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# Developing feedback visualizations to support older adults' medication adherence

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## Abstract

**Background:** Blood pressure control is critical for older adults because the prevalence of hypertension and resulting cardiovascular illness increases with age. Antihypertension medications are central to blood pressure treatment. However, nonadherence to antihypertension medications is high. Health technology such as smartphone apps provide an opportunity for users to manage their medication regimen and support processes related to medication-taking.

**Objective:** We implemented a user-centered evaluation approach to develop and refine adherence feedback visualizations for the MEDSReM© medication adherence app for older adults with hypertension.

**Methods:** We conducted a literature review and iterative usability testing to achieve this objective. We identified adherence goals, information needs, as well as design guidelines by reviewing theoretical frameworks and existing scientific evidence. We then used a two-phase iterative user-centered study and subject matter expert evaluation. Both quantitative and qualitative data were used to select and improve the current prototype and evolve to the next prototype.

**Results:** The need for daily, weekly, and monthly adherence performance information as well as visualization formats for conveying this information was identified from the literature review. Overall, the information shown in visualization prototypes was successfully interpreted by participants. Comprehension issues of visualizations were identified and addressed from visual



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Ethical approval
This study was approved by the University of Illinois Institutional Review Board, Champaign, IL. (Protocol#: Study 1a: 21699; Study 1b: 21985; Study 2: 22546).

Statement of human and animal rights
All of the research procedures involving human were conducted in accordance with the University of Illinois Institutional Review Board, Champaign, IL. (Protocol#: Study 1a: 21699; Study 1b: 21985; Study 2: 22546).

Statement of informed consent
Written informed consent was obtained from the participants for their anonymized information to be published in this article.

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

prototype revisions. Insights from both user and subject matter expert groups were used to select and refine the prototypes for the MEDSReM app.

**Conclusion:** Evidence-based and user-centered approaches were effective for developing visualizations about adherence performance feedback in the MEDSReM app and provided insight into how the app can be made easy to understand and use by older adults with hypertension, which will be evaluated in future effectiveness testing.

**Keywords**

Medication adherence; Health technology; Iterative user-centered design; Illness self-care; Subject matter expert

## 1. Introduction

Health-related smartphone apps are ubiquitous, but often do not benefit older adults. An important reason is the lack of guidelines for designing apps for older adults. For example, Morey et al. (2019) evaluated several mHealth apps developed for older adults and identified usability challenges related to perceptual-motor function (e.g., small font in displays, small buttons) and cognitive function (e.g., providing too many options for effective decision making, too many steps for data entry, inadequate guidance for navigation). Gomez-Hernandez et al. (2023) revealed analogous findings in their systematic review of 40 studies ofusability tests of smartphone apps with older adults. Following an interdisciplinary use-inspired basic research approach, we leveraged theories and methods from human factors, cognitive, and medical sciences to develop and evaluate an app-based system that supports older adults' medication taking and health outcomes.

This paper describes the development and initial evaluation of the visualizations in the Medication Education, Decision Support, Reminding, and Monitoring (MEDSReM©) system (Al-Saleh et al., 2024). MEDSReM is a digital therapeutic tool consisting of integrated app and companion website components. The goal is to help older adults self-manage their antihypertension medication taking through education about hypertension and its treatment; reminders to take their medications; and monitoring support through visual feedback to help them track progress in reaching their adherence goals and, ultimately, improve their health.

Consistent with user-centered design principles, we developed the visualizations by identifying user goals and information needs for adherence and blood pressure management, which informed the content of the visualizations, as well as identifying formats for presenting this content in ways that are easy to understand and support adherence planning and monitoring. These visualization prototypes were evaluated using a mixed methods approach in which they were iteratively evaluated and refined by measuring understanding of, preferences for, and use of the visualizations by older adults representative of the intended user group. To provide a context for our work, we next describe adherence-related challenges among older adults with hypertension, as well as the rationale for and development of the MEDSReM system.

### 1.1. Hypertension management and medication adherence: an age-related challenge

Blood pressure control is critical for older adults because the prevalence of hypertension and resulting cardiovascular illness increases with age (Benjamin et al., 2019). Roughly 70 % of adults over age 65 have hypertension (Mozaffarian et al., 2015). Managing hypertension requires clinicians to identify target blood pressure values for the patient, develop a treatment plan, and monitor blood pressure control over time. Antihypertension medications, along with lifestyle recommendations, are central to blood pressure treatment according to clinical practice guidelines. However, nonadherence to antihypertension medications is common, contributing to the high prevalence of uncontrolled blood pressure among older adults. By one estimate, at least 45 % of adults diagnosed with hypertension do not take their antihypertension medications as prescribed (Burnier et al., 2020; Dzau & Balatbat, 2019).

Medication nonadherence is associated with many factors related to the patient, the medication taking task, the social context, and the health care system (Unni & Bae, 2022). The role of patient cognition has often been investigated, including beliefs about the medication (e.g., perceived costs and benefits of taking medication) and health literacy (knowledge and abilities needed to obtain, understand, and use health information; see Unni & Bae, 2022, for a recent framework). An important cognitive factor is remembering to take medication. Nonadherence is often linked to forgetting to take medication, especially among older adults who have lower levels of working memory (e.g., Insel et al., 2006) and who encounter more distractions/disruptions in their daily life (e.g., Park et al., 1999). Adherence depends in part on prospective memory, which is remembering to perform actions in the future (Einstein & McDaniel, 1996).

### 1.2. MEDSReM system support for older adult adherence

The MEDSReM system is motivated by a theoretical analysis of the role of prospective memory in older adults’ medication adherence (Al-Saleh et al., 2024). Taking medication as prescribed requires encoding an intention to take the medication at specific times, storing the intention in memory, recalling this intention, performing the actions as intended, and then monitoring performance to ensure the action was taken (Insel et al., 2013, 2016). These prospective memory processes in turn depend on working memory and executive function (Einstein & McDaniel, 1996). Nonadherence among older adults is due in part to age-related declines in these cognitive resources (Einstein & McDaniel, 1996; Insel et al., 2006).

The Multifaceted Prospective Memory Intervention (MPMI), based on prospective memory theory, was developed to support adherence among older adults by reducing their reliance on age-vulnerable cognitive resources such as executive function (Insel et al., 2013, 2016). Nurses trained older adults to use strategies that supported planning; remembering to do actions; monitoring performance; and other prospective memory processes. These strategies included linking target medication times to participants’ specific daily routines and imagining medication taking to further encode the intention through action plans. The intervention improved adherence to antihypertension medications compared to an active education condition, but the effect was short-lived when nurse involvement was removed, suggesting the strategies were not effectively integrated into older adults' daily life (Insel et al., 2016).

