OPTIMIZING PATIENT COMPREHENSION OF INFORMATION VISUALIZATIONS FOR MEDICATION ADHERENCE AND BLOOD PRESSURE

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ABSTRACT

Adam J. Sage: Optimizing Patient Comprehension of Information Visualizations for Medication Adherence and Blood Pressure
(Under the direction of Delesha M. Carpenter)

Introduction: This dissertation focused on designing hypertension self-management visualizations that facilitate patient comprehension of blood pressure and medication adherence information. The objectives of this research were to: 1) assess patient preferences and understanding of visualization features; 2) assess whether condensing the display of blood pressure and medication adherence information into a single visualization improves patient comprehension of the inferred relationship between medication adherence and blood pressure control (compared to separate visualizations); 3) assess whether health literacy moderates the effect of condensed visualizations on comprehension; and 4) assess the validity and reliability of a newly developed hypertension-related visualization comprehension scale.

Methods: Patients with hypertension (n=6) participated in user assessments to understand preferences for visualization features. Another sample of patients with hypertension (n=6) participated in cognitive interviews that assessed understanding of visualizations that incorporated patient preferences. A survey experiment with patients with hypertension (n=137) then assessed whether condensed visualizations improved comprehension of blood pressure and medication adherence information. Multiple regression analysis was used to assess the main effect of visualization type (condensed versus separate display) on comprehension, and the moderating effect of health literacy on comprehension. Exploratory and confirmatory factor analysis were used to assess the validity and reliability of the comprehension scale.

Results: Patients preferred visualizations with blue/orange color-coded culturally recognizable symbols to show medication adherence, and the use of labeled blood pressure data points, horizontal reference lines, and a shaded "normal" blood pressure zone. Patients best understood a shaded "normal" blood pressure zone with color-coded symbols to show medication adherence. Condensed visualizations did not significantly improve comprehension, and health literacy did not moderate the relationship between visualization type and comprehension. However, greater health literacy (B=0.61, p=.0001) and hypertension knowledge (B=0.10, p<0.0001) were positively associated with comprehension. Exploratory and confirmatory factor analyses supported a unidimensional 4-item solution for the comprehension scale.

Conclusion: This study is an important step in developing useful and useable data visualizations for self-managing HTN. Condensed-display visualizations did not improve patient comprehension of BP and medication adherence information. Future research should further investigate how to design visualizations that improve comprehension, specifically for patients with low health literacy.

To my parents, Clifford and LuAnn Sage.
To my brother and best friend, Rusty Sage.

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LIST OF ABBREVIATIONS AND SYMBOLS

α	Intercept
β	Parameter estimate
BIC	Bayesian Information Criterion
BP	Blood pressure
CFA	Confirmatory Factor Analysis
DBP	Diastolic blood pressure
$\boldsymbol{\varepsilon}$	Error
Σ	Covariance matrix
EFA	Exploratory Factor Analysis
HIT	Human Intelligence Task
HLSI-SF	Health Literacy Survey Instrument Short Form
HTN	Hypertension
IFI	Incremental Fit Index
Λ	Factor loading
Mturk	Mechanical Turk
REALM	Rapid Estimate of Adult Literacy in Medicine
RMSEA	Root Mean Square Error of Approximation
RNI	Relative Non-centrality Index
SDP	Systolic blood pressure
TLI	Tucker-Lewis Index
χ^2	Chi-square statistic
VIF	Variance inflation factor
VSTM	Visual short-term memory

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Hypertension (HTN) is a chronic condition characterized by elevated blood pressure (BP), which over time can cause other issues such as coronary artery disease and even potentially deadly acute conditions such as heart attack and stroke. Hypertension affects nearly half (46%) of adults in the U.S. and is associated with $46 billion in health care costs, medication costs, and missed days of work.[1,2] What makes HTN particularly dangerous, and why it is referred to as a “silent killer,” is that patients often overlook symptoms of high BP or are asymptomatic, which makes self-monitoring (personal tracking of one’s own BP levels) of BP essential to management of disease.

