name below.

- Participant Fields: Name, Signature, and Date

Appendix F: Co-Design Artifacts:

In this appendix section, we include all co-design activity artifacts generated during the 10 sessions with stroke survivors and their participants, arranged by the slide's prompt. Not every prompt was completed for each participant during their session, if the content was covered in a different section or if the session time ran out.

F.1 Prompt: Chart Your Daily Activities

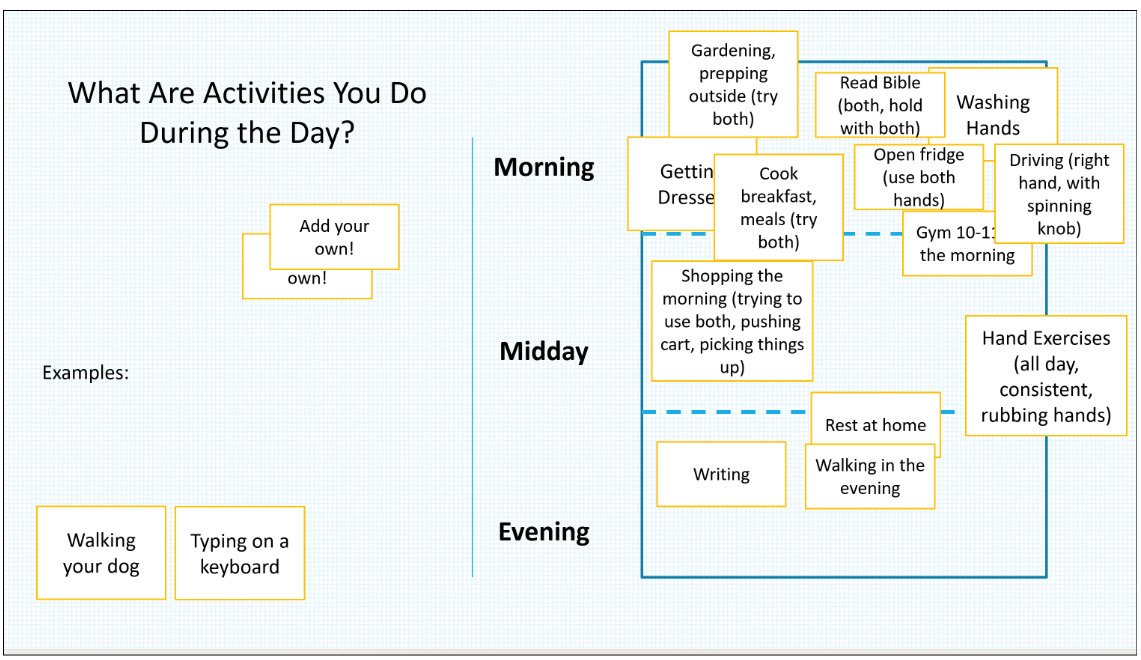

Figure F.1: *Chart Your Daily Activities* Prompt Response from P1

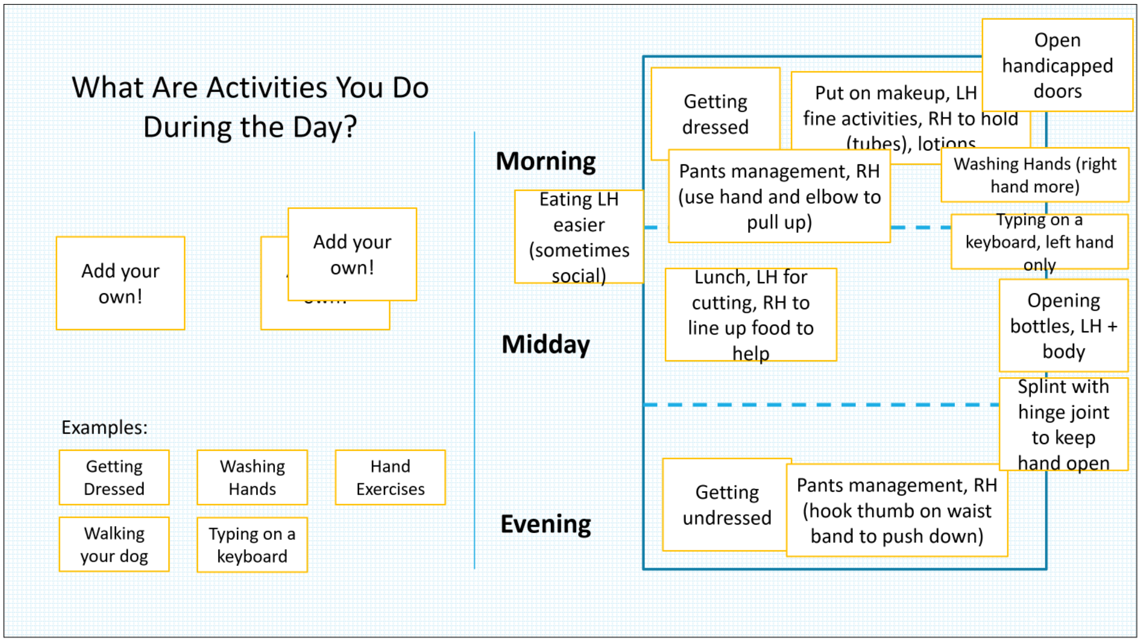

Figure F.2: *Chart Your Daily Activities* Prompt Response from P2

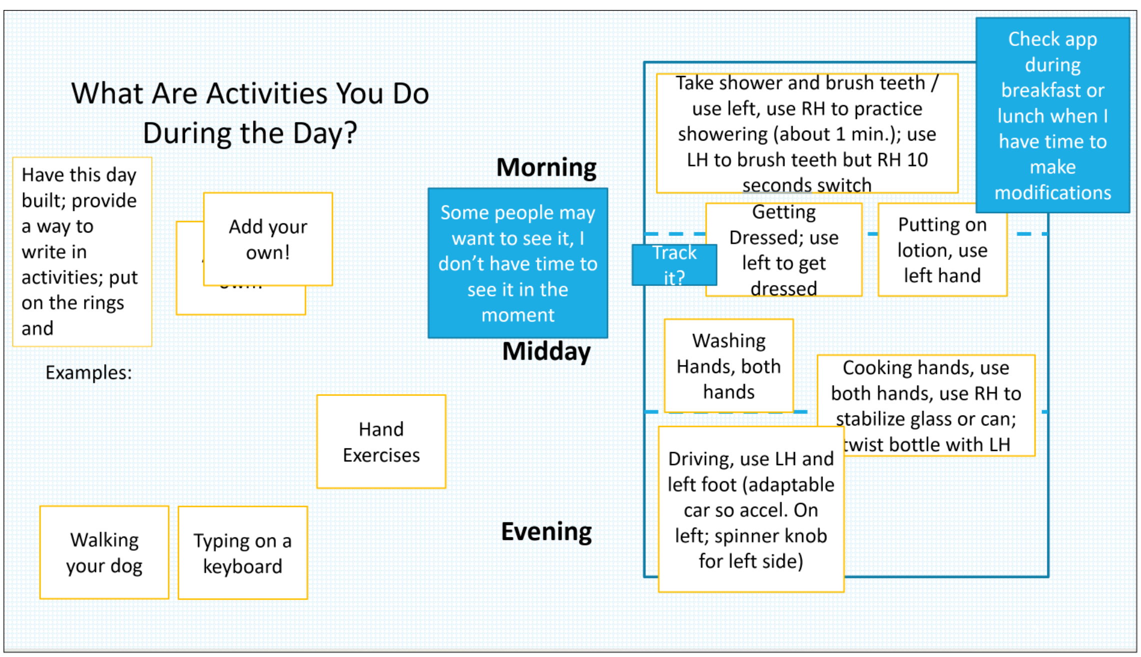

Figure F.3: *Chart Your Daily Activities* Prompt Response from P3

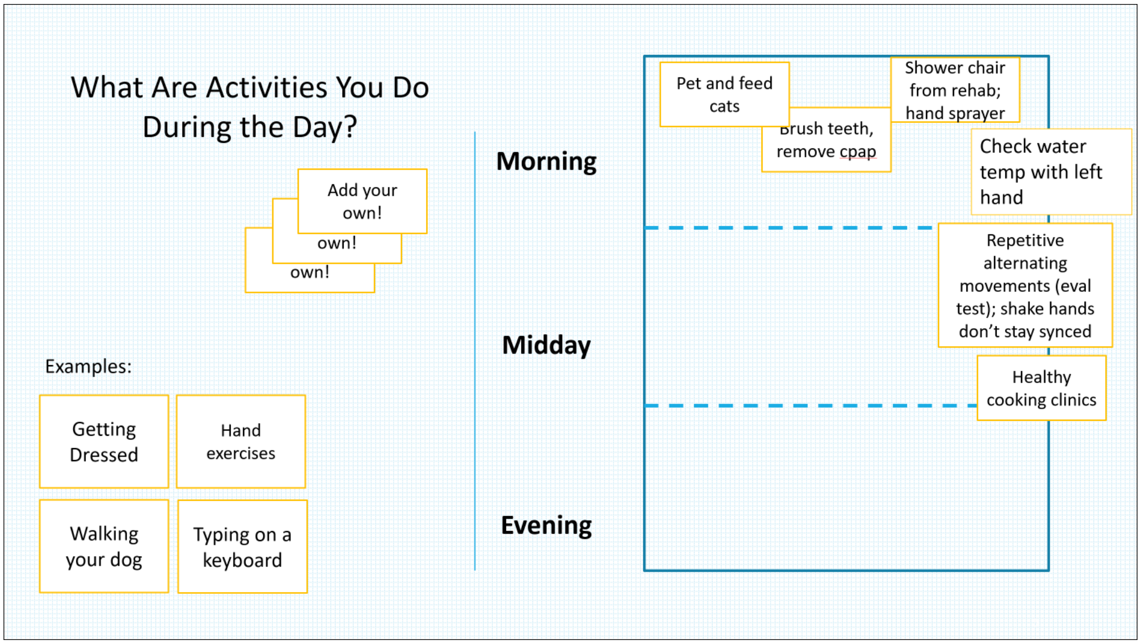

Figure F.4: *Chart Your Daily Activities* Prompt Response from P5

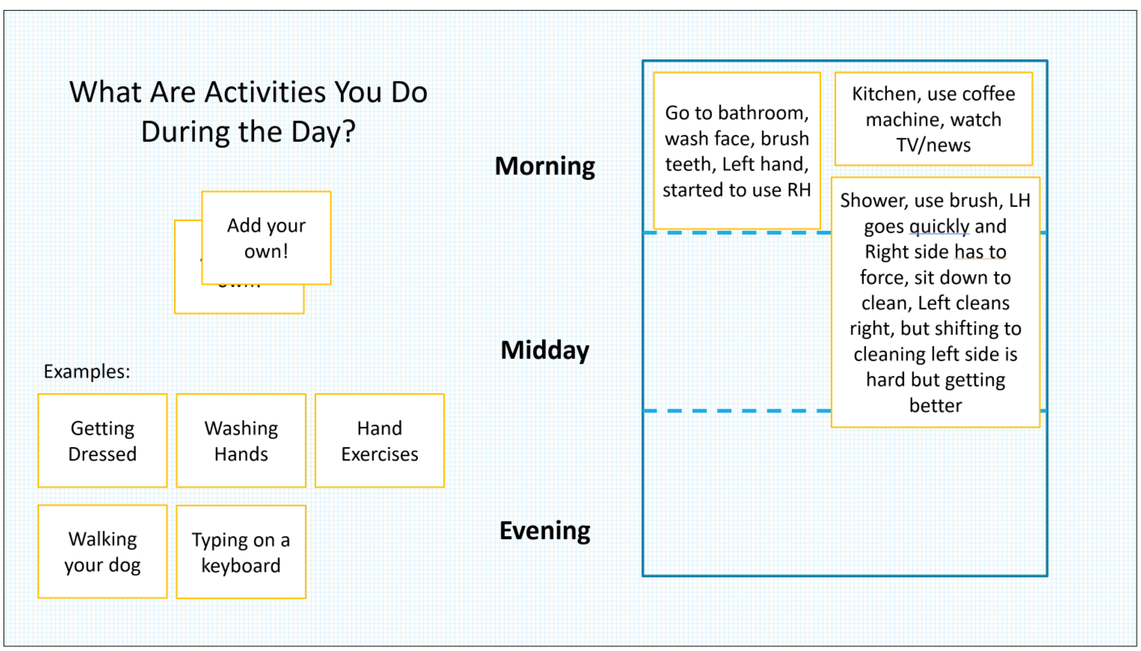

Figure F.5: *Chart Your Daily Activities* Prompt Response from P6

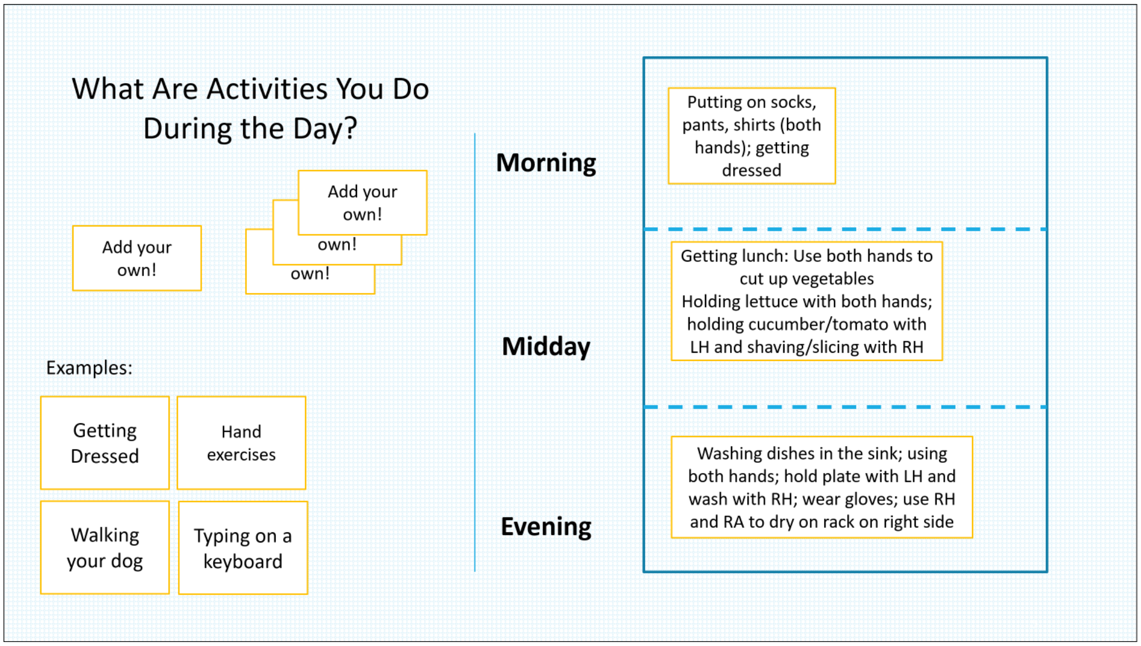

Figure F.6: *Chart Your Daily Activities* Prompt Response from P8

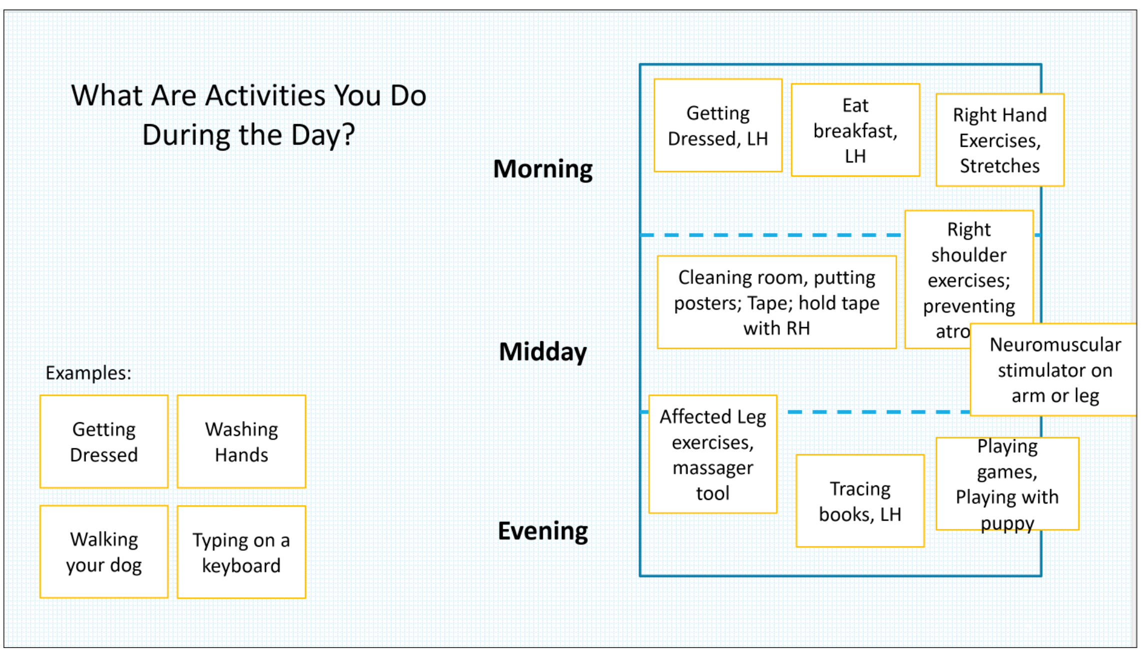

Figure F.7: *Chart Your Daily Activities* Prompt Response from P9

F.2 Prompt: What Does the Visualization Show You?