The MEDSReM system was designed to help sustain the benefits of using the MPMI strategies in the context of daily life. This digital therapeutic was implemented in a smartphone app linked to a companion website (Al-Saleh et al., 2024). Because smartphones are now a ubiquitous part of many older adults' lives, the MPMI intervention implemented as a smartphone/website system is likely to reach a broader segment of older adults and thus have a bigger impact on health outcomes.

The MEDSReM system was developed and evaluated by a multi-disciplinary team composed of clinician-researchers, behavioral scientists, and technology developers, who followed user-centered design principles that included iterative evaluation by target users. After initial usability testing (Al-Saleh et al., 2024), the MEDSReM design was refined and its function expanded to provide more comprehensive support for medication adherence and blood pressure management, which included targeting additional processes involved in adherence such as decision support. Central to this step was expanding the role of the visualizations that provide users with feedback about their adherence and blood pressure readings.

### 1.3. Overview of the studies

Our goal was to develop visualizations that reinforced the MPMI strategies and provided users with feedback about patterns of adherence performance for each antihypertension medication supported by MEDSReM. Users' blood pressure values were presented in visualizations to help contextualize adherence performance in terms of health outcomes. Collectively, these visualizations should help older adults understand their adherence trends, encourage them to act on this information to improve their health, and support the procedures of performing and monitoring medication taking. In the present paper we describe the development of the medication adherence visualizations (see Morrow et al., 2022 for details about the development and initial evaluation of the MEDSReM blood pressure visualizations). The visualizations were intended to be primarily used on the smartphone app – hence that was the focus of our evaluation. They could then be imported to the website for viewing on larger screens.

The visualizations were developed, refined, and evaluated using a theory-driven, multi-disciplinary approach that involved three phases (see Fig. 1), with the ultimate goal of having them available for a randomized controlled trial (RCT). The visualizations were developed in Phase 0. The content of the visualizations was determined by reviewing the adherence literature and consulting with the clinicians on the research team to identify user goals and information needs relevant to adherence and blood pressure management. Formats for presenting this content in ways that are easy to understand were identified based on theories of visualization comprehension, and age-related changes in cognition. Because some of the visualizations were already embedded in the initial MEDSReM system, developing the visualizations also required considering how to re-design and expand the functionality of the existing MEDSReM visualizations.

Phase 0 resulted in several alternative versions of each visualization. In Phase 1, these versions were iteratively evaluated across two studies in the context of scenarios typical of older adult medication taking. The evaluation used a mixed methods approach, collecting both qualitative data (e.g., participant responses to semi-structured interviews) and quantitative data (e.g., comprehension accuracy, navigational errors) from representative older adult users. The findings helped determine which versions were easiest to understand and were favored by users and why. In Phase 2, the visualizations judged most suitable based on these studies were organized into a set that provided feedback about daily, weekly, and monthly adherence. These visualizations were implemented in a software prototyping tool (Figma; https://www.figma.com) to simulate the MEDSReM app. They were further evaluated and refined in a final study that measured older adults' visualization comprehension, motivation, and preferences in the context of the simulated app presented on a smartphone, as well as their ability to use the visualizations to reason about their adherence performance, as they would need to do when using the app to support daily medication taking. Thus, this study allowed us to evaluate visualization comprehension, motivation, and preferences in a more representative context.

Throughout this process, visualization development and evaluation were informed by input from the interdisciplinary project team, which included clinical and behavioral science researchers and the app developers, to ensure that the visualizations would effectively target older adults with hypertension and could be implemented in the MEDSReM system. This project, along with similar work that evaluated the usability of instructional support and other MEDSReM system components (e.g., Azevedo et al., 2022; Hale et al., 2023), helped ensure that the system would be useful and easy to use by older adult users. The impact of this system on adherence to antihypertensive medications is now being evaluated in an RCT.

## 2. Phase 0: develop visualizations

### 2.1. Approach

**2.1.1. Visualization content—**The content of the visualizations was identified by analyzing user adherence goals and information needs relevant to performance feedback. This step was informed by reviewing the MPMI intervention that motivated the MEDSReM app development, the adherence literature, and theoretical frameworks relevant to self-care and health behavior change. According to several of these theories (e.g., Meyer et al., 1985; Schwarzer, 2008), self-care goals evolve during the course of illness, from accepting the illness at onset and the need for self-care, to establishing self-care (learning how to do self-care tasks), to sustaining these tasks. From this perspective, medication adherence, like other self-care tasks, requires accepting the need for the task, establishing it as part of daily life, and sustaining performance over time (Morrow et al., 2021). These three broad stages in turn require several goals and information needs, including motivating information about task importance and efficacy; explanation that supports learning about the task as well as planning and implementing strategies in daily life; and feedback about task performance that helps sustain performance (Morrow et al., 2021). Effective visualizations should support the goals related to these three stages. First, they should help older adults accept the task, for example by linking adherence to important outcomes such as blood pressure control. Second, they should help establish adherence strategies by providing feedback about initial actions (e.g., when, what, how) that helps older adults implement and evaluate how well the strategies are established. And third, they should help sustain adherence by providing feedback about adherence patterns over time (e.g., which medications are taken or missed and when) that support adherence monitoring and reduce errors such as under- or overdosing.

Visualizations may sustain adherence by showing the discrepancy between current and target performance level and goal progress to motivate effort over time. According to the Control/Self-Regulatory Theory, an individual could be motivated by perceiving a discrepancy between their performance and goals and attempt to reduce this discrepancy and achieve the goals through actions if there is sufficient opportunity and ability (Carver & Scheier, 1982).

**2.1.2. Visualization format—**Next, visualization formats (e.g., organizational principles, graphic features) for presenting the content were identified. We distilled, by reviewing theories of visualization design/comprehension and theories of cognitive aging, several principles for designing visualizations that are easy to understand and support adherence planning and monitoring (Nie, 2022). Visualizations for older adults should leverage cognitive resources that tend to increase with age (e.g., knowledge) as well as reduce demands on resources that decline with age (e.g., working memory; Morrow & Rogers, 2008). Such visualizations may benefit less numerate individuals of all ages (Garcia-Retamero & Cokely, 2017).

More specifically, visualizations can leverage older adults' existing resources by a) being organized in terms of familiar concepts that activate relevant knowledge (e.g., use traffic light color scheme to convey level of performance; Morrow et al., 2019; Tao et al., 2018), and b) by showing the discrepancy between current and target performance level to increase motivation, given that motivational factors such as emotion often become more important with increasing age (Charles & Carstensen, 2010; Spreng & Turner, 2021). Moreover, well-designed visualizations can reduce cognitive load involved in understanding them by c) making information easy to perceive (e.g., key concepts conveyed by salient graphical features); d) reducing clutter by minimizing information that is not relevant to adherence goals; and e) using consistent features across different visualizations (Boot et al., 2020; Moreno & Park, 2010; Morey et al., 2019; Shah & Hoeffner, 2002).