Medication non-adherence among patients with HTN is important because it has direct negative impacts on health outcomes, increases mortality, and contributes to $290 billion in costs to the U.S. health care system each year.[3] It is estimated that approximately 45% of patients prescribed at least one anti-hypertensive medication discontinue their medication within a year of initial prescription.[4] There are numerous determinants of non-adherence among patients with HTN, including age,[5–7] race,[6,8] health literacy,[8–10] knowledge about their condition,[11,12] a history of prior prescriptions for HTN,[7] knowledge about the prescribed treatment (e.g., the duration of treatment, the reason for the medication),[11] and length of diagnosis.[5,11]

Having more HTN knowledge is significantly associated with increased medication adherence, and understanding the effects of one's treatment is an important component of HTN knowledge.[11,13,14] Knowledge about health conditions (i.e., HTN knowledge) likely influences outcome expectations (i.e., the belief that a behavior will lead to a particular outcome) as well as one's characterization of observations about their disease. Several existing health behavior theories can help understand the likely causal mechanism linking HTN knowledge to medication adherence. For instance, the Health Belief Model posits that both perceived severity of an illness and perceived benefits of a treatment improve medication adherence,[15] and these relationships have been shown among patients with HTN.[16,17] Similarly, within Social Cognitive Theory,[18] self-regulation of chronic disease relies on a process where outcome expectations are influenced by the self-observations and self-judgments that one makes during the course of disease self-management.[19] Information and knowledge gained by self-monitoring likely influence outcome expectations. With many current technology-based self-monitoring tools, such as mobile apps and web-based patient portals, such information allows individuals to see how outcomes are tied to behaviors (e.g., medication adherence influencing BP control), which facilitates self-observation. These visual pieces of information are often communicated using data visualizations.

Tufte defines visualizations as visual displays of "measured quantities by use of points, lines, a coordinate system, numbers, symbols, words, shading, and color."[20] In other words, data visualizations are abstract representations of numbers, variables, and relationships between numbers and/or variables. Data visualizations are tools we use to make better sense of complex information in ways that harness our visuospatial sense. For HTN self-monitoring, disease information can be conveyed using data visualizations that display medication adherence and BP information. It follows that visualizations displaying medication adherence and BP information could influence HTN patients' knowledge levels and outcomes.

Mobile applications (apps) to self-monitor HTN and medication adherence are increasingly accessible. The most recent estimates indicate that 77% of U.S. adults own a smartphone.[21] Furthermore, among patients with HTN, mobile self-monitoring of BP and medication adherence have been shown to improve BP control.[22–25] Several apps are now available for HTN and medication adherence self-monitoring; approximately 18% provide visual feedback.[26]

Information visualizations within apps are often intended to convey data back to the patient, which is an important aspect of self-monitoring. However, patient comprehension of information visualizations may be suboptimal since over a third of adults lack sufficient health literacy to perform common tasks such as following prescription drug label directions or making simple calculations from a chart.[51] In addition, visual short-term memory or one's capacity to store visualized information then recall it seconds or minutes later, can limit patients' ability to interpret visualizations of health data. Evidence indicates the volume of information presented to patients affects health-related decision-making in that highlighting important information and removing less important information reduces cognitive load, resulting in improved health-related decision-making.[27] However, it is currently unknown how the visual presentation of such information (e.g., types of data visualizations) affects health behaviors, particularly HTN patients' ability to interpret, understand, and respond to BP and medication adherence feedback.

1.2 Study Aims

This dissertation addresses an important gap in the health behavior, medication adherence, and information visualization literature by examining how to optimally display medication adherence and BP information in data visualizations to promote patient comprehension of the information. This project has three specific aims:

Specific Aim 1: To assess: a) patient preferences for data visualizations that display medication adherence and BP data and to document how patients would use visualizations to self-monitor their HTN, b) patient preferences for visualizations that condense the display of BP and adherence information, and c) patient understanding of key features of visualizations that display BP and adherence information.

Specific Aim 2: To conduct a randomized experiment to assess whether visualizations that condense the display of information improve patient comprehension of BP and adherence data and evaluate whether health literacy moderates the relationship between visualization type and patient comprehension.