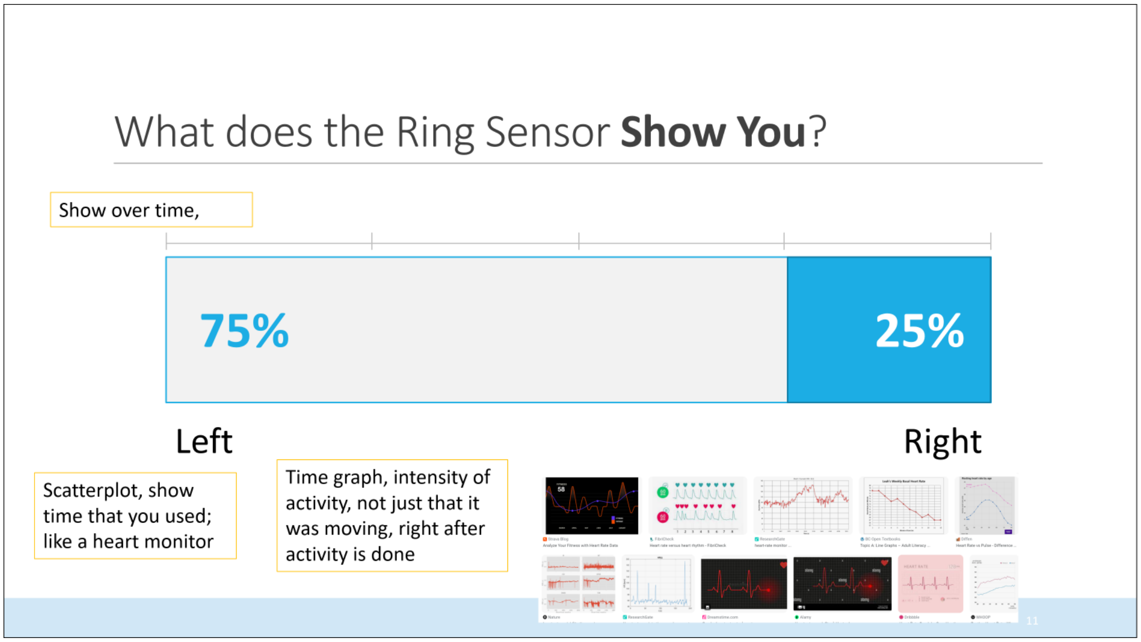

Figure F.8: *What Does the Visualization Show You?* Prompt Response from P3

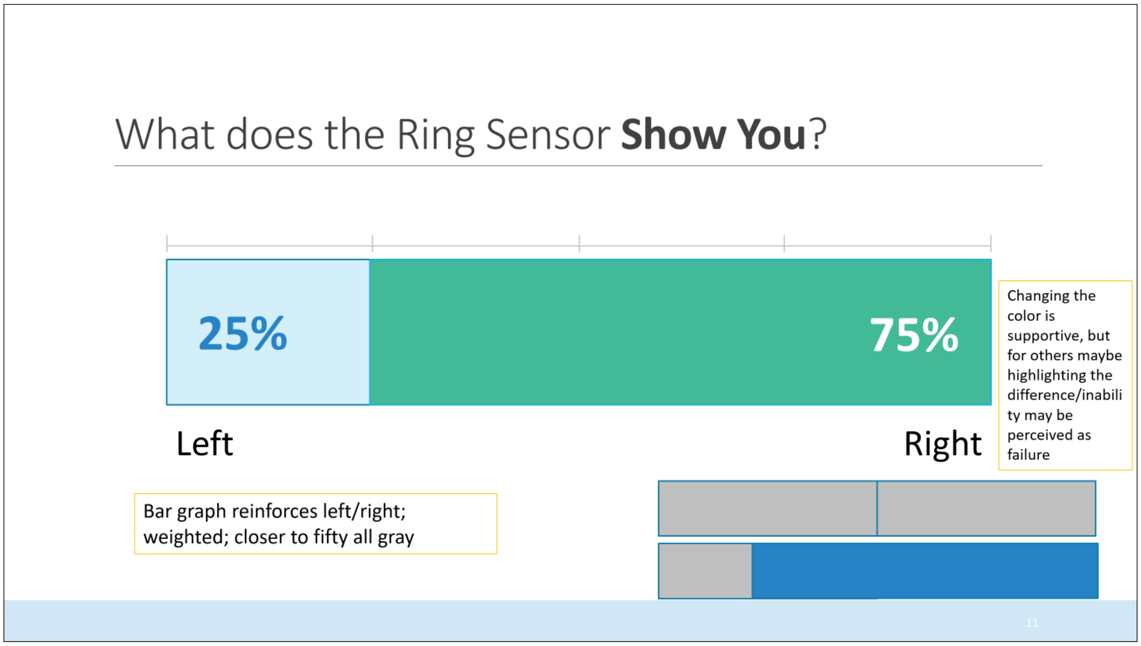

Figure F.9: *What Does the Visualization Show You?* Prompt Response from P5

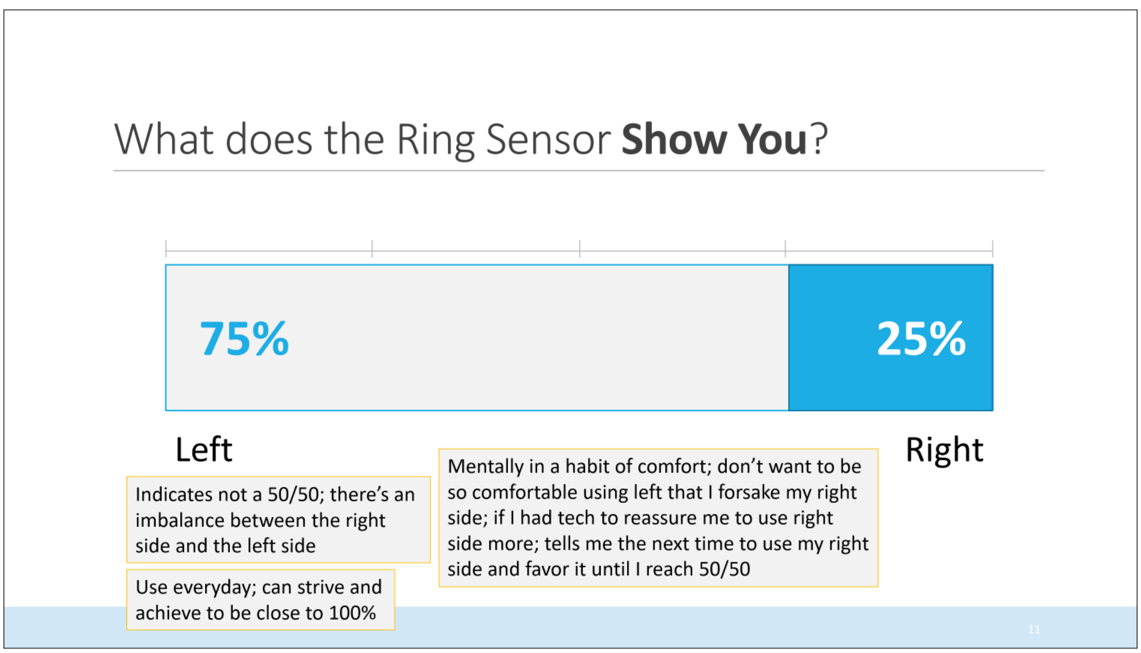

Figure F.10: *What Does the Visualization Show You?* Prompt Response from P6

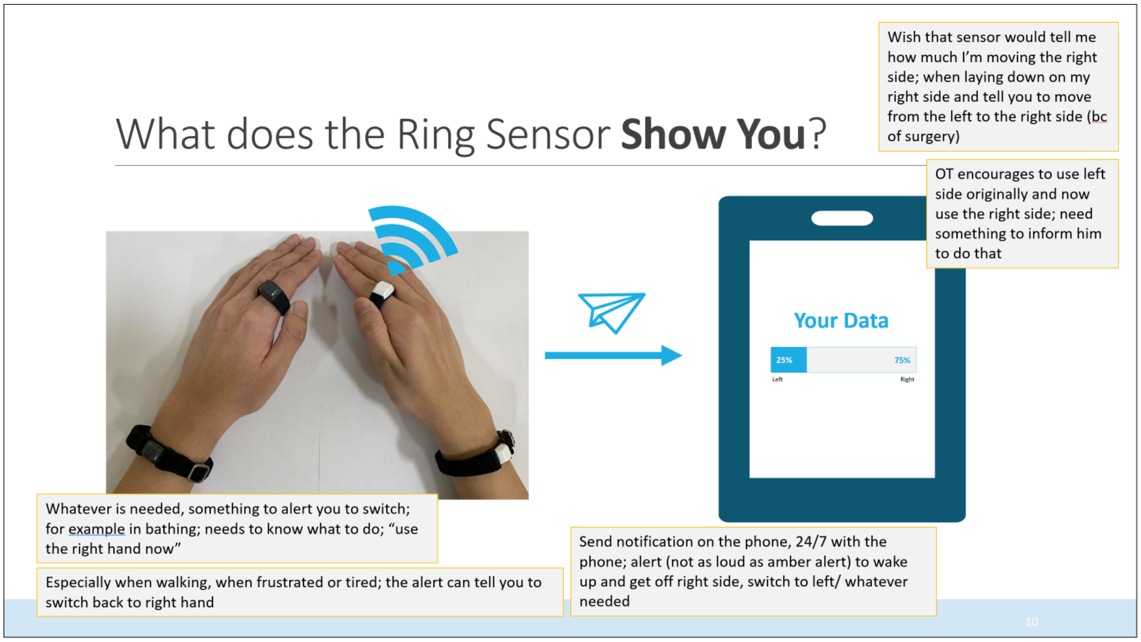

Figure F.11: *What Does the Visualization Show You?* Prompt Response from P6 (continued)

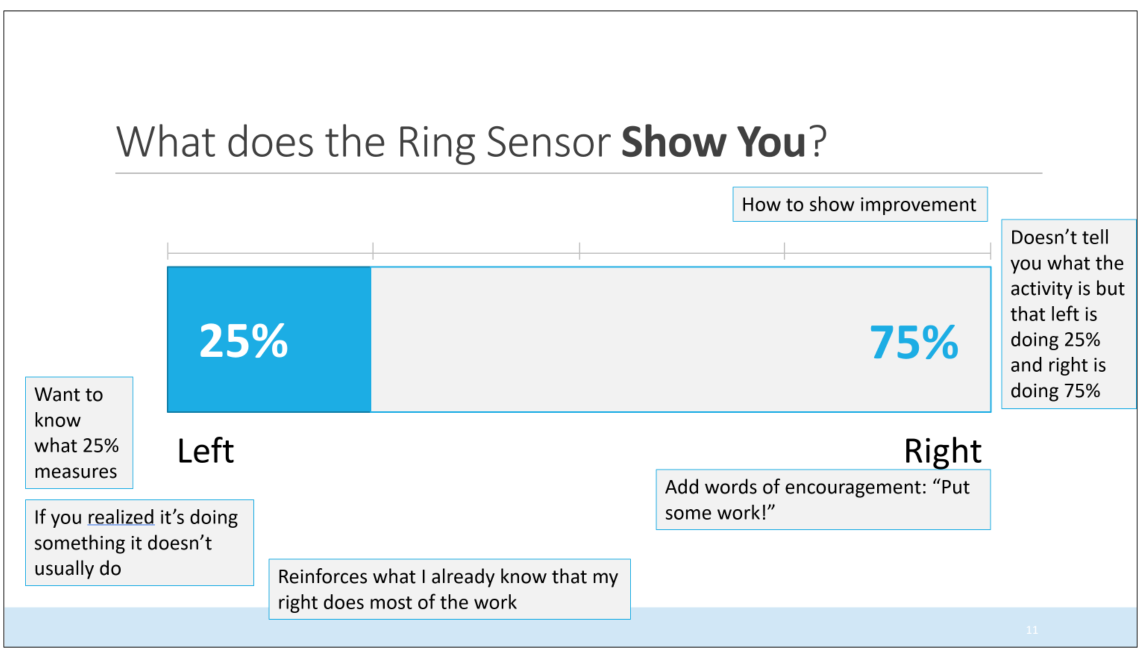

Figure F.12: *What Does the Visualization Show You?* Prompt Response from P7

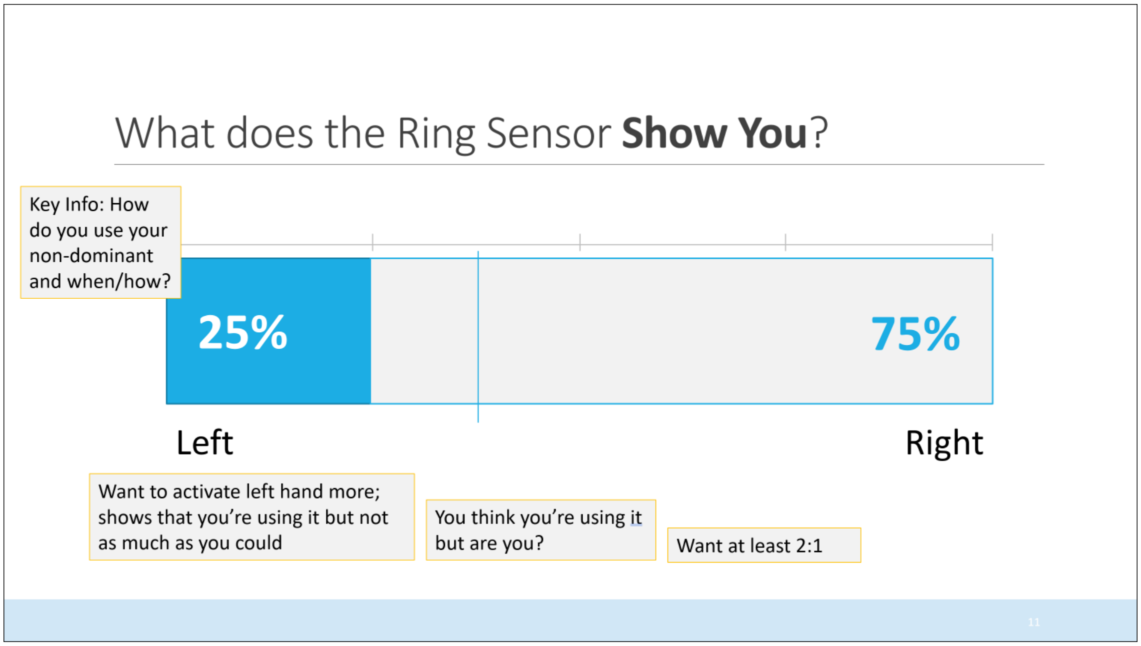

Figure F.13: *What Does the Visualization Show You?* Prompt Response from P8

F.3 Prompt: How Would You Change This Chart?