## 2.2. Results

We next describe key findings for each type of adherence visualization in the MEDSReM system. For each visualization, we summarize user goals and information needs that should be supported by the visualization content, as well as the relevant design guidelines for formats to convey this content. Fig. 2, Fig. 3, Fig. 4 present the alternative format versions that we developed and evaluated for each visualization for all phases.

### 2.2.1. Daily medication summary

**2.2.1.1. User goals and information needs.:** The Daily Medication Summary helps users monitor daily adherence progress by showing whether the person took their medications on a given day. The focus is to help people understand a single value for each medication-taking event: Did they take the medication or not? It may help them understand daily patterns of these values such as whether adherence differed across the day or across medications. By linking medication names with daily events such as meals, this visualization may help users reflect on possible reasons for missing doses and support planning for more accurate adherence. This visualization may encourage users to improve performance by increasing awareness of nonadherence patterns.

**2.2.1.2. Design guidelines.:** This visualization was designed following several guidelines:

***(i) Organize visualizations around familiar concepts.:*** Older adults tend to rely on daily routines, which can support medication adherence (Park et al., 1999). The MPMI intervention capitalizes on this strategy by encouraging older adults to link medication-taking times and place to their daily routine events (e.g., breakfast; bedtime) to support prospective memory. Visualizing feedback about medication-taking performance in terms of the daily cycle may reinforce this strategy. Two potential formats for the daily Medication Summary used the familiar daily cycle to indicate when medications should be taken, with times anchored to daily events such as meals (i.e., breakfast). The *Box* format (Fig. 2. Version A) conveyed the daily cycle implicitly through a sequence of boxes representing morning, evening, and night segments of the cycle. Target medication times, linked to daily events such as breakfast, were indicated in the appropriate box. A similar format (the Universal Medication Schedule) has been found to improve memory for medication schedules compared to typical verbal formats for medication containers (Wolf et al., 2016). The *Timeline* format (Fig. 2. Version B) more explicitly conveyed the cycle with a 24-hour timeline and medication names (with familiar icons indicating day, night, meals, etc.) to indicate target medication taking times and to provide feedback about whether medications were taken on time. Similar formats have been found to improve older adults' memory for medication schedules compared to verbal formats (Morrow et al., 1998).

In both formats, feedback about whether each scheduled medication was taken on time was indicated by using the familiar traffic light color scheme: A green 'Taken' message indicated the medication was taken thin the scheduled medication safety window (duration of the window depending on the pharmacokinetics of the medication), and a red 'Missed' message indicated the medication was not taken at all. The traffic light scheme not only leverages the mapping between specific colors and concepts (green-go, red-stop, or yellow-warning), but reflects the more general design guideline to use 'semantically resonant' colors that are associated with meaningful data trends (green=good, high levels of performance; red=poor, or low levels of performance; Schloss et al. 2018). Traffic light color formats can improve comprehension of health information among people with diverse abilities (e.g., Arcia et al. 2016; Morrow et al., 2019).

***(ii) Use uncluttered visualizations.:*** The visualizations were designed to be simple as well as familiar to support comprehension. However, although the more explicit timeline format (Fig. 2. Version B) uses a familiar schema to convey feedback, it is also more cluttered than the box format (Fig. 2. Version A) because of the added timeline and daily event icons.

***(iii) Make information easy to perceive.:*** We used both color-coded text and icons as salient features to highlight the key information of medication taken and missed. Green color and check marks were used to indicate medication taken; red color and “x” marks were used to indicate medication missed. According to theories of color perception, using complementary colors (green and red) should attract user attention (Bleicher, 2015). Icon shape (and word meaning) as well as color was used to code adherence information in part because red-green color blindness impairs use of color as a cue for some users (4–8 % for males; about 0.5 % for females; Frane, 2015).

### 2.2.2. Weekly medication summary

**2.2.2.1. User goals and information needs.:** The Weekly Medication Summary helps users monitor adherence progress by showing how well users took each medication during the current or past weeks. The visualization should help them understand their adherence success for each medication (how close to perfect adherence) as well as compare adherence across medications during a given week. The information needs supported by this visualization may be more complex than for the Daily Medication because current performance for each medication is compared to a reference value (100 % adherence), and these values are compared between medications to indicate which is taken more accurately.

**2.2.2.2. Design guidelines.:** The Weekly Summary was designed following several guidelines:

***(i) Organize visualizations around familiar concepts.:*** Bar (Fig. 3 Version A) and ring (Fig. 3. Version B) formats were chosen to summarize adherence because both are often used to indicate performance of health-related activities (e.g., eating specific foods, walking). For example, rings are used in the Apple watch and other exercise apps to show progress toward goals, and bars are also used in these apps to show progress over time (Gouveia et al., 2016; Yacef et al., 2018). Both formats are familiar ways to support understanding of current performance relative to goals and to engage and motivate users by linking to metaphors for progress (‘close the rings’; ‘complete/fill the bars’; Arcia et al., 2016).

***(ii) Make information easy to perceive.:*** Both formats use salient perceptual features of the visualizations to support understanding of key concepts: Level of performance (proportion of bar or ring ‘filled’ with color) and comparison of performance levels (length of the bar and proportion of the ring that is filled for each medication). The bar format (Fig. 3. Version A) may be more effective because of the salience of horizontal lines for comparisons (Shah & Hoeffner, 2002). Bar/line length also provides a salient visual feature that supports gist memory for numerical concepts such as relative level of performance (Reyna, 2008).

***(iii) Use uncluttered visualizations.:*** The idea of figure/ground from Gestalt and cognitive psychology was leveraged in this visualization: White space in both formats helped people perceive, interpret, and compare weekly performance for each medication by providing the background needed to easily separate and focus on the bars or rings. Higher color contrast and luminance contrast (e.g., black/dark green on white background), as well as plain background are important determinant of legibility of symbols and text (Hill & Scharff, 1999; Scharff et al., 2000). In addition, minimizing clutter may especially benefit older adults who experience declines in the ability to inhibit irrelevant information (McCarley et al. 2012).

### 2.2.3. Monthly medication calendar

**2.2.3.1. User goals and information needs.:** The Monthly Medication Calendar helps users monitor progress by showing how well they took all their medications each day and week of the month (see Fig. 4). If multiple medications are taken each day, summary adherence across these medications is shown to reduce the complexity of feedback at this level of summarization. Thus, daily performance is summarized at a higher level than in the Daily or Weekly Summary.

Daily performance in the Calendar is implicitly compared to the reference value of perfect performance (all medications taken on time that day). The Calendar may help people understand adherence patterns, such as whether they took medications more accurately on certain days (e.g., weekdays versus weekend) or weeks (e.g., adherence declines or improves across the month). In sum, the Calendar is designed to support the most global level of understanding of medication-taking performance, compared to the other visualizations. However, it is the most complex visualization because it summarizes performance across all medications in the app and displays adherence patterns at all levels (day, week, and month).