Specific Aim 3: To assess the validity and reliability of a newly-developed 6-item scale to assess patient comprehension of data visualizations.

In order to achieve these aims, I first conducted user assessment interviews with HTN patients to elicit overall preferences related to visualizations for BP and medication adherence information. Results from these interviews were used to inform the design of visualizations used in the subsequent cognitive interviews and survey experiment portions of this study. I then conducted cognitive interviews that assessed patient understanding of key features of three visualizations that condensed the display of BP and medication adherence information. The best performing condensed visualization from the cognitive interviews was used as the treatment group visualization design for the subsequent survey experiment. As part of the cognitive interviews, I also assessed the reliability, face validity, and construct validity of a new 6-item scale I developed to assess comprehension of medication adherence and BP information visualizations. Finally, I conducted a randomized experiment to test whether information visualizations that condense the display of BP and medication adherence information improve patient comprehension in comparison to separate visualizations for displaying BP and medication adherence information. Data was analyzed using SAS Version 9.4, and R Lavaan structural equation modeling package.

1.3 Organization of the Dissertation

This dissertation comprises nine chapters. The second chapter provides a review of the literature and describes the background and significance for this study. The third chapter presents the study's three specific aims and the accompanying research questions and relevant hypotheses. The fourth chapter provides an overview of the methods that used to complete Aims 1 through 3, which included user assessment interviews, cognitive interviews, a randomized experiment, and factor analysis. The results of Aims 1 through 3 are summarized in three separate manuscripts (Chapters 5 through 7) and a chapter dedicated to describing the validation procedure for the comprehension scale (Chapter 8). Chapter 5 (Manuscript #1) presents the results of the Aim 1 user assessment interviews, Chapter 6 (Manuscript #2) summarizes the results of cognitive interviews related to information visualizations, and Chapter 7 (Manuscript #3) reports the results of the randomized experiment. Detailed validity and reliability data for the 6-item comprehension scale validity assessment are presented in Chapter 8. Additional data analyses not included in the manuscripts are included in Chapter 8 as well. The last chapter (Chapter 9) is a discussion of the overall results and directions for future research. Lastly, the appendices include all study materials, including user assessment and cognitive interview protocols, the web-survey instrument, and all visualizations used in this project.

CHAPTER 2: BACKGROUND AND SIGNIFICANCE

2.1 Introduction

In this chapter, I begin by providing background information on hypertension (HTN), including its prevalence and the characteristics of people with hypertension, the risks of hypertension, and the behaviors associated with developing and managing hypertension. I then discuss three models of health behavior (the Health Belief Model, Social Cognitive Theory and a model of self-regulation for control of chronic diseases, and the Theory of Planned Behavior), and how knowledge obtained via HTN self-management influences certain key constructs of these models. I then provide a review of medication adherence and the factors associated with medication adherence among people with hypertension. One important factor of hypertension medication adherence and self-monitoring related to the current study is health literacy and numeracy, which I review in detail.

Because this dissertation focuses on the ability of hypertension patients to comprehend information visualizations related to BP and medication adherence, I next review the literature on visual short-term memory and cognitive capacity for comprehending visual information. I then discuss mobile health and wearable technologies for self-managing BP and medication adherence, as well as best practices for designing information visualizations and whether these are adhered to in current publicly available mobile apps for BP and medication adherence monitoring. Finally, I provide a synthesis whereby I propose a conceptual model to demonstrate how information visualization designs can influence theoretical pathways of self-regulation for patients using mobile and wearable technologies to self-monitor their BP and medication adherence.