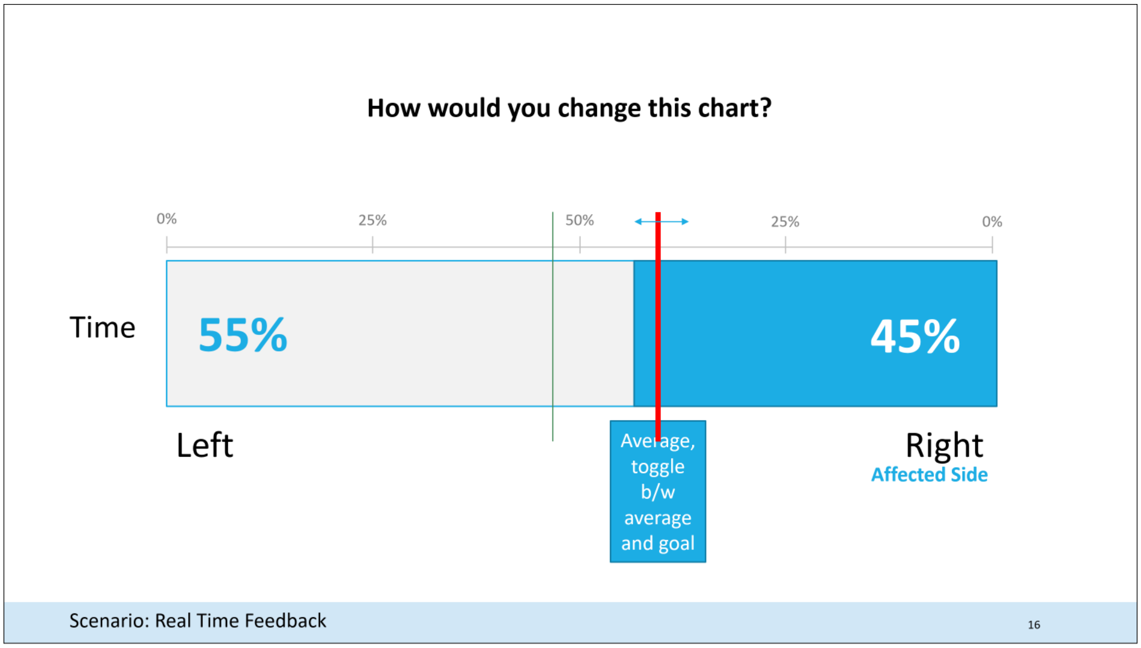

Figure F.14: *How Would You Change This Chart?* Prompt Response from P2

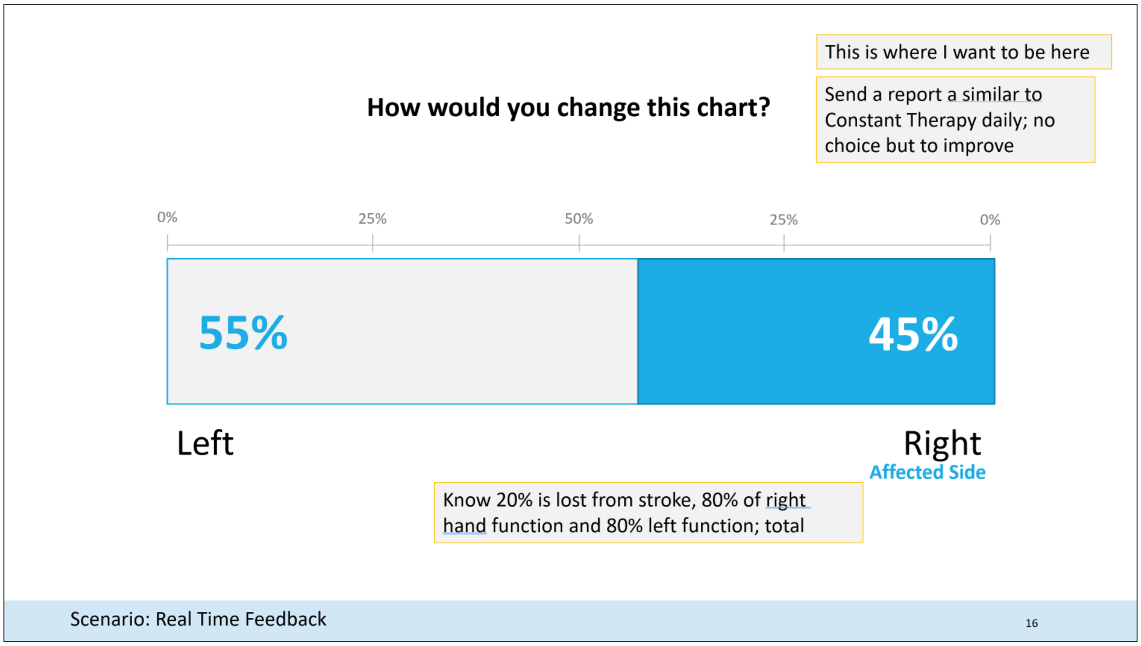

Figure F.15: *How Would You Change This Chart?* Prompt Response from P6

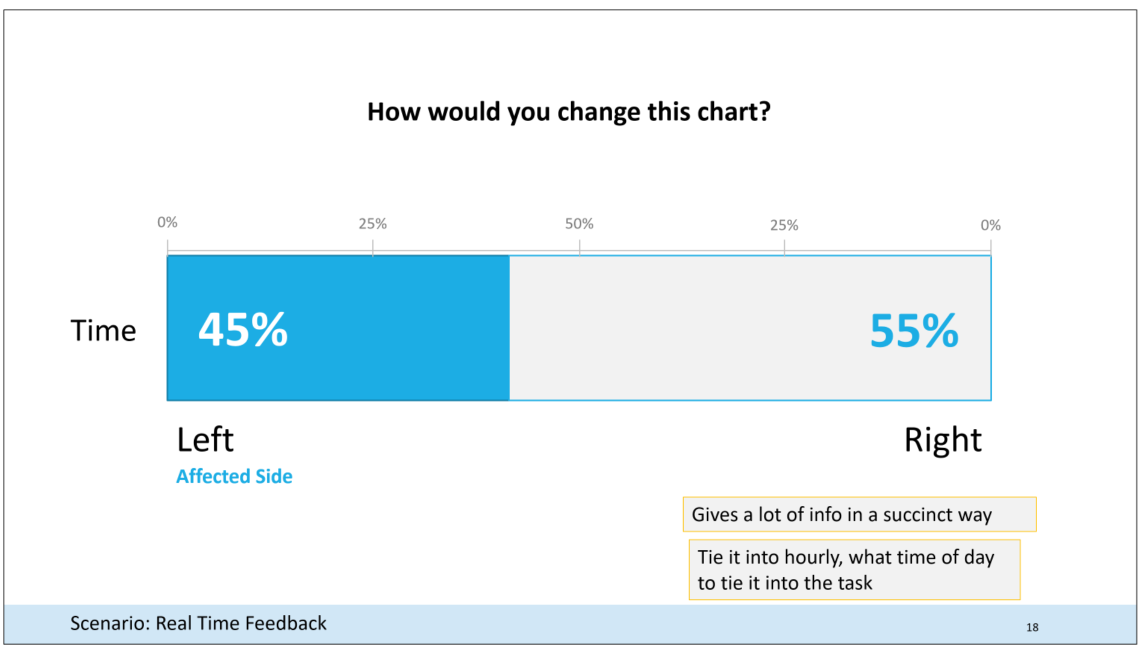

Figure F.16: *How Would You Change This Chart?* Prompt Response from P8

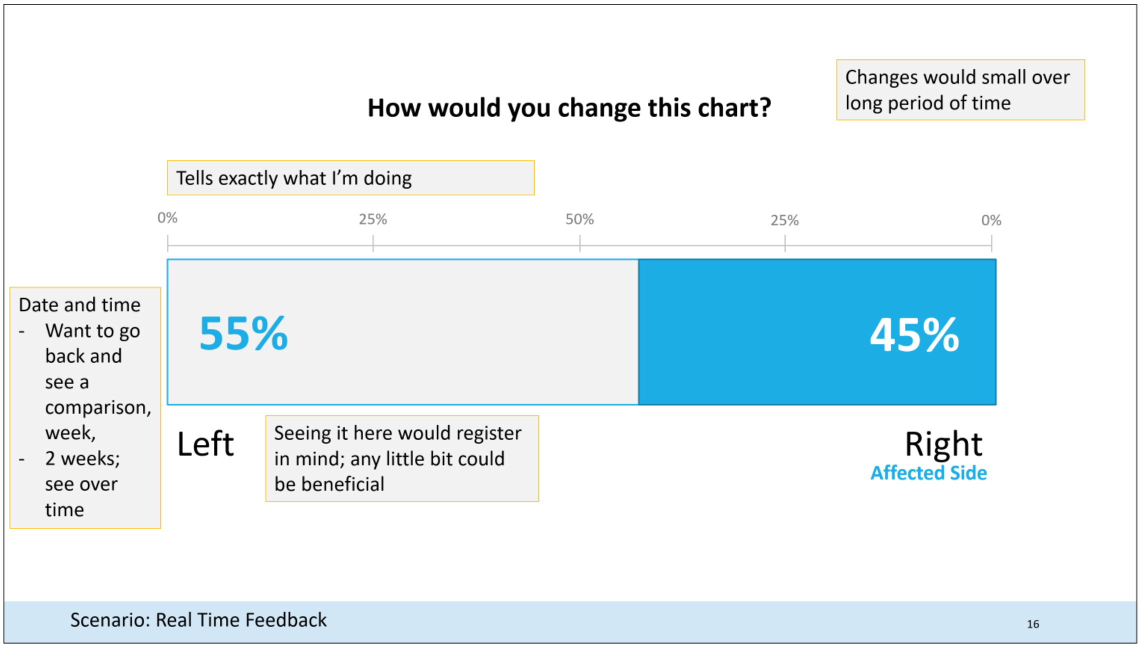

Figure F.17: *How Would You Change This Chart?* Prompt Response from P9

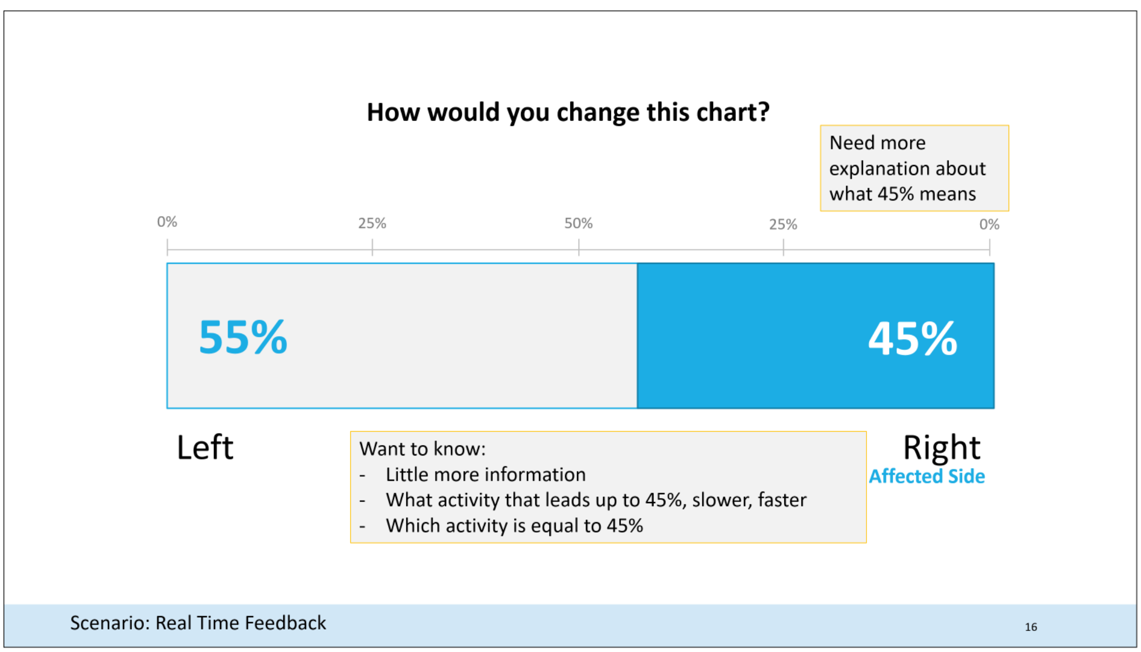

Figure F.18: *How Would You Change This Chart?* Prompt Response from P10

F.4 Prompt: Co-Design the Visualization

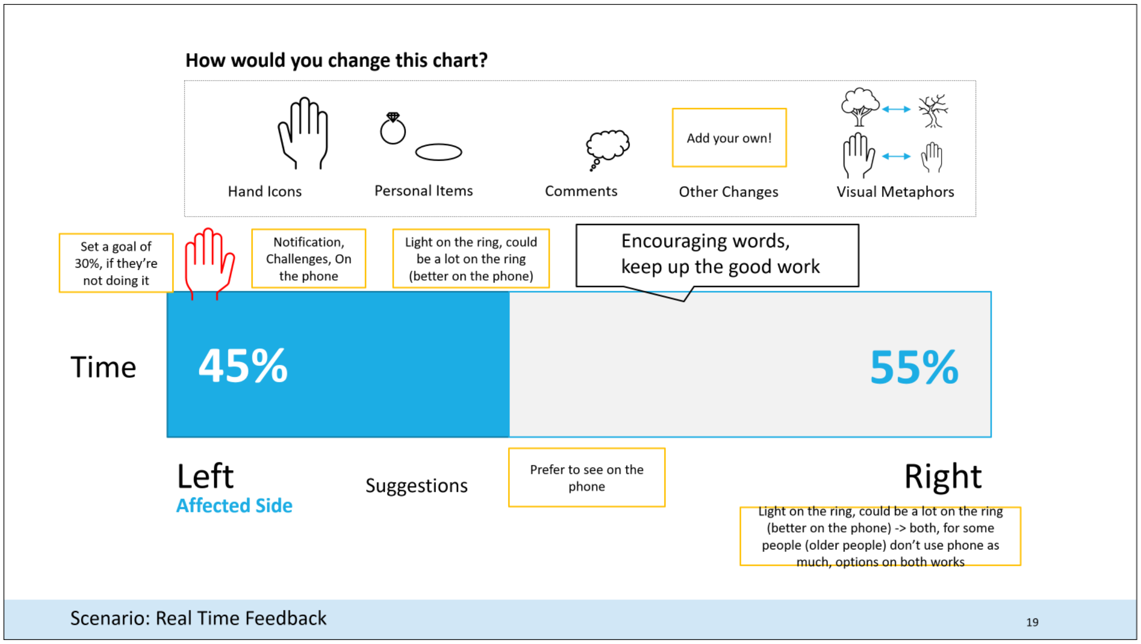