**2.2.3.2. Design guidelines.:** This visualization was designed following several guidelines:

***(i) Organize visualizations around familiar concepts.:*** The calendar format was chosen because it is a very familiar way to show monthly events. Calendars are almost universally used to support planning (e.g., scheduled appointments for the month) and have transitioned from paper to digital environments, now being embedded in many apps. They are used in reminder systems (e.g., pill organizers; unit dose packaging) to support adherence by showing when medications should be taken and to remind people about these times. Like the Daily Medication Summary, the familiar traffic light scheme is used in the Calendar to show daily performance (in this case, summarized across medications): All medications taken (green), some taken (yellow/amber), and none taken (red; see Fig. 4. Version A).

***(ii) Make information easy to perceive.:*** In addition to the traffic light scheme, a sequential color palette format was developed to indicate a level of daily medication adherence, with different darker shades of green indicating all, some, or no medications (respectively) taken on a given day (Fig. 4. Version B). Sequential color palettes are effective for indicating levels of ordinal dimensions, in part because a salient perceptual ordinal dimension (color) is used to represent the conceptual ordinal dimension (in this case, level of adherence). In fact, single-hue palette displays support some tasks such as trend detection more effectively than multiple-hue displays do (e.g., Warden et al., 2022; Zikmund-Fisher et al., 2017, see also: Tao et al., 2018). In addition, the specific colors in both the traffic color and sequential palette formats were chosen to facilitate the perception of general values and trends over more specific information. Thus, they may also support gist (compared to verbatim) memory for adherence level (Reyna, 2008), which may help users track their performance.

Finally, for both formats, 'streaks' (same level of adherence across successive days) were used in some formats to perceptually emphasize consistent performance by linking the individual (same) colored disks indicating the same performance for the successive day (see Fig. 4. Version C and D). The traffic light scheme was used (e.g., green streaks to indicate successive good adherence days) so that level of performance was reinforced by both perceptual and familiarity strategies, which may help motivate adherence (for green streaks; see Fig. 4. Version C).

***(iii) Use uncluttered visualizations.:*** White space to emphasize figure/ ground relationships helped people perceive and interpret daily performance for each day and across the days of the month for both formats.

***(iv) Use consistent features across visualizations.:*** Consistency in representing adherence performance across different visualizations was emphasized by using the traffic light colors to indicate good performance (green), fair performance (yellow/amber), and poor performance (red) for both the Daily Summary and some formats of the Monthly Calendar.

## 3. Phase 1: selecting visualization versions

### 3.1. Approach

We next evaluated the alternative versions of each visualization in the MEDSReM system to select the most effective one for further testing (see Phase 1 in Fig. 1). Studies 1a and 1b evaluated the prototype visualizations in the context of scenarios typical of older adults' use of antihypertension medications, which were generated by the clinical experts on the research team. As a safety measure during the COVID pandemic, both studies were conducted over Zoom, with an experimenter interacting with the participant following a script. The session began with a brief description of the purpose of the visualizations within the MEDSReM app to help participants interpret the visualizations. Next, participants were shown the prototypes separately. For each, they were asked two types of comprehension questions to probe how well they interpreted the information conveyed by each visualization. The first probed whether they understood the meaning of visualization features, whereas the second probed how well they understood patterns of adherence performance conveyed by these features. They were asked preference questions to explore their likes and dislikes about each visualization. They were then asked questions requiring them to compare alternative formats of each visualization to determine which they preferred and why. Collectively, these questions probed participant comprehension and preferences related to each visualization. The preference measures likely reflected motivation to use the visualizations as well as the ability to understand the information (preference questions were asked after the comprehension questions). Table 1 provides information about participant samples and Table 2 provides information about interview questions for each study.

## 3.2. Results

We next describe key findings from the two usability studies as well as input from the project team for each type of visualization.

### 3.2.1. Daily medication summary

**3.2.1.1. Study 1a findings.:** Six of the eight participants[1] evaluated both the box and the timeline formats for the Daily Medication Summary (Fig. 2). All six understood the adherence information conveyed by these formats: They correctly identified which medication was taken more accurately and whether adherence was better during or after the morning. However, most participants (87.5 %) preferred the box over the timeline format.

The box format was also preferred by team members because this less cluttered format would be easier to view and read on the small screen of a smartphone. Other recommendations included further streamlining the box format by eliminating the icons that indicated morning/afternoon/night phases of the daily cycle, as well as replacing the wording of “taken” with “on time”, “early”, and “late” to indicate whether medications were taken in or out of the safety window. A yellow ‘early/late’ message indicated the medication was taken, but before or after the safety window.

Based on Study 1a findings and input from the project team, the box format of the Daily Summary was chosen and refined for further evaluation in Study 1b. We added a title of the page, enlarged font size, removed icons and timeframes (e.g., morning, afternoon), used yellow font to indicate medication taken early or late, and increased the saturation of the green and red font (lighter versus darker) used to indicate medication taken on time and missed. These changes were made so the visualization would be less clustered, more consistent with font size and color in other components of the app and more understandable.

**3.2.1.2. Study 1b findings.:** All participants correctly identified which medication was not taken on time and they understood the meaning of the colors to indicate which medications were taken on time, early/late, or missed. Some participants (4/17) were confused about the meaning of the yellow color used to indicate that a medication was taken early or late because they did not understand how much time was meant by ‘early/late’. This finding may be an artifact of presenting the visualization out of context of the MEDSReM app, wherein the meaning of early/late would be explained as part of instructional support for the system (Azevedo et al., 2022). Half of the participants (8/17) liked the traffic color theme to indicate a person’s performance and liked the red color as a warning. Some participants (2/17) liked the simplicity of the layout (for more information about Study 1b findings see Nie et al., 2022).

[1]Nine participants were recruited in Study 1a, however one participant was dropped due to technical difficulty. There was no record of two participants’ responses to the comprehension questions.

The results of Study 1b converged with those of the first study, increasing our confidence that the Daily Medication Summary was easy to understand. The darker green version was chosen based on input from the project team and consistency with the hue used in the other visualizations.

### 3.2.2. Weekly medication summary

**3.2.2.1. Study 1a findings.:** All eight participants in Study 1a evaluated both the bar and ring formats of the visualization (Fig. 3). Every participant correctly answered all comprehension questions for both formats. They correctly identified the current level of performance (percent doses taken) for each medication, identified which week was displayed in the visualizations, and which medication was taken more frequently. The majority (63 %) preferred the bar format; the rest preferred the ring format. The project team members had mixed preferences for the bar/ring format, but the app developer preferred the ring format because it was already embedded in the initial version of the app.