2.2 Hypertension

Surveillance definitions of hypertension (HTN) or high blood pressure vary, however, prior to the release of new HTN guidelines by the American Heart Association in November 2017[28] accepted standard definitions of HTN included: 1) systolic blood pressure (SBP) ≥ 140 mmHg or diastolic blood pressure (DBP) ≥ 90 mmHg,[29] 2) taking any antihypertensive medication, or 3) being told by a physician or other health professional that one has HTN on at least two occasions.[1,30] According to accepted standard definitions for HTN prior to the release of the new guidelines, HTN affects approximately 75 million (32%) adults over 20 years of age in the U.S., and disproportionally affects older (≥ 65 years of age) women (57%) more than older men (54%),[31] and Blacks (42.1%) more than non-Hispanic Whites (28%) and Hispanics (24.7%).[32] According to new HTN guidelines, 46% of adults over 20 years of age in the U.S. have HTN.[28]

In 2011, the annual cost of HTN to the U.S. healthcare system was over $46 billion, and projections indicate these costs could climb to $274 billion by 2030.[29] Hypertension also contributed to over 360,000 deaths in the U.S. in 2013, many of which are a result of a heart attack, stroke, heart failure, or kidney disease.[29] Many of these deaths, however, are avoidable, as common risk factors for HTN are linked to health-related behaviors, including non-adherence to antihypertensive medications, inadequate self-monitoring of BP, poor diet, tobacco use, and lack of exercise.[29] Other individual factors including socioeconomic status,[29] body weight,[29] race,[32] ethnicity,[32] age,[32] and sex are also linked to a higher risk of HTN.[29] For those diagnosed with HTN, altering lifestyle behaviors makes it a manageable condition. Unfortunately, only about half (54%) of people with HTN have their condition under control.[29] Two major contributing factors to wide-spread uncontrolled HTN is lack of adherence to antihypertensive medication and insufficient monitoring of one's condition.[29] In fact, one study has shown that approximately half (45%) of patients with hypertension stop taking their medication within the first year.[33]

Among hypertensive adults in the U.S., 77.3% use at least one antihypertensive drug, and 47.7% use 2 or more antihypertensive drugs (i.e., polytherapy) to treat their condition.[34] Overall, 35.8% of adults with HTN use diuretics (90.8% of which are used in polytherapy), 27.6% use thiazide diuretics (90.9% of which are used in polytherapy), 31.9% use β-blockers (81.2% of which are used in polytherapy), 20.9% use calcium channel blockers (82.2% of which are used in polytherapy), 33.3% use angiotensin-converting enzyme inhibitors (67.0% of which are used in polytherapy), and 22.2% use angiotensin receptor blockers (72.5% of which are used in polytherapy).[34]

2.2.1 Hypertension Self-Management

Self-management of HTN, including self-monitoring of BP and medication adherence, can lead to improved BP levels.[22–25] Despite the evidence, self-monitoring is underutilized by patients with HTN.[35] In a 2012 survey of 559 patients with HTN, just over half (54%) reported using a home BP monitor.[36]

2.2.1.1 Physicians and Hypertension Self-Management

Physicians play a key role in encouraging patients to self-monitor their BP, and reviews have found that interventions involving physicians (e.g., through physician-led patient education or recommendations to self-monitor HTN) when combined with self-management interventions lead to improved BP control.[25,37] However, in a 2008 survey of 5 patients with HTN, just 35% of those patients recalled a doctor ever recommending the use of a home BP monitor.[35]

2.2.1.2 Technology and Hypertension Self-Management

The use of technology in self-management of HTN has also been shown to improve BP control.[38] In a 2016 review of seven digital technology-based interventions to promote HTN self-management, five studies used various self-monitoring technologies, including a website (one study), a mobile phone (three studies), and contact via telephone (one study).[38] In another review of 12 technology-based HTN self-management interventions in primary care settings, four interventions used the Internet for telemonitoring, three used a telephone, one used a kiosk, and one used an online patient portal and personal health record.[37] When comparing interventions incorporating self-monitoring to no self-monitoring, there was a significant effect of self-monitoring on improving diastolic BP, but not systolic BP.[38] However, these results should be interpreted with caution as they are based on findings from just seven studies. Other effective patient-focused intervention techniques to improve self-management of HTN have included patient education, counseling, and appointment reminders.[25] Unfortunately, many technology-based interventions are not based on theories of behavior change, which could limit their effectiveness at causing long-term meaningful change in BP monitoring and patient clinical outcomes.