Figure F.19: *Co-Design Visualization* Prompt Response from P1

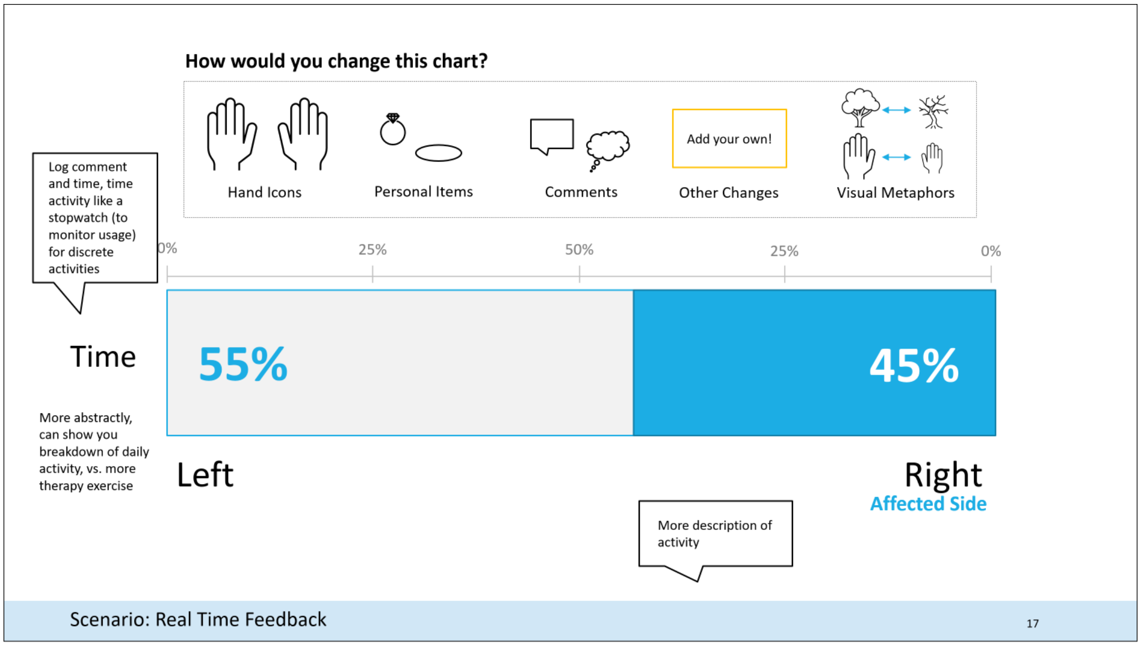

Figure F.20: *Co-Design Visualization* Prompt Response from P2

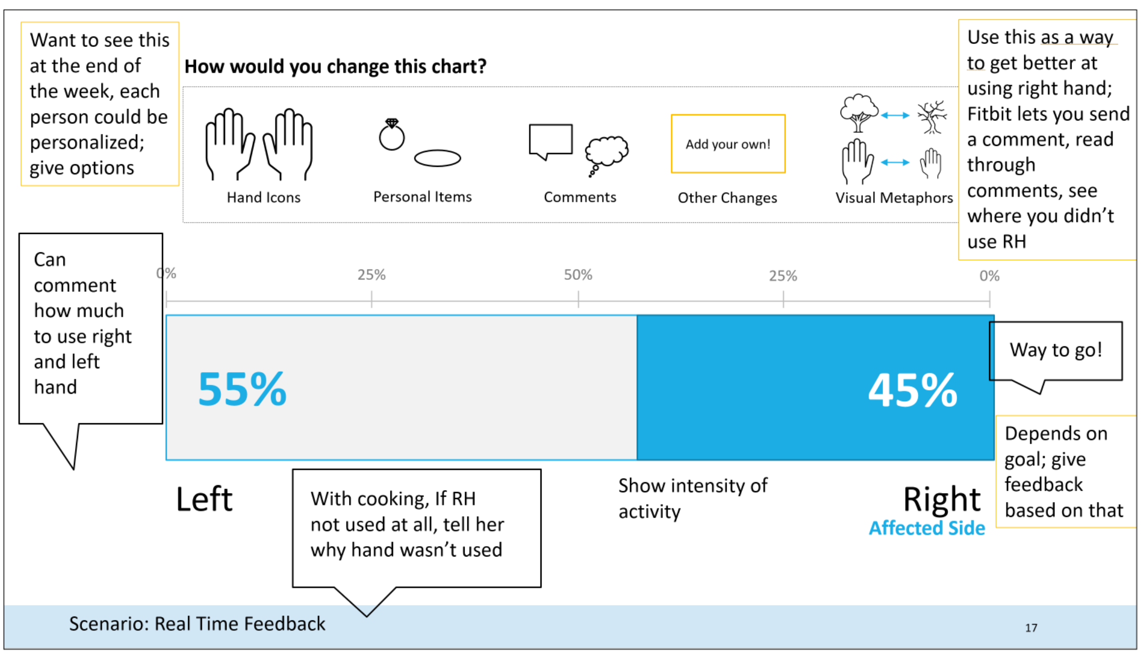

Figure F.21: *Co-Design Visualization* Prompt Response from P3

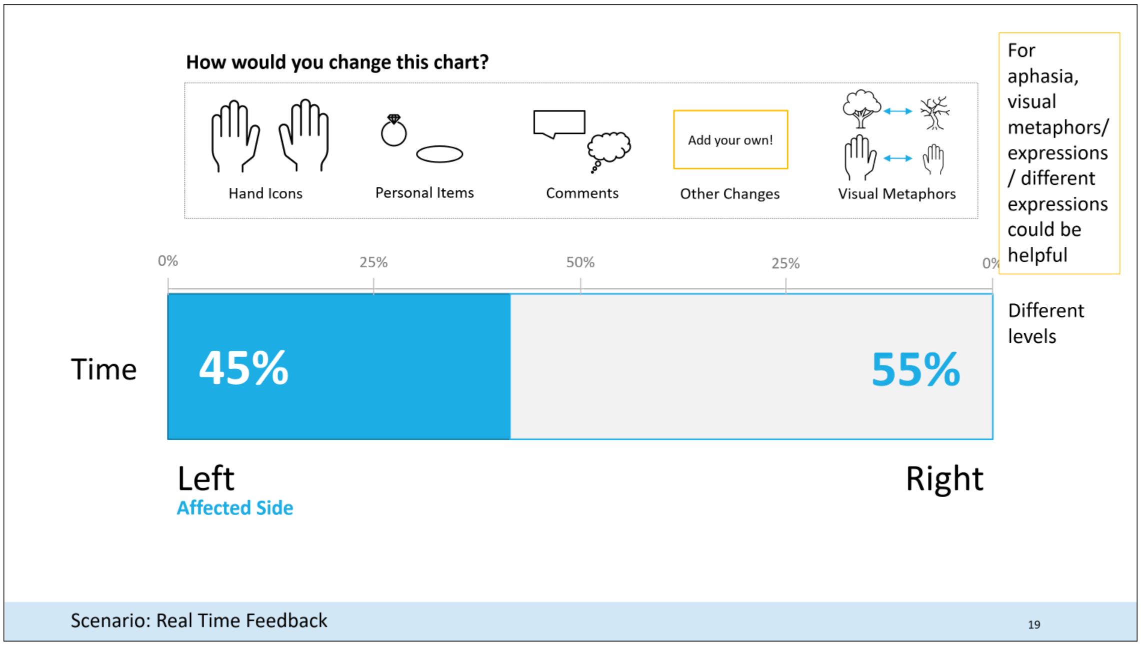

Figure F.22: *Co-Design Visualization* Prompt Response from P5

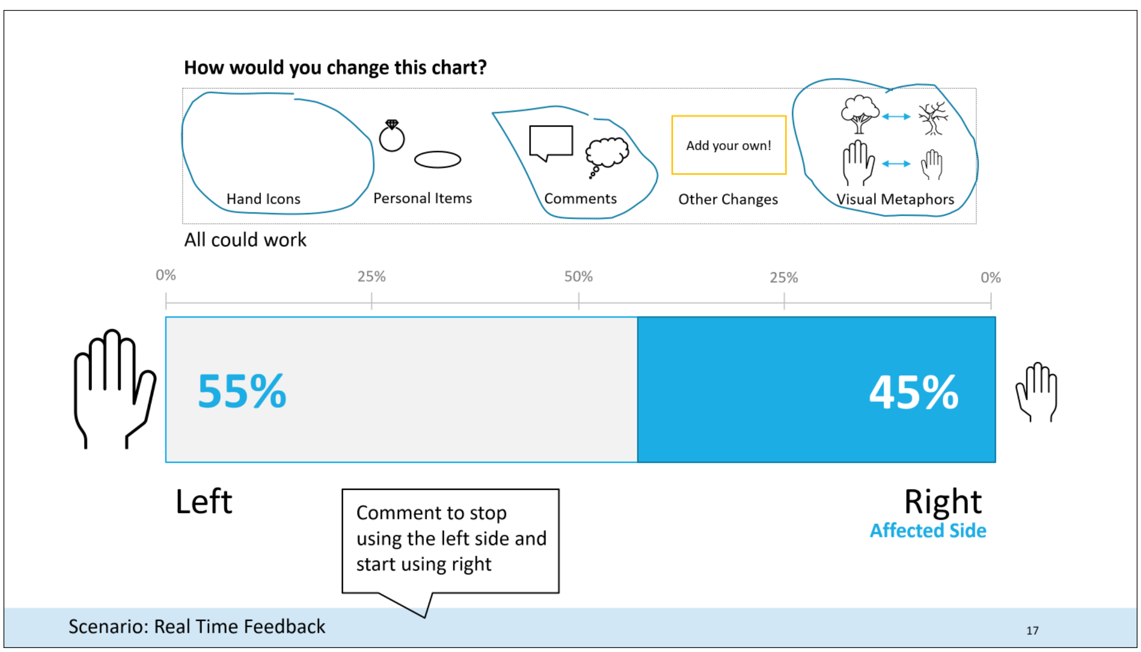

Figure F.23: *Co-Design Visualization* Prompt Response from P6

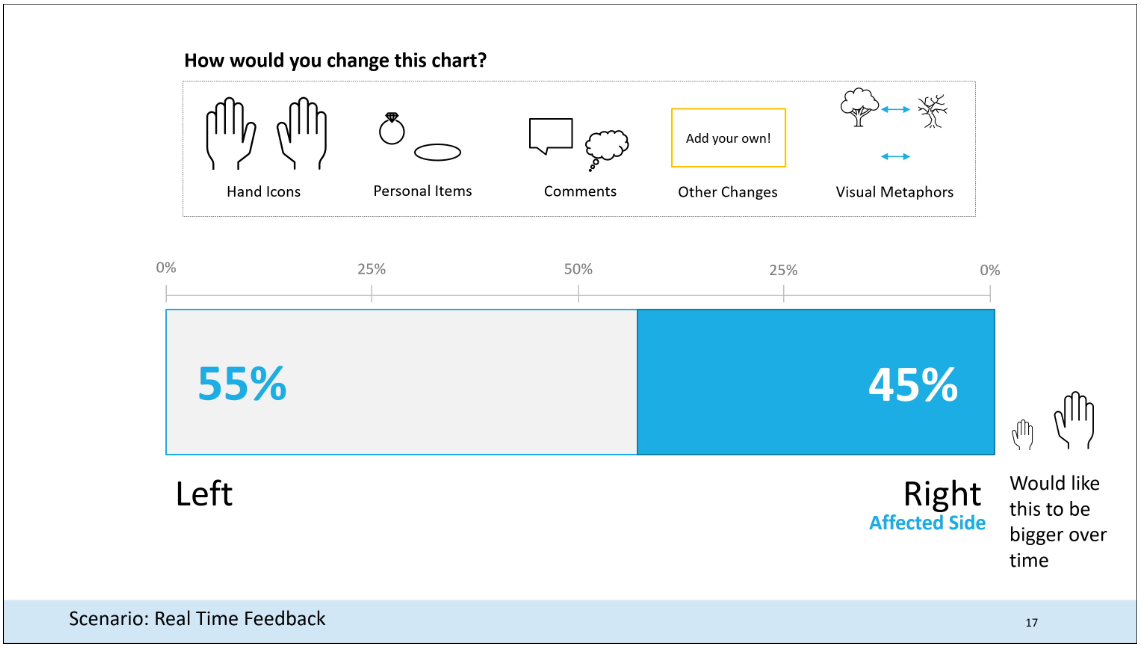

Figure F.24: *Co-Design Visualization* Prompt Response from P10

F.5 Prompt: What if Data Could Speak to You?