Although Study 1a participants tended to prefer the bar over the ring formats, we further tested both formats in Study 1b in the context of a schedule involving three medications. This more complex schedule (requiring three rings or three bars to represent level of adherence for each medication) provided a more comprehensive test of the potential impact of format clutter and visibility on comprehension and preferences because the size of the display components (e.g., ring or bar, text) had to be reduced to fit the display.

In addition, in the bar format, the position of the digits indicating the percent of medication doses taken was left- rather than right-justified within each bar. In this way, the digits were superimposed on the filled portion of the bar so that these two cues (digits and green segment) were integrated, consistent with the proximity compatibility principle of display design (Wickens & Carswell, 1995). The color of the digit was changed from black to white to increase contrast with the green background.

**3.2.2.2. Study 1b findings.:** Study 1b results converged with the first study to show that people understood the adherence information conveyed by both the ring and bar formats. All participants correctly interpreted the adherence level for both formats (e.g., the meaning of "57 %" for Hydrochlorothiazide). They also correctly identified which medication was taken least (or most) often during the week. We further evaluated comprehension by asking which direction the filled portion of the rings or bars would change to indicate better adherence. All participants answered this question correctly for both formats.

Results for the preference questions revealed a small preference for the bar format: 47 % thought the bars were easier to understand (33 % favored the rings), 53 % thought the bars made it easier to identify which medication was taken more accurately (18 % favored the rings), 41 % thought the bars were more motivating (24 % favored the rings), and 63 % had an overall preference for the bars (25 % favored the rings). For each question, the remaining participants did not favor one format over the other. Some participants (6/17) liked both ring and bar formats because they perceived them as intuitive and uncluttered. Some (4/17) liked the metaphor of filling in the rings/bars to demonstrate how well an individual is doing with respect to their goal of fully filled rings/bars. Almost half (47 %) suggested using the traffic light color scheme to indicate lower performance levels. They suggested using the yellow or red color for caution or failure to take the medications respectively, to contrast with using green to indicate success. However, this suggestion was not implemented because the adherence literature does not identify what adherence levels would be clinically indicated by yellow or red ring/bar segments (for more information about the study findings see Nie et al., 2022).

Both studies provided some evidence that participants preferred the bar over the ring format for the Weekly Summary. Nonetheless, the ring format was chosen for further testing for several reasons. First, participants in both studies understood the adherence information conveyed by the ring as well as the bar format. Second, the ring format may be more familiar to potential MEDSReM app users because it is featured in many existing fitness apps (e.g., Apple Watch; Gouveia et al., 2016; Yacef et al., 2018). Finally, the ring format had already been implemented in the first version of the app and therefore was more feasible to implement.

### 3.2.3. Monthly medication calendar

**3.2.3.1. Study 1a findings.:** The results showed that the color cues in both the traffic light and sequential color calendar formats were well understood (Fig. 4). All participants correctly answered the questions about the meaning of the colors (which level of adherence was indicated by each color) for both formats. Participants also understood patterns of feedback across days and weeks indicated by these color cues. All participants correctly answered the question about level of adherence on a specific day in the calendar. Most participants (88 %) correctly identified which week of the month had the best performance for the traffic light format; accuracy was lower for the sequential palette format (63 % correct).

The pattern of preferences for the different formats was somewhat complex but tended to converge with the comprehension results to suggest participants favored the traffic over the sequential color format. For the formats without streaks, five participants (63 %) preferred the traffic light and three (37 %) preferred the sequential colors. Participants also tended to prefer formats with streaks, the majority (63 %) preferring this version over versions without streaks for both the traffic light and the sequential palette formats. Finally, when all four formats (traffic light and sequential palette with and without streaks) were presented together, 50 % of participants preferred the traffic format with streaks, 25 % preferred the sequential color format with streaks, 13 % preferred the traffic format without streaks, and 13 % preferred the sequential color format without streaks. To sum up, participants tended to like the Calendar format with traffic colors and streaks.

Project team members preferred the traffic light over the sequential (green) Calendar format because of its familiarity to participants and because of consistency, given that it was also used in the Daily Summary visualization. They were also concerned about the yellow and red streaks, which not only may have added clutter to the Calendar but could potentially reduce motivation to improve adherence by perceptually emphasizing poorer performance.

Based on the input from the Study 1a participants and the project team, the sequential color format was eliminated, and the yellow and red streaks were dropped from the traffic color format. In addition, because some participants thought the key that defined the meaning of the color disks would be difficult to notice, the font size of the key labels was enlarged, and a box added to increase the key's salience. In addition, to keep the color theme consistent with other visualizations and increase contrast, more saturated/darker color disks were implemented and digits indicating day of the month were presented in white rather than black font in the darker color version.

**3.2.3.2. Study 1b findings.:** Study 1b evaluated the two traffic color formats (with and without green streaks) for the calendar. The results converged with Study 1a to show the Calendar was accurately interpreted. All participants correctly answered the questions about the meaning of the color disks. However, 24 % of participants were uncertain what 'some medications missed' meant for the yellow disks because adherence was combined across different daily medications. This confusion might not occur for users of the actual app because they can see adherence for each medication in the Daily and Weekly Summaries. All participants correctly answered the questions about level of adherence on a specific target day in the calendar and whether adherence increased or decreased from Week 1 to Week 2. They also correctly identified adherence as better during weekdays compared to the weekend. Color version did not influence comprehension.

In contrast to the first study, Study 1b results did not generally favor the use of streaks in the Calendar. Only 25 % of participants thought the streak formats were easier to understand and only 29 % thought the streaks were more motivating. The formats with streaks were preferred by only 35 % of participants. Interestingly, 53 % of participants suggested using yellow and red as well as green streaks. This finding might help explain why streaks were not preferred in Study 1b (green streaks only) but were in Study 1a (green, yellow/amber, and red streaks). However, this suggestion was not implemented due to concern that it might add clutter and reduce motivation to improve adherence.

Based on the results of Study 1b and input from the project team, the darker color format without streaks was chosen for further evaluation.

## 4. Phase 2: refining visualizations

### 4.1. Approach

In the final study, the version of each visualization judged most suitable based on the first two studies was organized into a set showing daily, weekly, and monthly adherence performance. These visualizations provided complementary information about adherence. For example, the Monthly Calendar showed daily adherence collapsed over all medications taken on that day, whereas the Daily Summary provided an expanded, finer-grained view of adherence for each medication on that day and could be accessed from the Calendar. Therefore, it was important to evaluate not only how easily older adults understood each visualization, but also how well they could integrate information across the visualizations to reason about their adherence performance.