2.3 Medication Adherence

Medication non-adherence is important because it has direct negative impacts on health outcomes, increases mortality, and contributes to $290 billion in costs to the U.S. healthcare system each year.[3] Although average adherence to treatments (medication and otherwise) for cardiovascular diseases averages 76.6%,[39] estimates of medication adherence among patients with hypertension is still low. Among patients with HTN, 43% to 65.5% of are non-adherent to their medication.[40,41] Such medication non-adherence among patients with hypertension contributes to over $46 billion in avoidable HTN-related healthcare costs annually.[29]

There are numerous determinants of non-adherence that span all levels of a social ecological framework, ranging from intra-personal factors to institutional and policy-level factors.[42] The World Health Organization (WHO) categorizes medication non-adherence into five dimensions: 1) patient-related factors (e.g., patient health literacy, self-efficacy, treatment outcome expectations), 2) condition-related factors (e.g., severity of symptoms, priority among comorbidities), 3) therapy-related factors (e.g., previous treatment failures, side effects), 4) social and economic factors (e.g., cost of medication, lack of social support, socio-economic status), and 5) health system and healthcare team factors (e.g., patient-provider communication, lack of knowledge and training of healthcare providers).[42] Studies have suggested all five of these dimensions are determinants of non-adherence among patients with hypertension.[4,8,9,11,12,33,43–48] Table 2.1 summarizes these dimensions and studies that have shown their influence on medication adherence among patients with HTN. I will now describe these studies in greater detail.

2.3.1 Patient-related Factors

Patient-related factors that influence medication adherence include characteristics of the patient. Patient-related factors associated with poor medication adherence among patients with hypertension include age (being younger),[5–7,48] gender (male),[48] race (non-White),[6,8,48] higher body mass index (BMI),[6,48] having comorbities,[7,48] having a mental illness,[48] substance abuse,[48] less perceived control over their condition,[44] lower health literacy,[8–10] less knowledge about their condition,[11,12] a history of previous treatments for HTN (fewer previous treatments),[7] and less knowledge about the prescribed treatment (e.g., the duration of treatment, the reason for the medication),[11] and more emergency room and hospital visits.[48] Medication discontinuation is also associated with a patient's ability to accurately and consistently adhere to a prescribed regimen on a daily basis.[33]

2.3.2 Condition-related Factors

Condition-related factors that can impact medication adherence include the severity of one's symptoms and perceived importance of addressing such symptoms. The duration of HTN diagnosis is associated with adherence,[34] and having HTN for five or more years has been associated with greater adherence.[11]

2.3.3 Therapy-related Factors

Therapy-related factors associated with medication adherence include the side effects of certain medications or previous treatment failures, which can be a result of the specific medication. Evidence suggests that more complex medication regimens are associated with poorer medication adherence among patients with hypertension.[4,5,8] Differences in adherence to antihypertensive medication has also been shown between types of medications (e.g., calcium channel blocker versus angiotensin-converting enzyme inhibitor),[45,46] which suggests that for some patients, adherence could be influenced by unique factors associated with a medication (e.g., side effects, cost, dosing frequency, and polytherapy). Unfortunately, these studies only assessed differences in types of medication, and not other factors that may have influenced adherence, such as cost, side effects, or dosing frequency.

2.3.4 Social and Economic Factors

Social and economic factors that influence medication adherence including factors such as socioeconomic status (e.g., income, education), social environment (e.g., support from family and friends), physical environment (e.g., geographic proximity to healthcare facilities and resources), culture and beliefs about illnesses and healthcare, and financial access to healthcare. More social support[5,9] and higher household[5] income have also been shown to increase adherence to anti-hypertensive medications. More specifically, a meta-analysis of 32 peer-reviewed articles found functional social support, such as emotional, instrumental, and informative support is associated with better medication adherence among patients with HTN.[47] Culturally-driven beliefs about treatments have also been shown to influence medication adherence among patients with HTN.[9] It is important to note that there are no known studies that have linked an underlying latent construct of socioeconomic status (i.e., using factor analysis) to poor adherence; however, income (a component of socioeconomic status constructs) has been linked to poor adherence.[5] Poor adherence among individuals with more complex medication regimens could also be explained in part by the economic burden of prescription drug costs, and research has shown that increased copayments for lipid-lowering medication lowers adherence significantly more for patients with a higher cost burden (e.g., paying copayments for all drugs, some drugs, with a payment cap, or no copayment).[49]