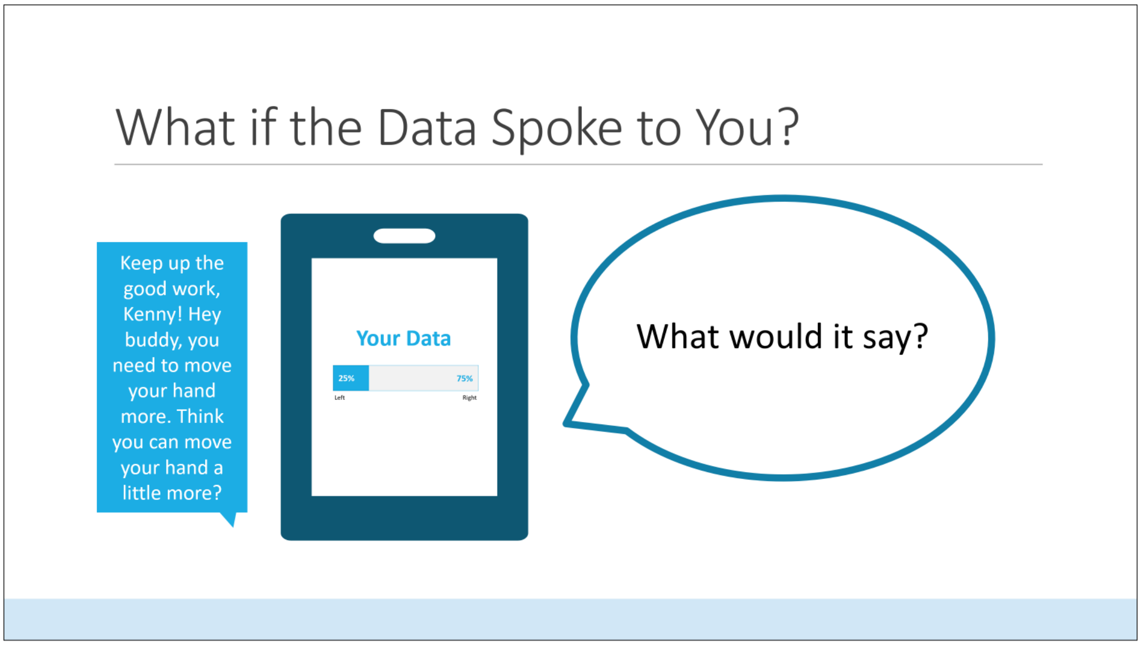

Figure F.25: *What if Data Could Speak to You?* Prompt Response from P1

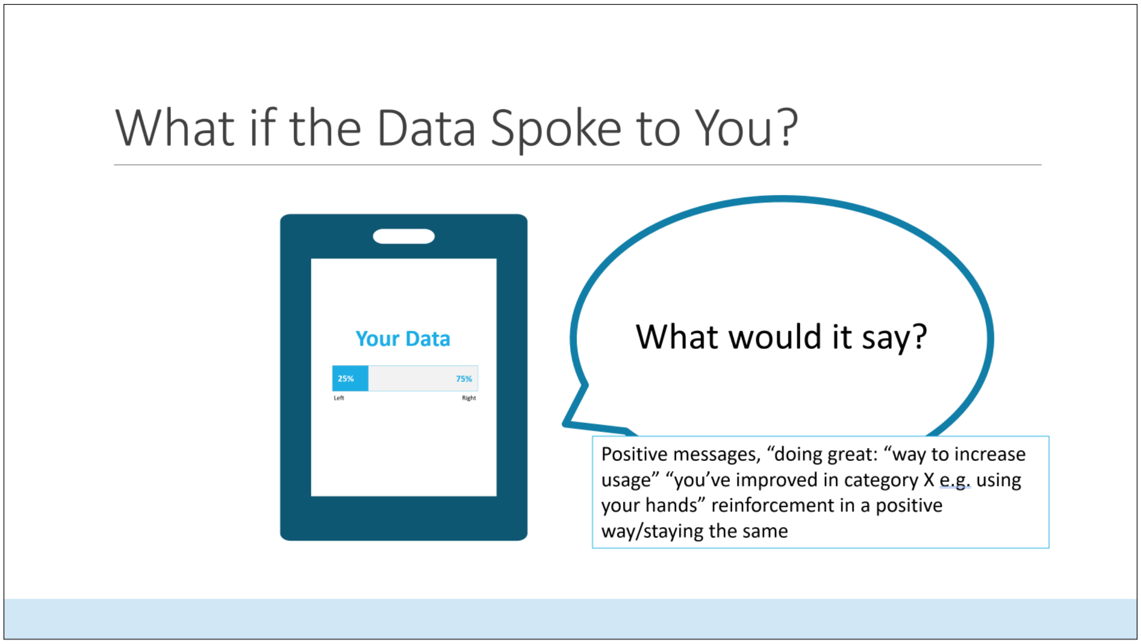

Figure F.26: *What if Data Could Speak to You?* Prompt Response from P2

Figure F.27: *What if Data Could Speak to You?* Prompt Response from P3

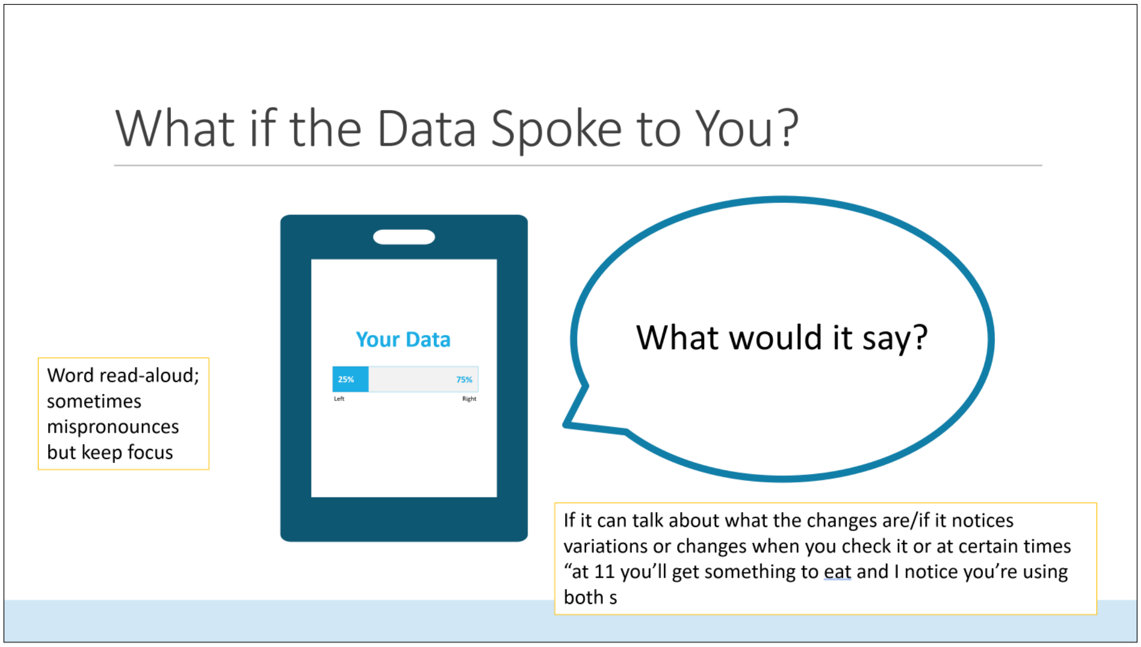

Figure F.28: *What if Data Could Speak to You?* Prompt Response from P5

Figure F.29: *What if Data Could Speak to You?* Prompt Response from P6

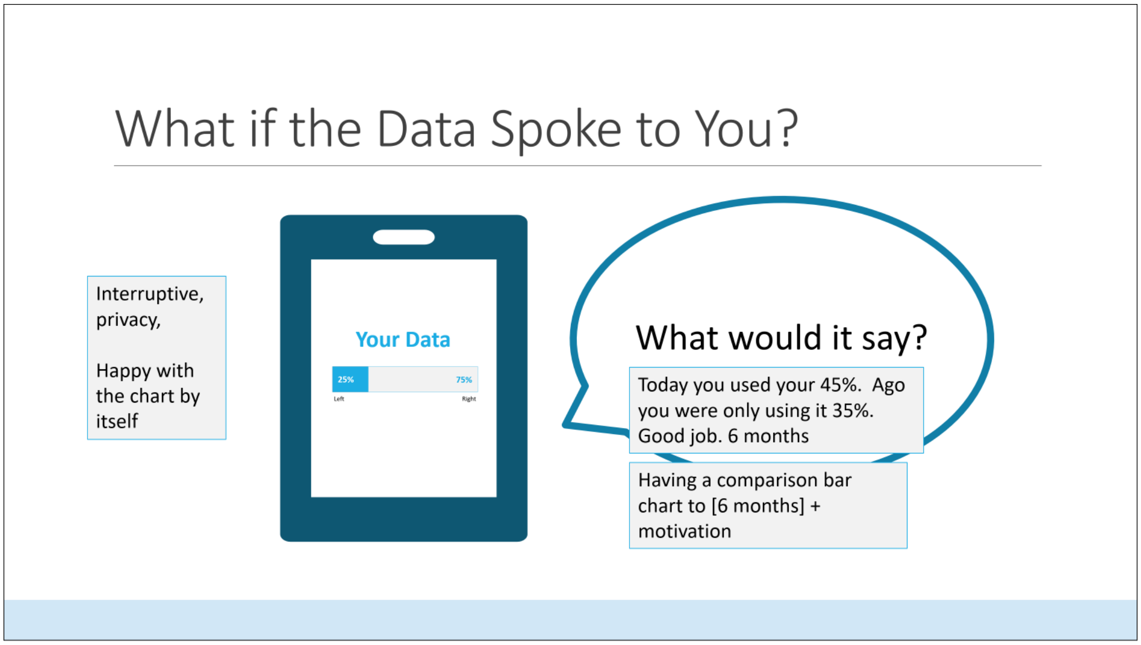

Figure F.30: *What if Data Could Speak to You?* Prompt Response from P7

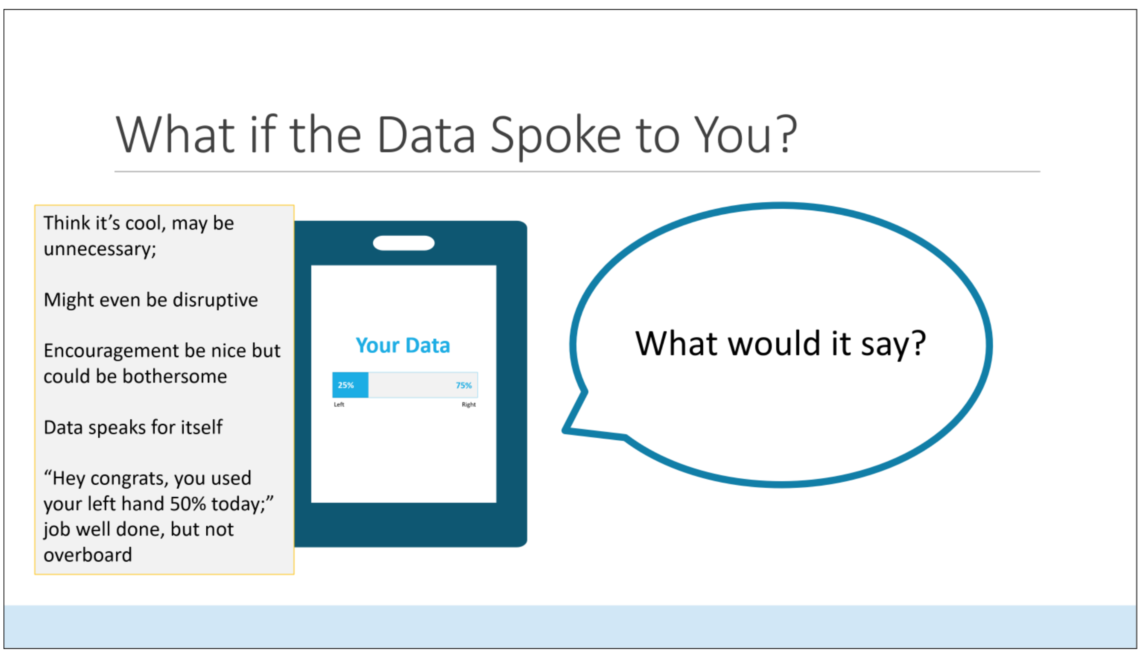

Figure F.31: *What if Data Could Speak to You?* Prompt Response from P8

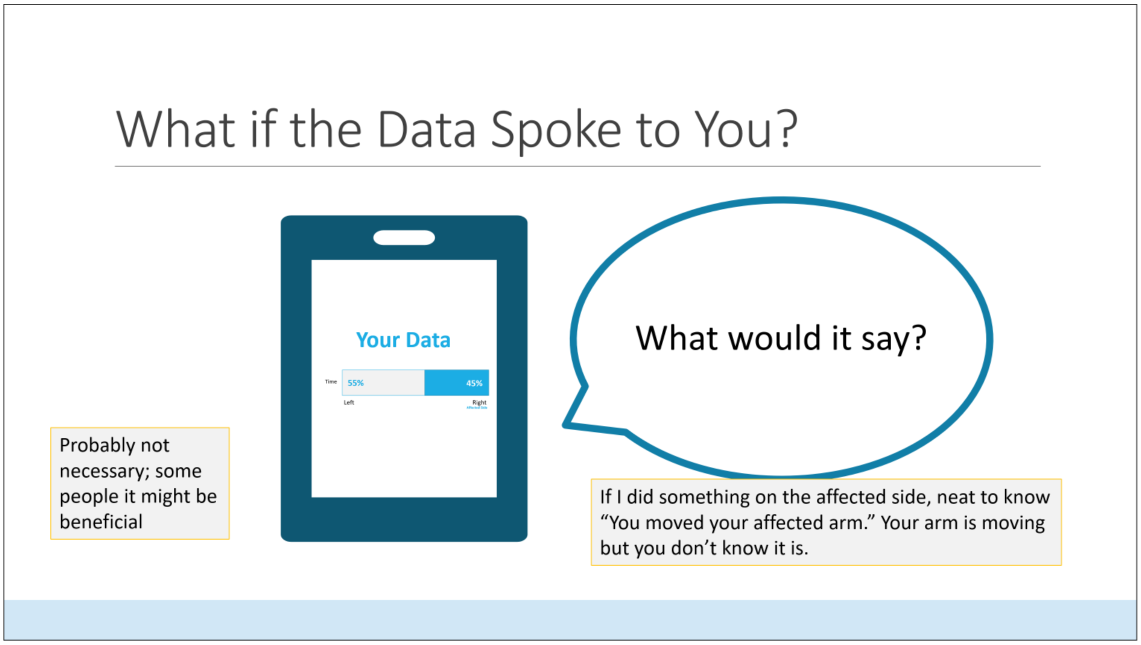

Figure F.32: *What if Data Could Speak to You?* Prompt Response from P9

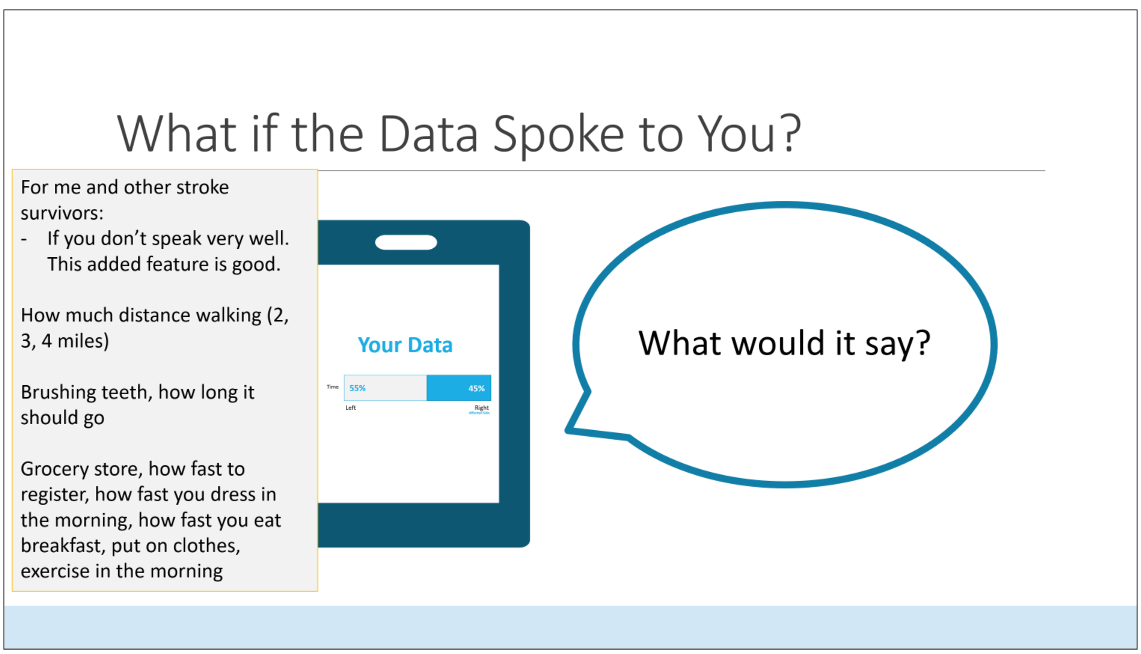

Figure F.33: *What if Data Could Speak to You?* Prompt Response from P10

F.6 Prompt: How Would You Change This Audio?