The visualizations were prototyped in Figma, a tool that allows users to interact with the visualizations in real-time on mobile devices. The Figma-based visualizations simulated adherence performance feedback from common medication-taking scenarios provided by the project team. They were presented on an iPhone rather than on a computer screen, as they had been in the first two studies. The iPhone was used because the RCT will evaluate the MEDSReM app implemented on iPhone smartphones. Users interacted with the phone as they would if using the MEDSReM app in daily life. The visualizations were therefore evaluated with a smaller screen than in the earlier studies and were accessed as part of unfolding scenarios. This allowed us to evaluate visualization comprehension and preferences in a more representative context, as well as to assess how easily older adults could interact with the phone and use the set of visualizations to accomplish specific tasks related to adherence. As noted earlier, the visualizations could also be imported to the website to view on a larger screen, but our assessment of usability was on the iPhone to evaluate the smaller screen.

A navigation page was developed to help users interact with the set of visualizations to accomplish the tasks. The page presented a menu that provided an overview of the adherence and the blood pressure visualizations. The menu was a list of icons, each one semantically associated with the name of one of the adherence visualizations (see Fig. 5). Users accessed the visualizations by clicking on the corresponding icons (see Morrow et al. 2022 for more information about development and evaluation of the navigation page).

Data collection involved two experimenters. One interviewed the participant following a script, as in the previous studies. The second experimenter monitored the recordings during the session and noted any problems related to participant interaction with the visualizations on the phone screen as well as their ability to move through the set of visualizations, using a note-taking tool based on the script. The phone screen during the session was also screen-recorded.

During the session, each participant first freely explored the visualizations accessed from the navigation page, thinking aloud as they did so. This procedure helped participants become familiar with the visualizations, including how they were organized and accessed from the navigation page. The next part involved guided exploration of the visualizations. Participants accessed each visualization in a specific sequence (Daily Medication Summary, Weekly Medication Summary, and Monthly Medication Calendar) to further evaluate their understanding of each visualization. As in the previous studies, both quantitative and qualitative questions were asked to gauge how well the participants understood each visualization and what they (dis)liked about it, now in the context of the set of visualizations. The interview was video recorded. The results described below are based on experimenter notes taken during the sessions and/or during later review of the recordings.

### 4.2. Results

Findings related to the evaluation of the visualizations in context (understanding of and likes/dislikes about the visualizations) are presented first, followed by findings related to participants' ability to interact with and use the visualizations to answer the questions about adherence performance.

#### 4.2.1. Contextual evaluation of visualizations

**4.2.1.1. Comprehension.:** In general, participants encountered no major problems interacting with the Figma versions of the visualizations on the iPhone. All participants correctly answered the comprehension questions about each visualization. Thus, they understood the adherence information conveyed by each visualization in a context where they accessed and compared the visualizations to reason about their adherence performance, as they would if using the actual MEDSReM app to support medication taking.

**4.2.1.2. Visualization likes/dislikes.:** The qualitative data highlight user positive responses to the visualizations as well as uncovering some potential design issues. First, comments emphasized potential motivational benefits of the visualizations. Three of the four participants commented that they would be encouraged to take their medication because of the colors on the Daily Medication Summary. In addition, three participants mentioned that they would be more motivated to take their medications if they could use the Monthly Calendar.

The comments raised some potential design issues. First, two participants were confused about the meaning of the yellow color in the Daily Summary (indicating taking a medication early or late), echoing comments from participants in the other studies. This potential confusion would likely be addressed by the instructional support to be provided when older adults learn how to use the actual MEDSReM app.

Some participants were also confused about aspects of the Weekly Medication Summary, including what ‘percentage taken’ meant in this context and why only the green color rather than the traffic light scheme was used. There was some disagreement about how motivating this visualization was. One participant mentioned it was not as useful as the Daily Summary whereas another said it would motivate them to do better. Such comments prompted us to refine the design of this visualization by increasing the font size of the percentage definition to make it more noticeable, as well as rephrasing the definition as “Percentage means your success rate for the week”. The instructional support for this visualization could also emphasize that the visualization summarizes over a week period, what ‘percentage taken’ means in this context, and explain that the green color in the rings indicates good performance toward the goal of taking all medications every day of the week (indicated by completely filled rings).

A few confusions arose from interacting with the Calendar, which may reflect the fact that participants in this study were navigating among the different visualizations. First, two participants did not notice they could access the Daily Summary from each day in the Calendar. Changing the position of the prompt for this action and/or instructional support may address this issue. Second, one participant was confused about the meaning of the yellow/amber color in the Calendar, because that color means ‘taken early/late’ in the Daily Summary whereas it means ‘some medications taken’ in the Calendar. Instructional support for the app has been developed to reinforce the different meanings of the yellow color that is indicated in the keys for the two visualizations.

**4.2.2. Interaction with the visualizations—**The results based on experimenter observations suggested the participants had little difficulty interacting with and moving among the visualizations in the set during free exploration or when accessing specific visualizations to answer questions. Two participants had some interaction difficulty, primarily because they had to press some buttons several times to move between screens. This likely reflects the technical challenge of the browser based Figma that caused low screen touch sensitivity and would not occur when using the actual MEDSReM app. Indeed, when all participants were given the opportunity to use a version of the visualizations that had been implemented on the actual MEDSReM app, they had no trouble navigating among the visualizations. Therefore, we encourage future researchers to download Figma app to smartphone and test prototypes in the app to avoid such technical issues. We were also encouraged to evaluate the app in the RCT, given the consistent findings across studies 1a and 1b and the minimal problems navigating among the visualizations in the prototype MEDSReM app in study 2.

## 5. Discussion

### 5.1. Summary of key findings

In this project, we used an iterative user-centered evaluation approach to develop a set of visualizations implemented in the app and companion website of the MEDSReM system. Different versions of visualizations about daily, weekly, and monthly adherence performance were created by reviewing relevant literature to identify adherence goals and information needs that defined the content of the visualizations, as well as alternative formats for conveying this content. The most appropriate version for each type of visualization was selected and iteratively refined in two usability studies with target users. In general, all the versions of the visualizations were understood by participants and were often seen as likely to encourage adherence (e.g., partially filled ring encourages adherence by ‘closing the ring’). However, some versions had an advantage in terms of comprehension (e.g., traffic light compared to sequential color format for the Calendar), participant preferences (e.g., box compared to timeline format for the Daily Summary), and/or input from the project team (e.g., ring compared to bar format for the Weekly Summary because of familiarity to iPhone app users and implementation feasibility).

The most appropriate version of each visualization was integrated into a set of visualizations that provided complementary information about adherence performance, implemented as interactive visualizations in a simulated app, and evaluated and refined in Study 2. Participants understood each visualization and could navigate among them with little difficulty. The few confusions identified in Study 2 (e.g., the different meaning of the yellow color in the Daily Summary and the Calendar) were addressed by developing instruction support and clarifying the workflow for users of the MEDSReM app. The impact of this system on adherence in daily life is now being evaluated in an RCT in which participants use the system to manage their adherence to antihypertensive medications that have been prescribed by their providers.