2.3.5 Health System and Healthcare Factors

Healthcare providers and the broader health delivery system have been identified as important factors in medication adherence by the WHO.[42] These factors are often assessed through associations between clinicians' interactions with patients and health behaviors (i.e., medication adherence). In a 2010 Cochrane review of interventions used for improving BP control among patients with hypertension, four studies were identified that involved clinician involvement in patient education or monitoring and resulted in improved medication adherence.[25] In addition, a 2015 study was able to show improved adherence to antihypertensive and lipid-lowering agents as a result of a multi-faceted pharmacist-led intervention consisting of collaborative care, medication review, and tailored adherence counseling with motivational interviewing and telephone follow-ups.[43] Results indicated significantly less non-adherence among patients in the intervention group (n = 231, 20.3%) compared to the control group (n = 285, 30.2%).[43]

Table 2.1 Determinants of medication adherence among patients with HTN

Citation	**WHO Adherence-related Factor(s)**	**Specific Factor(s)**	**Study Population (n)**	**Study Design**
Vrijens et al (2008)[33]	Patient-related	Ability to adhere daily (effect on medication discontinuation)	HTN Patients (n=4783)	Retrospective Cohort
Patel & Taylor (2002)[44]	Patient-related	Perceived Control of HTN	HTN Patients (n=240)	Cross-sectional
Bailey et al (2012)[48]	Patient-related	Gender, Age, Race, Obesity, Mental Illness, Substance Abuse, Comorbidities, ER and Hospital Visits	Medicaid HTN Patients (n=49,479)	Cross-sectional
Malik et al (2014)[12]	Patient-related	HTN Knowledge	HTN Patients (n=209)	Cross-sectional
Krousel-wood et al (2009)[6]	Patient-related	Age/Race/BMI	HTN Patients (n=2,087)	Cross-sectional
Briesacher et al (2008)[7]	Patient-related	Age, Comorbidities, History of trying other drugs to treat HTN	HTN Patients (n=457,395)	Retrospective Cohort
Karaeren et al (2009)[11]	Patient, Condition-related	HTN Knowledge, Length of Diagnosis	HTN Patients (n=220)	Cross-sectional
Ma (2016)[5]	Patient-related, Condition-related, Therapy-related, Social, and Economic-related	Age/Income, Length of Diagnosis, Pill Regimen Complexity, Social Support	HTN Patients (n=1,159)	Cross-sectional
Wannasirikul et al (2016)[9]	Patient-related, Social, and Economic-related	Health Literacy, Social Support/Beliefs about Treatment	HTN Patients 60 to 70 years old (n=600)	Cross-sectional
Gazmararien (2006)[8]	Patient-related, Therapy-related	Race/Ethnicity, Education/Health Literacy, Pill Regimen Complexity	Patients with coronary heart disease, HTN, diabetes mellitus, and/or hyperlipidemia (n=1,549)	Cross-sectional
Wogen et al (2003)[45]	Therapy-related	Type of Medication	HTN Patients (n=142,945)	Retrospective Cohort
Xie et al (2014)[4]	Therapy-related	Pill Regimen Complexity	HTN Patients (n=17,465)	Retrospective Cohort
Magrin et al (2014)[47]	Social and Economic-related	Social Support	Social support and medication adherence literature (n=32 journal articles)	Meta-analysis
Hedegaard et al (2015)[43]	Health System and Healthcare	Healthcare (Pharmacist-led motivational interviewing)	HTN Patients (n=532)	RCT (Intervention)

2.4 Theories of Health Behavior

To understand how improving comprehension of medication adherence and BP information may lead to improved outcomes (e.g., improved medication adherence or BP control), it is important to understand how comprehension, or the knowledge gained by facilitating comprehension, are related to factors known to influence health behaviors. I have identified two theories of health behavior where comprehension of medication adherence and BP information could play an important role in influencing medication adherence: the Health Belief Model and the process of self-regulation within Social Cognitive Theory.