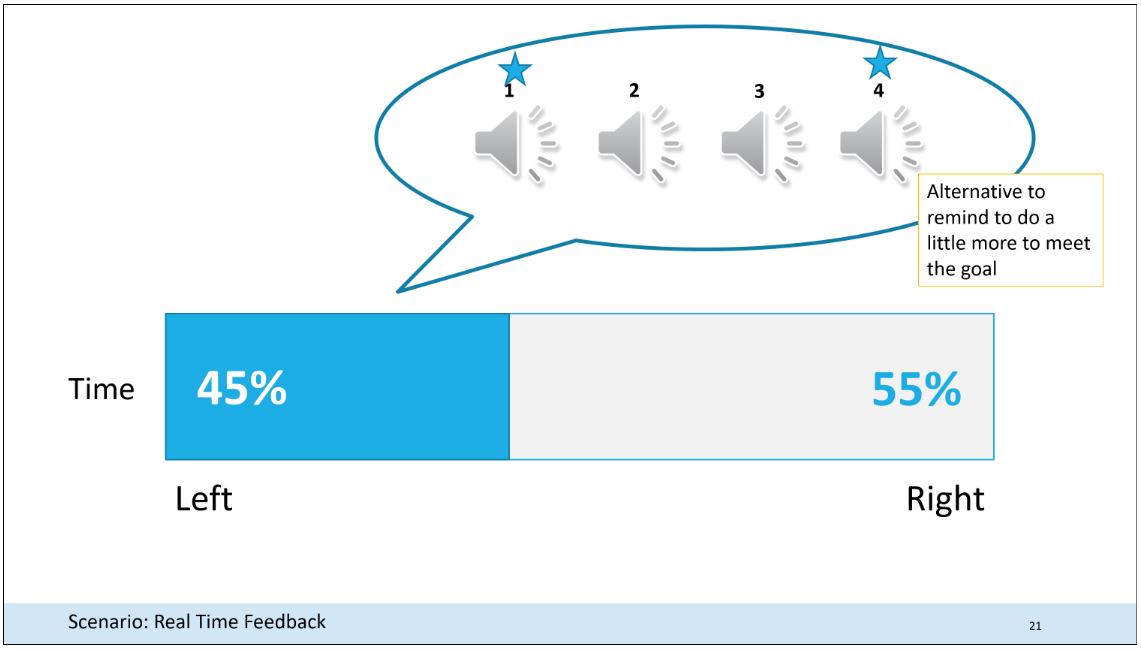

Figure F.34: *How Would You Change This Audio?* Prompt Response from P1

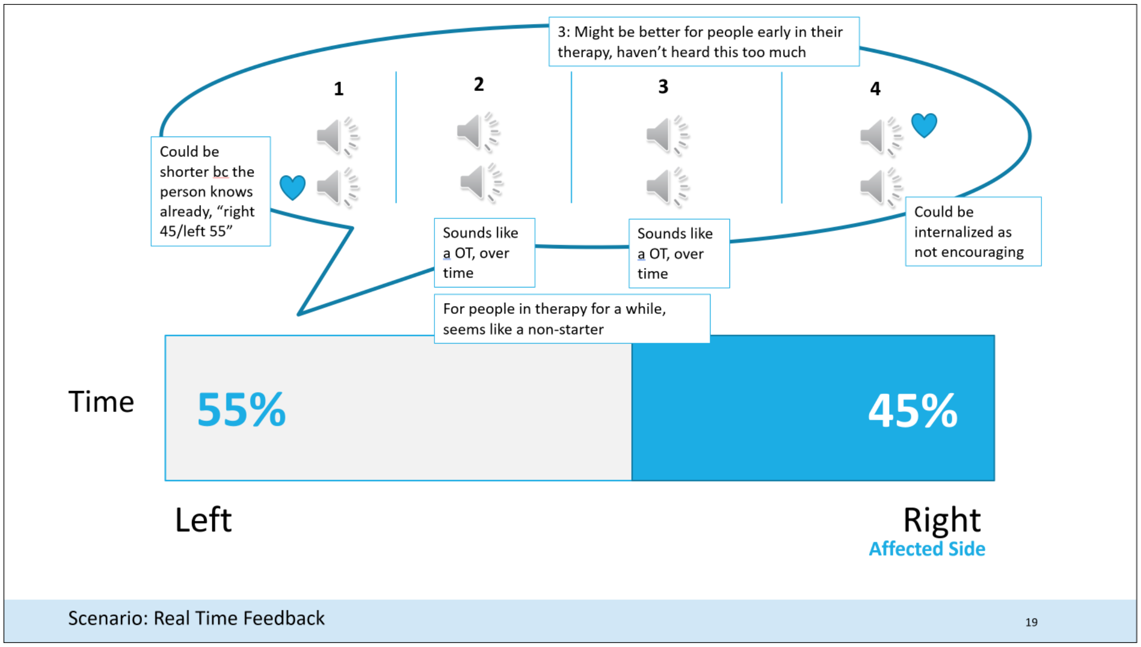

Figure F.35: *How Would You Change This Audio?* Prompt Response from P2

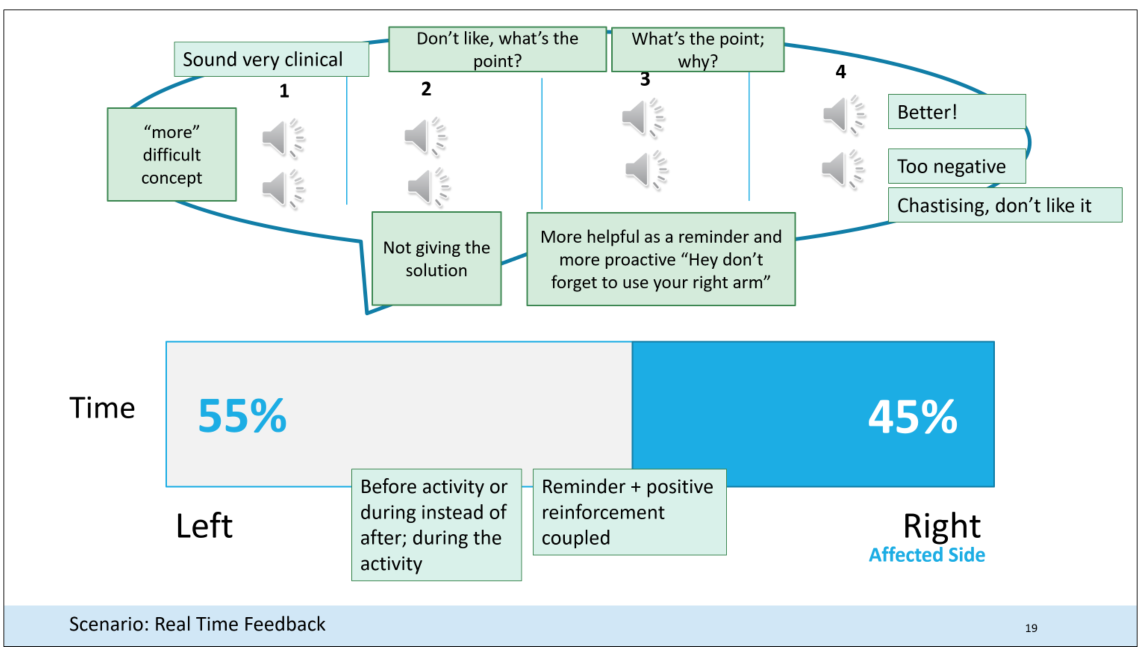

Figure F.36: *How Would You Change This Audio?* Prompt Response from P4

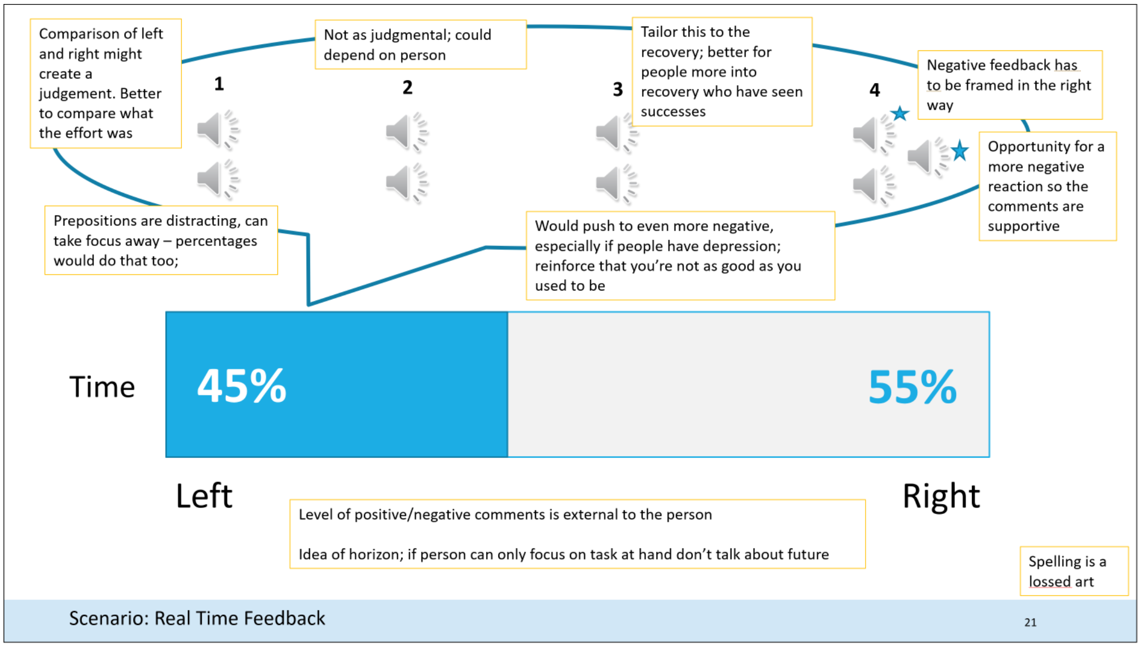

Figure F.37: *How Would You Change This Audio?* Prompt Response from P5

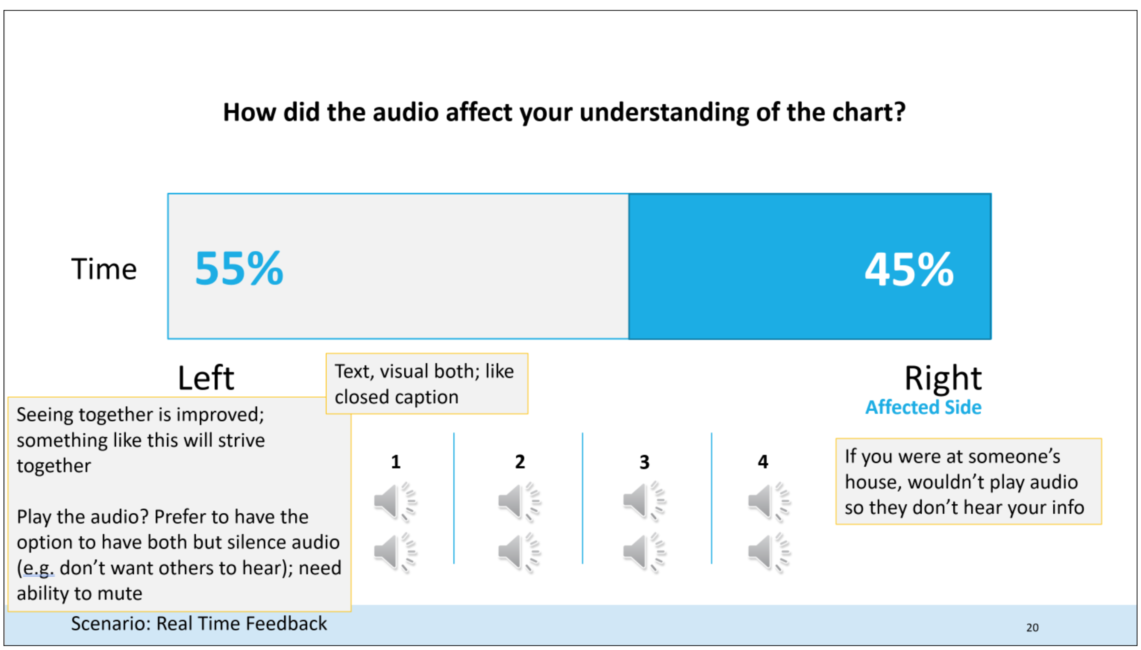

Figure F.38: *How Would You Change This Audio?* Prompt Response from P6

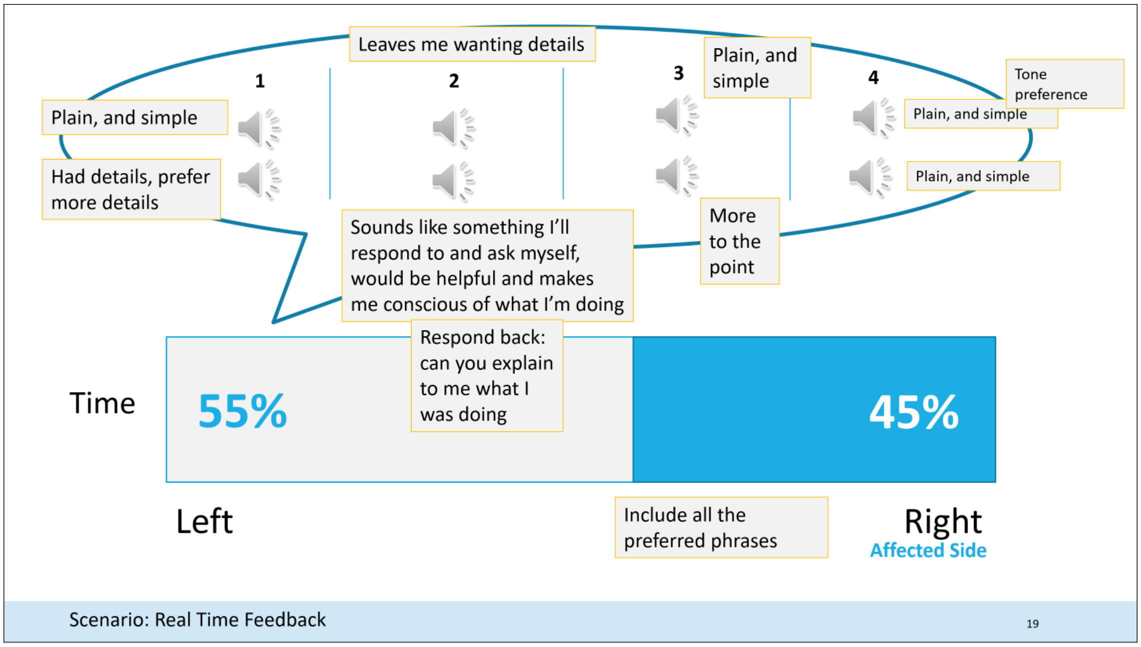

Figure F.39: *How Would You Change This Audio?* Prompt Response from P6 (Continued)