### 5.2. User-centered evaluation approach to developing visualizations

Our project implemented a user-centered evaluation approach with three iterations leading to the development of feedback visualizations in the MEDSReM app. We combined theory-based and mixed method approaches to understand target users' adherence goals and information needs, and then developed and evaluated adherence feedback visualizations. Theories about aging, behavior change, and display design guided the design and evaluation of the adherence feedback visualizations. To identify the content of the visualizations, we reviewed theories about technology support for illness self-care and behavioral change, both generally and in the context of smartphone app use. The visualization content aligned with the adherence goals and information needs across illness self-care stages (Morrow et al., 2021).

To present this content in a way that is easy to perceive and understand by the target user group, we considered both visualization characteristics and users' cognitive ability to facilitate the processes of attention, encoding, and interpretation of the information (Information Processing Theory; McGuire, 1968). We generated design principles to make the visualizations easy to notice, perceive, and understand. We added motivational elements such as green vs. red colors that could motivate action (Murnane et al., 2020; Tsai et al., 2007). In addition, iterative evaluations with target users provided insights in developing understandable and useful adherence feedback visualizations, which are critical to the success of adherence smartphone applications for older adults with hypertension.

### 5.3. Rationale for limiting statistical analyses in problem discovery usability testing

The goal of our research was to discover and remedy usability issues in the iterative testing and our sample sizes were sufficient for that goal. The sample sizes in our usability studies were consistent with recommendations for formative usability studies, which identify a sample of five participants as sufficient to identify 80 % of usability problems (Nielsen & Molich, 1990).In addition, our approach produced evidence that the results would generalize to the target population of users. For example, key findings replicated across three studies, including Study 2, which used a more representative platform (smartphone) and measures (navigating among the set of visualizations).

### 5.4. Limitations and future directions

The present research approach served our objective of identifying usability problems for older adults that could be rectified in design iterations. However, the small sample sizes reduce the generalizability. The participants were predominantly highly educated, female, and white and a more diverse sample might experience more or different usability challenges. Moreover, our design evaluations did not specifically consider the needs of color-blind individuals. Strategies such as redundantly coding information (e.g., shape, color) may address this limitation. To generalize the findings, it is important to test the visualizations with larger samples that are more diverse in terms of race/ ethnicity, gender, education, and perceptual-cognitive function.

The contrast ratio between the white number on yellow background in the Monthly Medication Calendar Visualization might be insufficient if it is used for other purposes, although participants in all the usability studies had no problem of selecting yellow dates from the calendar to complete tasks and none of them complained the legibility of the calendar. Future research could consider using black number on yellow background to increase contrast ratio and improve legibility.

We did not implement participants' suggestion of using green, yellow, and red ring/bar segments to indicate good, moderate, and poor adherence levels, because we found inconsistency of the cutoff distinguishing the adherence levels and none of them was clinically standardized (e.g., 0.8 vs. 0.9 was classified as adherent; Esposti et al., 2011; Matsumura et al., 2013; Schulz et al., 2016). Future research should synthesize current adherence literature and unify the standard to provide guidance for researchers.

Our design decisions were based on measures of comprehension, motivation, and preferences. Experimental studies with objective measures such as behavioral data (medication adherence) would be beneficial to evaluate the effectiveness of the adherence feedback visualizations. Moreover, our findings raised some display design issues that should be more thoroughly addressed in future research, such as trade-offs among principles used to develop the visualizations. For example, the timeline format helped increase the familiarity of the Daily Summary by explicitly linking medication taking times to daily events, but it also increased display clutter compared to the box format. Also, the traffic light color scheme was used in the Daily Summary and the Monthly Summary because of it is a population stereotype that is familiar to users. However, traffic colors were not used in the Weekly Summary (because the literature does not specify target adherence levels corresponding to yellow and red colors in the display), contrary to the consistency principle. Converging evidence from the usability studies and the subject matter experts helped us reconcile these tradeoffs, but future work should more comprehensively address design trade-offs related to developing visualizations.

### 5.5. Implications for designing effective adherence feedback visualizations

Our project has implications for how to design and evaluate visualizations for older adults in the context of using apps to manage self-care. These implications are important given the ubiquity of smartphone apps on the one hand, and the paucity of evidence for their effectiveness on the other. First, we illustrated the importance of using a mixed-methods evaluation approach to provide converging evidence related to the usability and usefulness of the visualizations that supports design decisions.

Second, we described the importance of implementing principles from existing theories and scientific evidence and conducting usability assessments before investing time and resources in a large study evaluating the effect of an adherence application on behavior change and healthcare outcomes. Our findings will hopefully increase the chances of successful implementation, acceptability, and sustained use over time by target users.

Third, the project suggests the value of a multi-disciplinary team that brings diverse perspectives and complementary insights to help interpret the study findings and ensure the visualizations are both relevant to older adults' adherence challenges and could be implemented in smartphones. Our approach to evaluating the visualizations and other components of the MEDSReM system helps ensure that the intervention is evaluated from a systems perspective.

Fourth, our MEDSReM system is a starting point for a broader systems perspective that may increase the potential impact of the intervention. The system could be expanded to support patient/provider collaborative management of medications by sharing adherence data with providers through patient portals to Electronic Record Systems. This would be especially valuable if providers could visualize adherence to the same medications by all the patients in their practice (Schneiderman et al., 2013).

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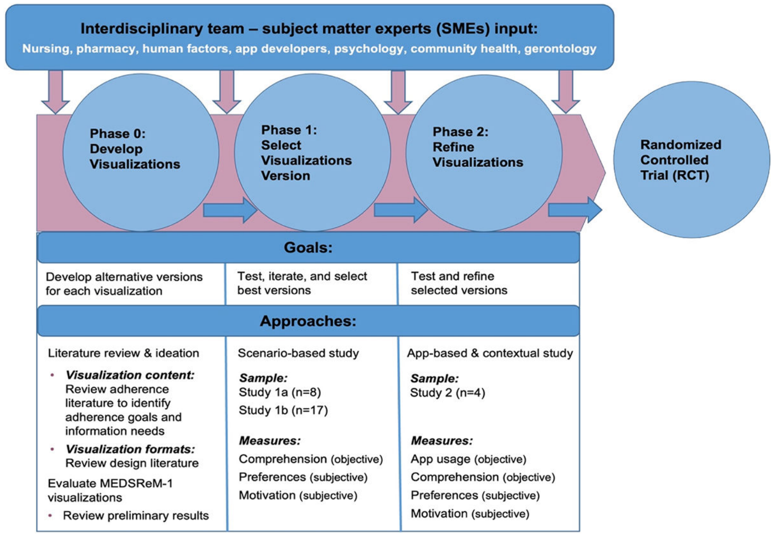


**Fig. 1.**

Feedback visualization development process.

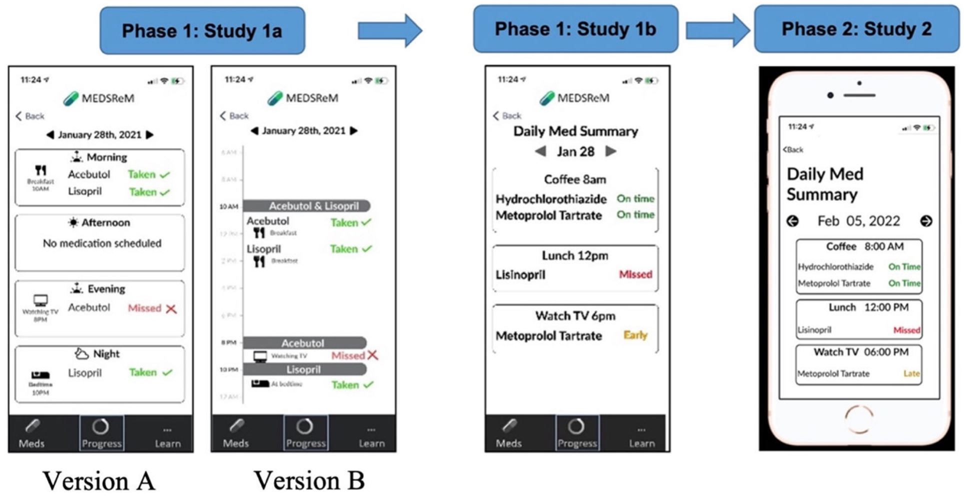


**Fig. 2.**
Daily medication summary visualizations evaluated in each study.

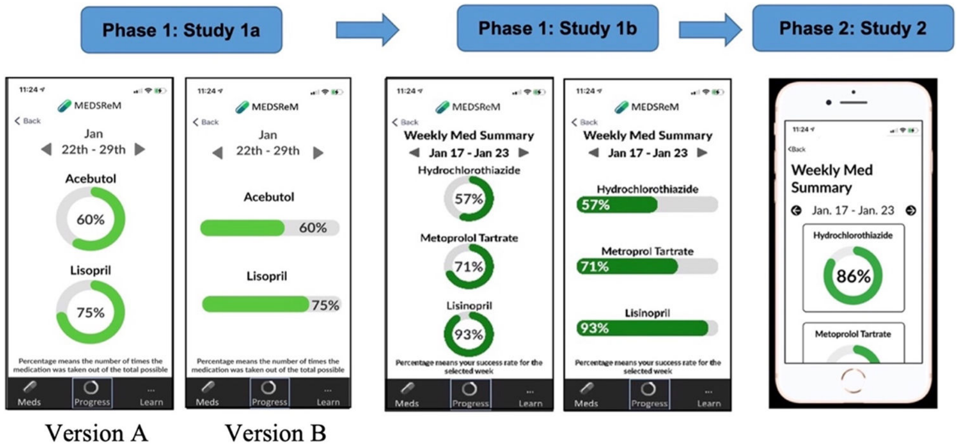


**Fig. 3.**
Weekly medication summary visualizations evaluated in each study.


**Fig. 4.**
Monthly medication calendar visualizations evaluated in each study.

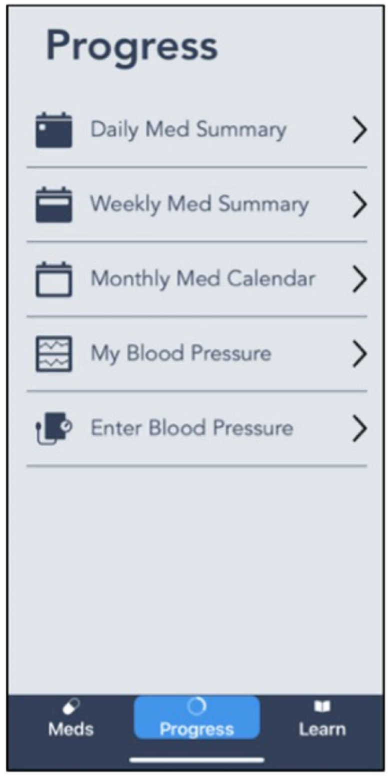


**Fig. 5.**
Navigation page.

**Table 1**

Demographic characteristics for study participants.

| **Demographic characteristics** | **Study 1a (*N* = 8)** | **Study 1b (*N* = 17)** | **Study 2 (*N* = 4)** |
|---|---|---|---|
| Age (Mean, Range) | 69.5 (64–76) | 65.6 (60–74) | 70.2 (65–76) |
| Gender | | | |
| Female | 5 | 13 | 4 |
| Male | 3 | 4 | 0 |
| Education | | | |
| High school | 0 | 1 | 1 |
| Some college/Associate’s degree | 0 | 1 | 0 |
| Bachelor’s degree | 1 | 7 | 1 |
| Master’s degree | 3 | 2 | 2 |
| Doctoral degree | 4 | 6 | 0 |
| Race | | | |
| Asian | 0 | 2 | 0 |
| Black/African American | 0 | 1 | 0 |
| White/Caucasian | 8 | 14 | 4 |
| Health status | | | |
| Fair | 2 | 0 | 0 |
| Good | 2 | 8 | 2 |
| Very good | 4 | 7 | 1 |
| Excellent | 0 | 2 | 1 |
| Number of prescription medication taken per day | 5.38 (1–14) | 2.8 (0–5) | 2.5 (0–5) |

**Table 2**

Interview questions.

| |
|---|
| Daily Medication Summary-Comprehension questions |
| Which medication was not taken at the right time? |
| What does the color red/yellow/green mean? |
| Weekly Medication Summary-Comprehension questions |
| Can you tell me what the 57 % means? |
| Which medication was taken least/most often? |
| Which medication was taken least/most often? |
| If you take your medications better, how will the rings/circles change? |
| Monthly Medication Calendar-Comprehension questions |
| What does the color red/yellow/green mean? |
| Please tell me how you did on Jan 7th? |
| Did you take your medications better for week 1 or week 2? Week 1 is from Jan 3rd to Jan 9th, week 2 is from Jan 10th to Jan 16th. |
| Did you do better during the weekdays or the weekend days? |
| Like/dislike questions |
| What do you like and dislike about this image? |
| Is there anything on this page you think is confusing or unnecessary? |
| Do you have other comments or ideas about the images that help you to take your medications? |
| Weekly Medication Summary-Ring & bar comparison questions |
| Which version do you think is easier to understand? Why? |
| Which version makes it easier for you to see which medication you take better? Why? |
| Which version do you think would encourage you to take your all your medications better? Why? |
| Which version do you like better? Why? |
| Monthly Medication Calendar-With and without streaks comparison questions |
| Which version is easier to understand? Why? |
| Do you think the streaks make the calendar easier to understand? Why? |
| Do you think the streaks encourage you to do better? Why? |
| Which version do you like better? Why? |