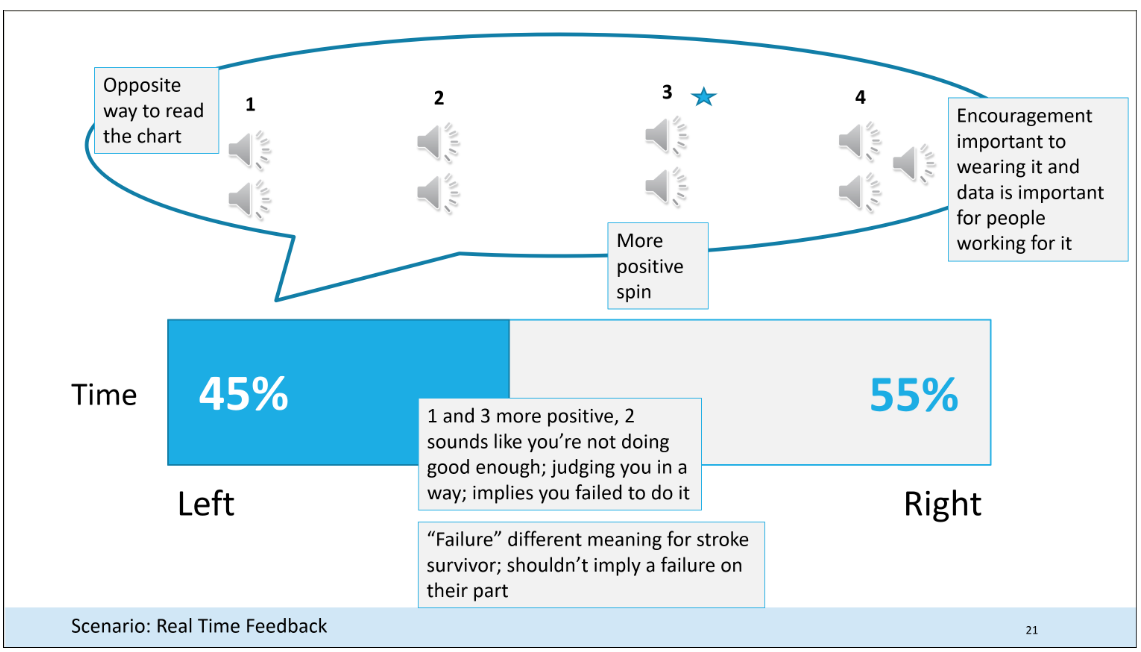

Figure F.40: *How Would You Change This Audio?* Prompt Response from P7

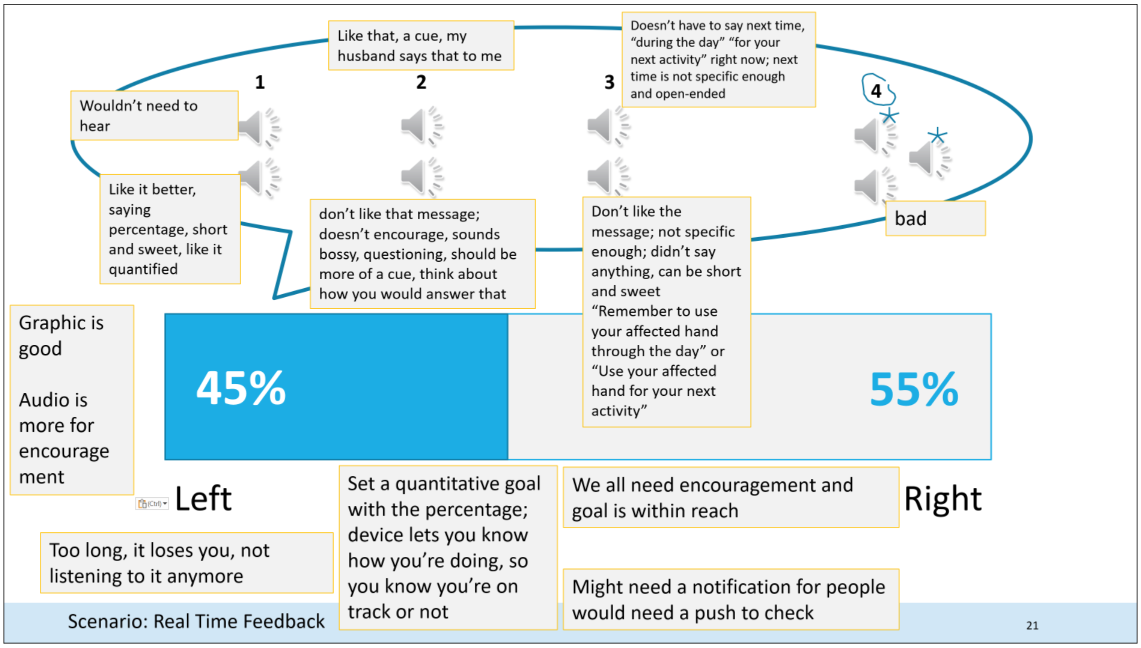

Figure F.41: *How Would You Change This Audio?* Prompt Response from P8

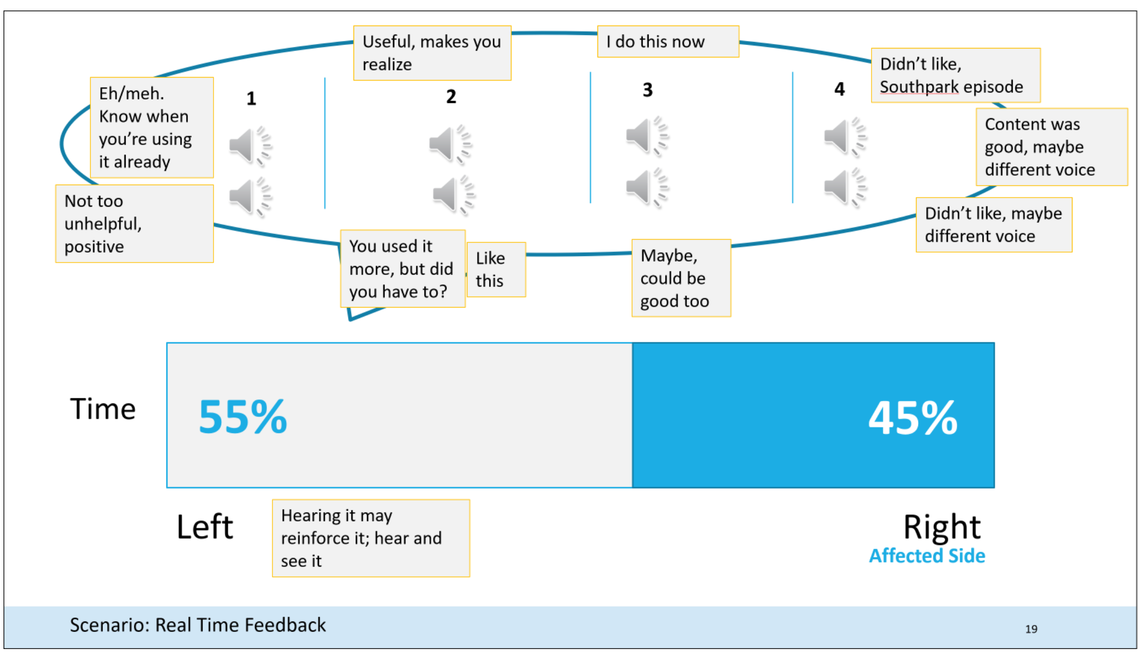

Figure F.42: *How Would You Change This Audio?* Prompt Response from P9

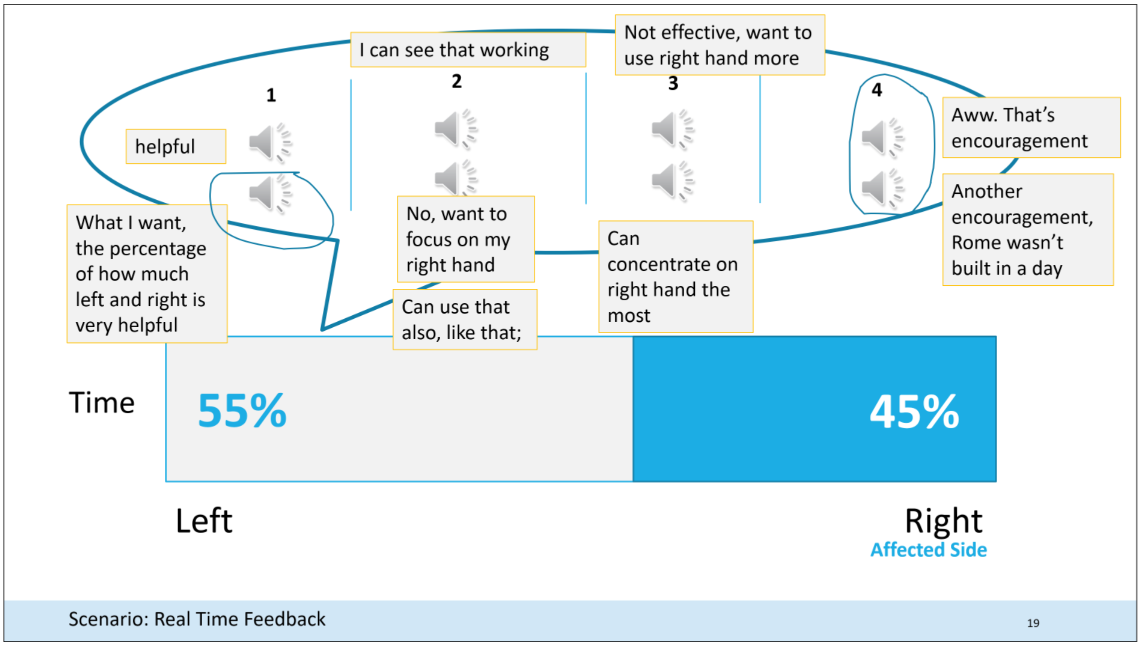

Figure F.43: *How Would You Change This Audio?* Prompt Response from P10

F.7 Prompt: Co-Design the Audio Narrative

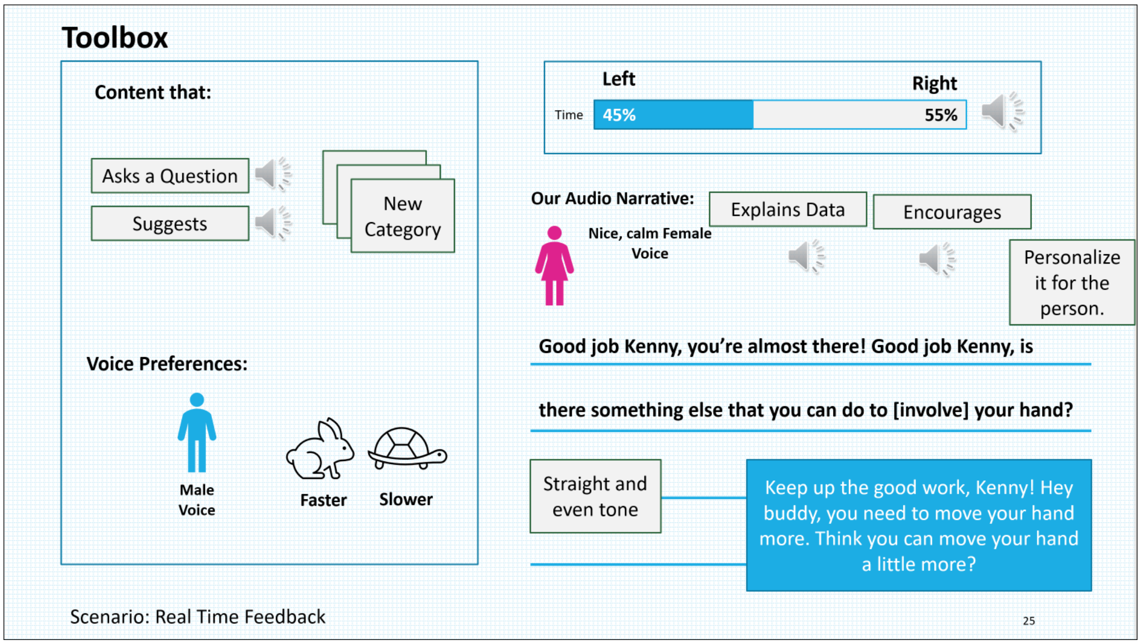

Figure F.44: *Co-Design the Audio Narrative* Prompt Response from P1

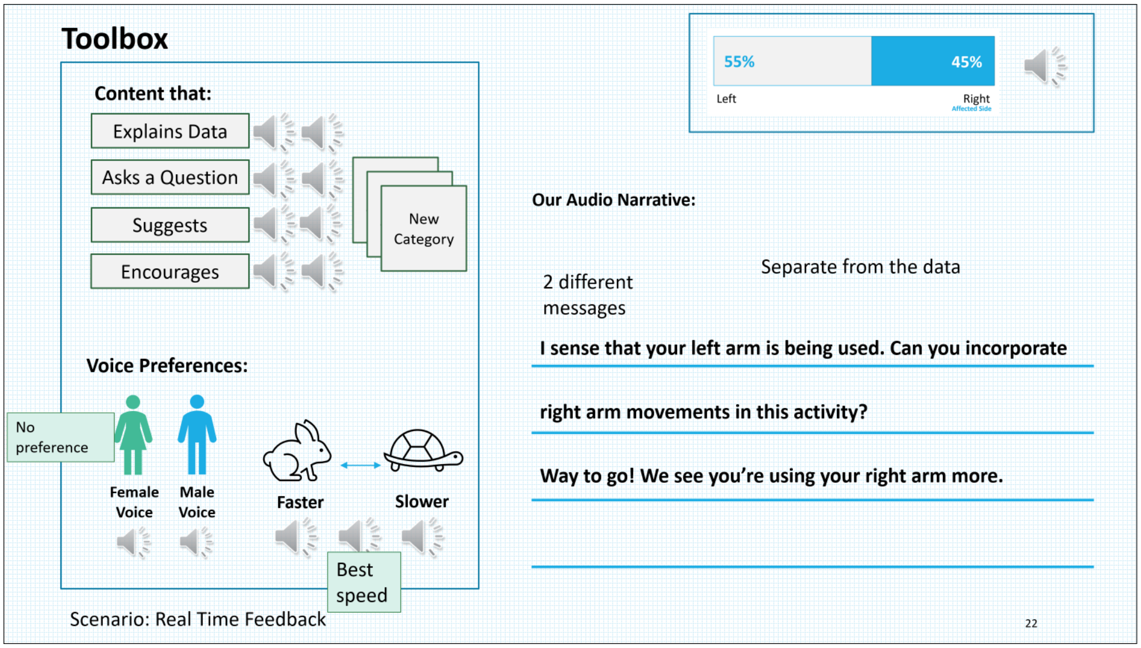

Figure F.45: *Co-Design the Audio Narrative* Prompt Response from P4

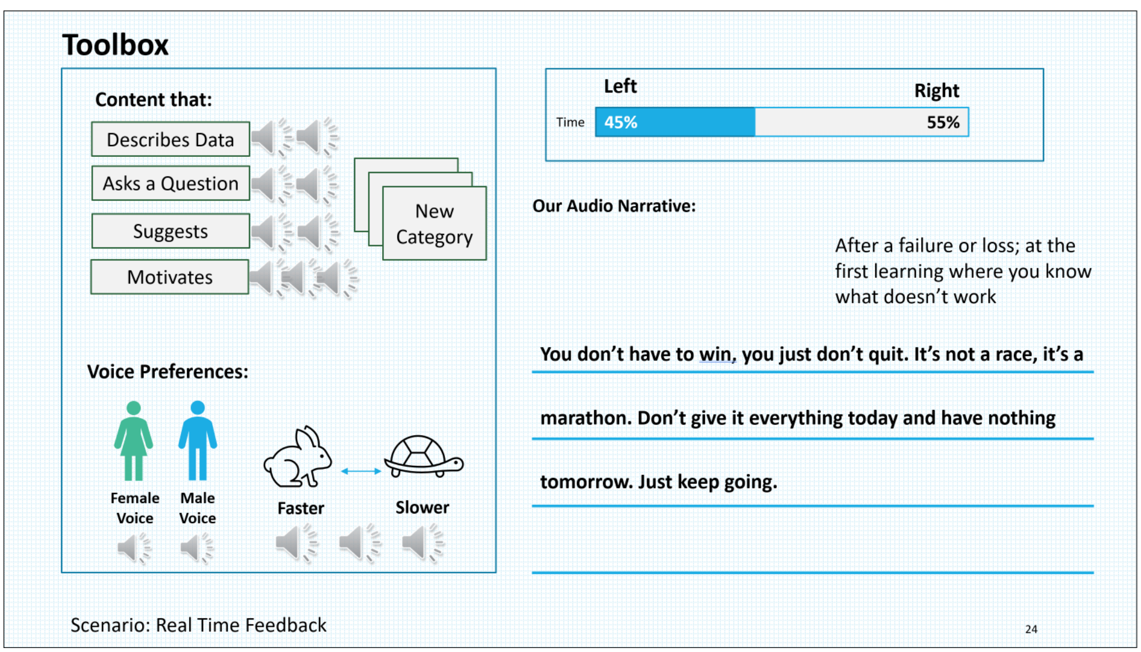

Figure F.46: *Co-Design the Audio Narrative* Prompt Response from P5

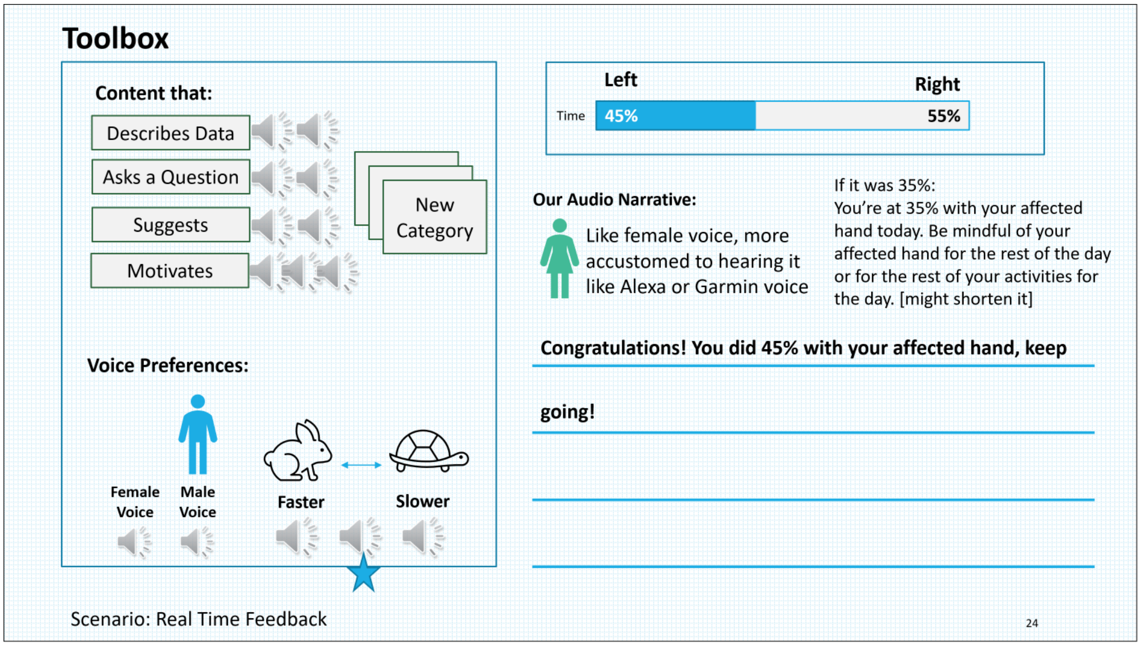

Figure F.47: *Co-Design the Audio Narrative* Prompt Response from P8

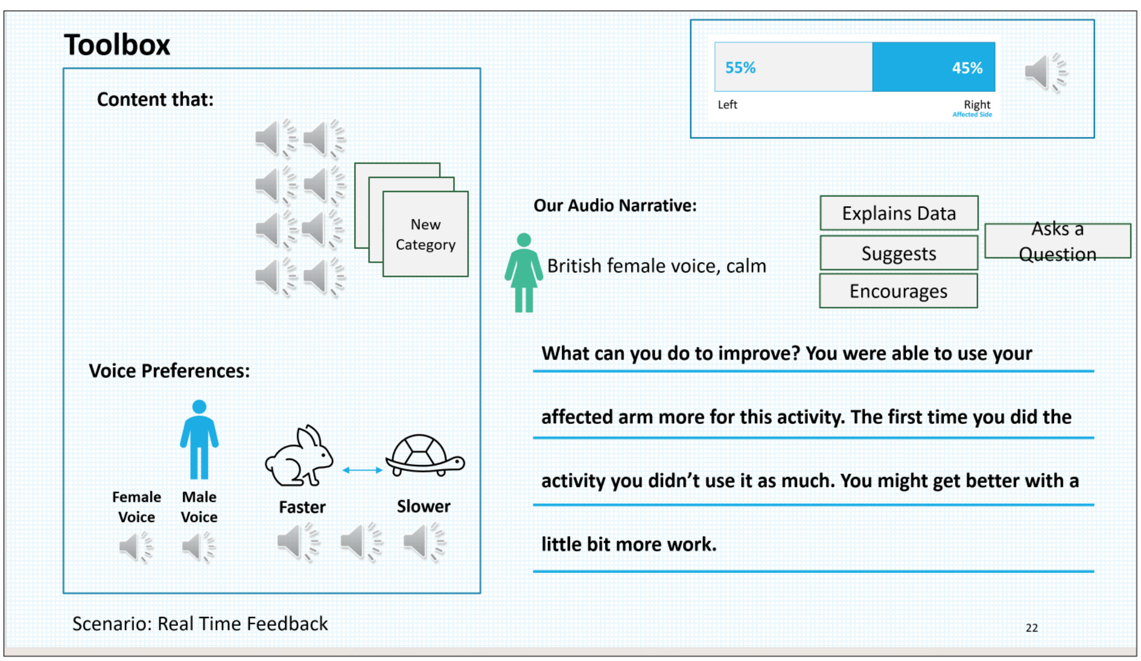

Figure F.48: *Co-Design the Audio Narrative* Prompt Response from P9

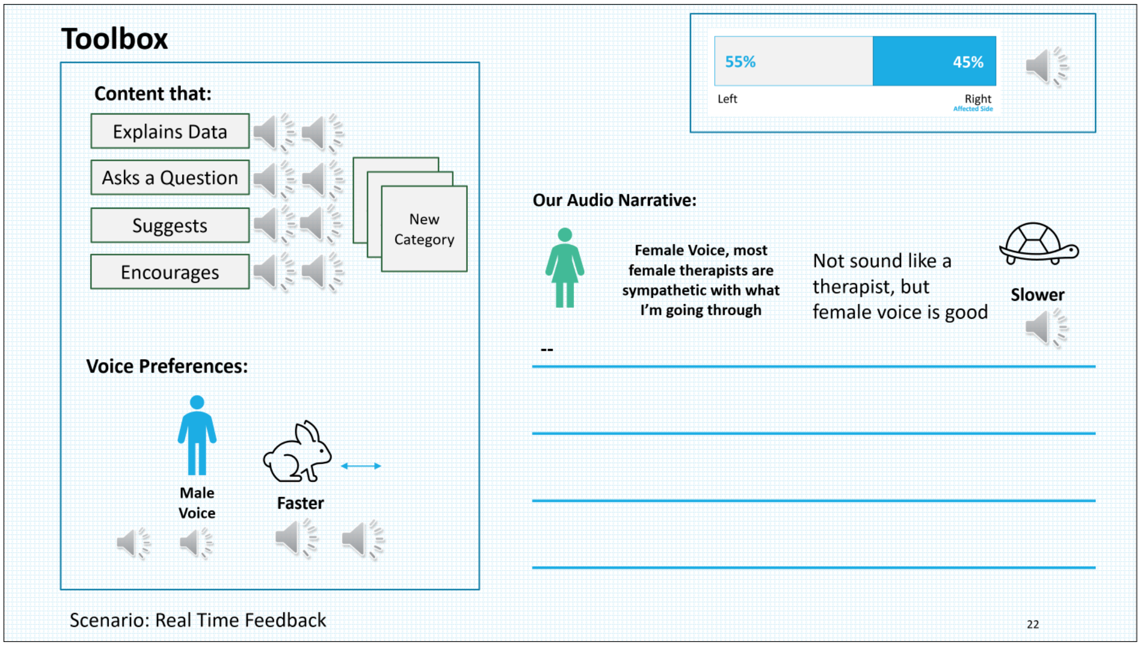

Figure F.49: *Co-Design the Audio Narrative* Prompt Response from P10

F.8 Prompt: Audio Narratives of Longer Term Data

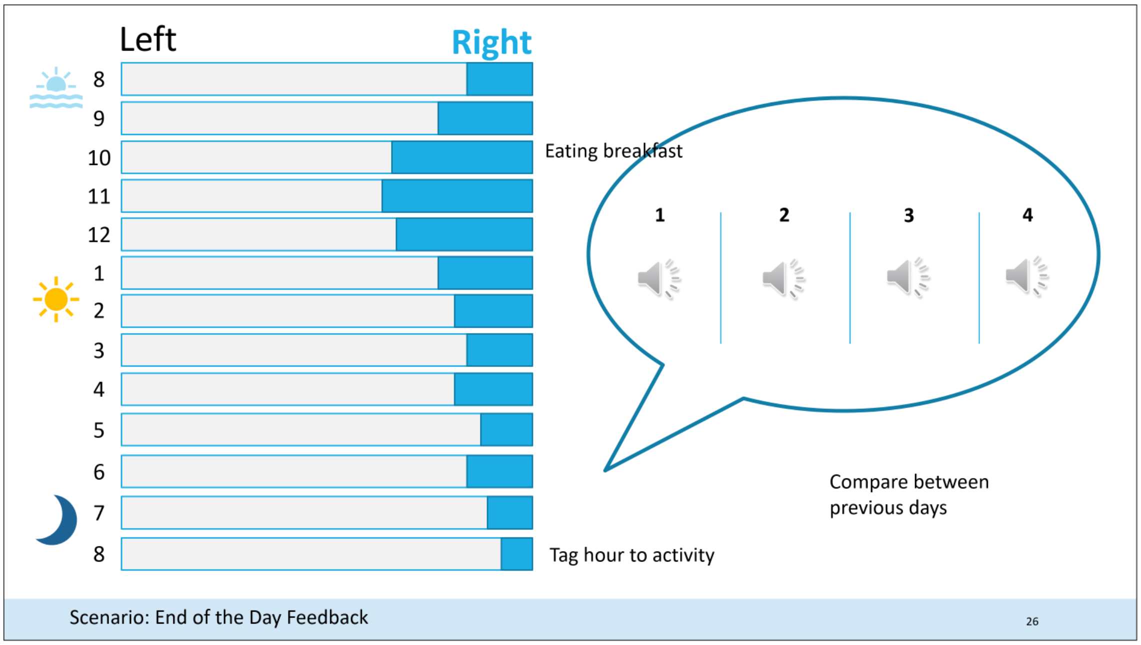

Figure F.50: *Audio Narratives of Longer Term Data* Prompt Response from P2; Daily Report

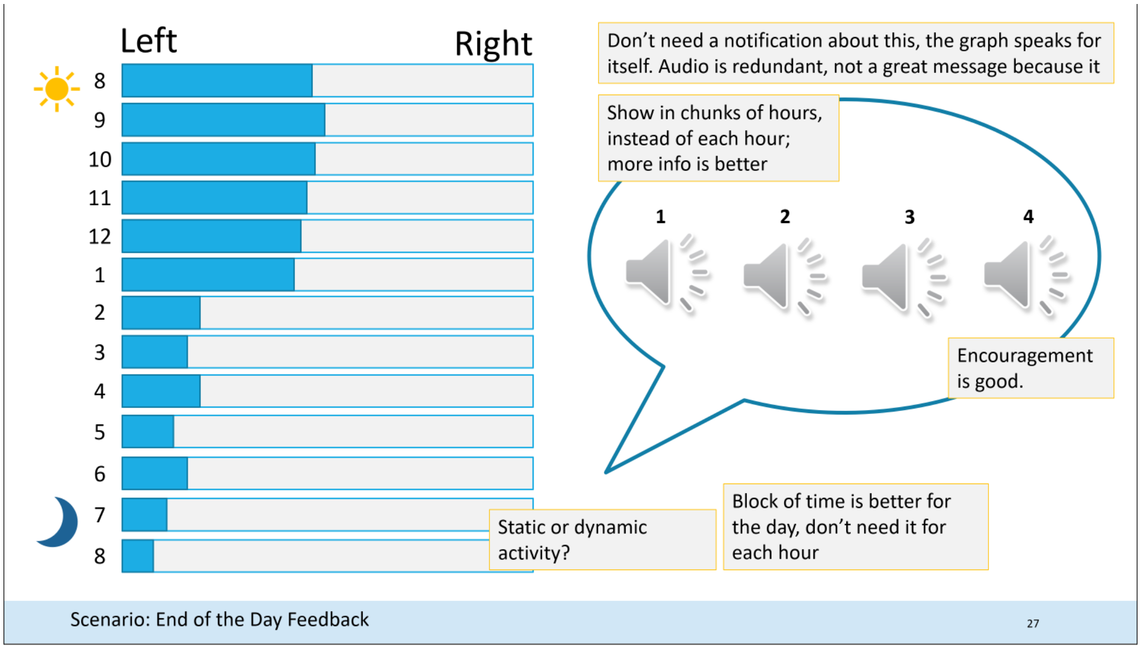

Figure F.51: *Audio Narratives of Longer Term Data* Prompt Response from P8; Daily Report

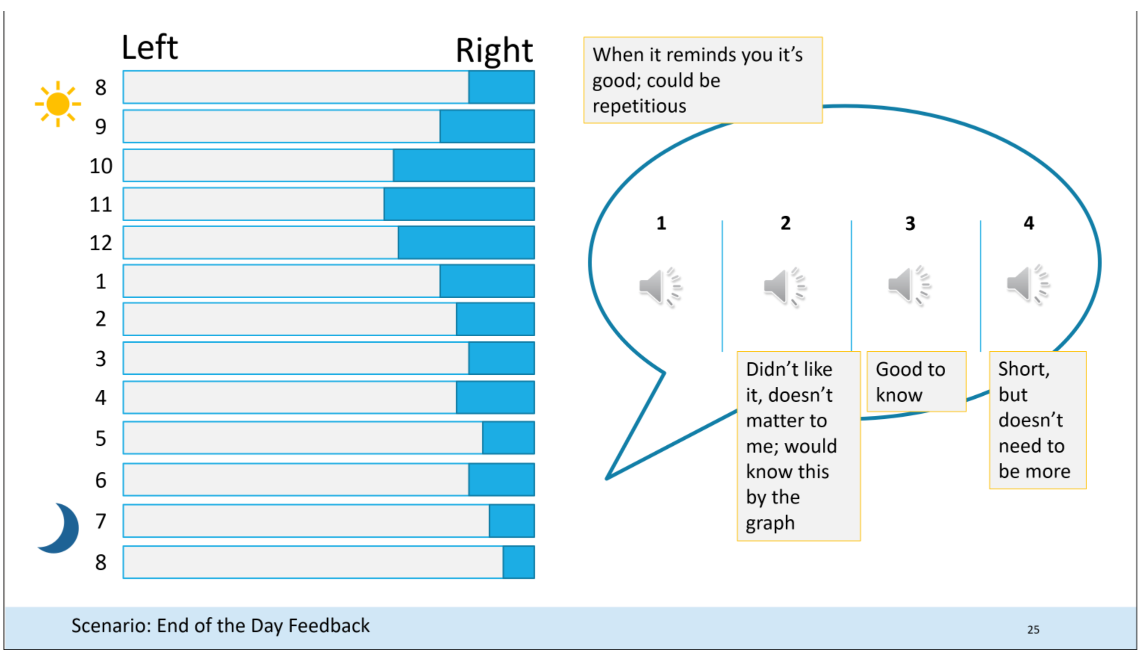

Figure F.52: *Audio Narratives of Longer Term Data* Prompt Response from P9; Daily Report

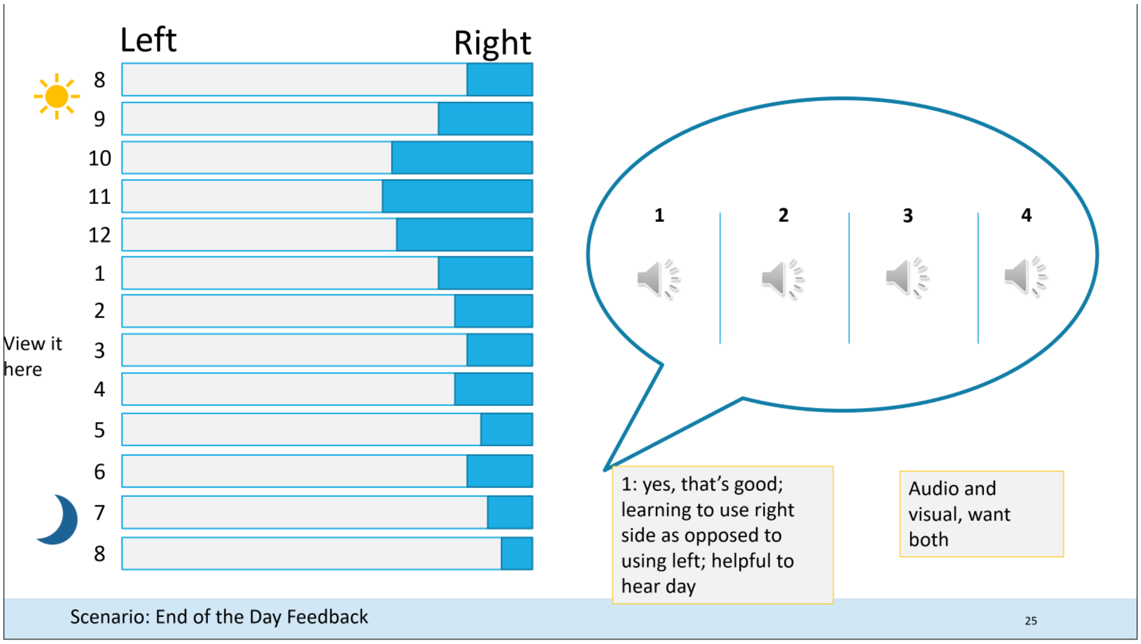

Figure F.53: *Audio Narratives of Longer Term Data* Prompt Response from P10; Daily Report

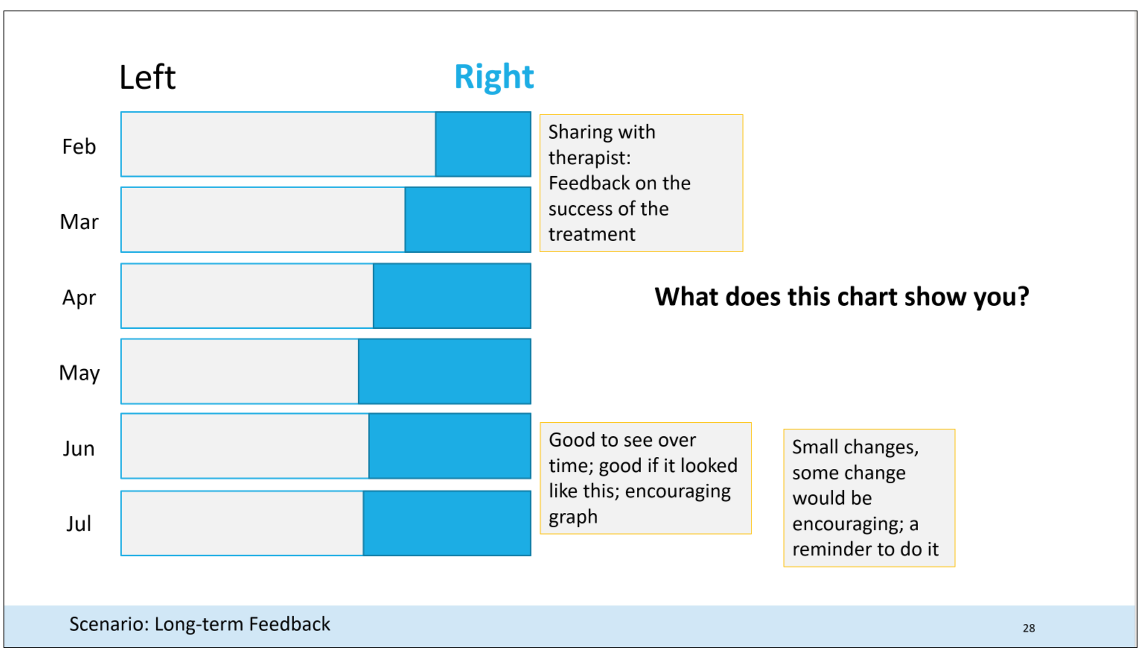

Figure F.54: *Audio Narratives of Longer Term Data* Prompt Response from P9; 6 Months Report

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