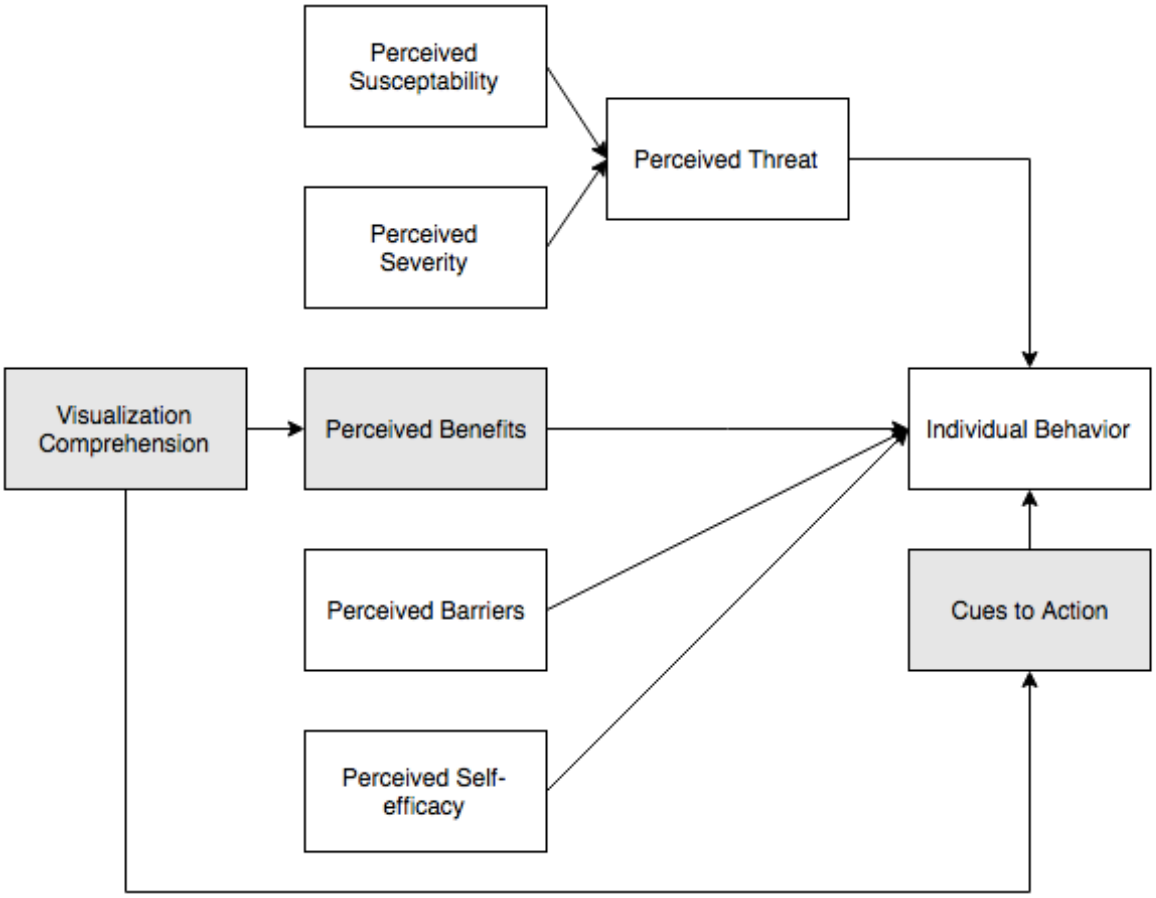
2.4.1 Health Belief Model

The Health Belief Model (HBM) posits that certain personal perceptions and cues to action influence individual behaviors, including disease self-management behaviors.[15] According to the HBM, the personal perceptions that influence behaviors are: 1) perceived susceptibility, or beliefs about one's vulnerability to a disease or condition, 2) perceived severity, or beliefs about the seriousness and consequences of a disease or condition, 3) perceived benefits, or beliefs about the value (personal or otherwise) of behaving in a way that reduces the perceived threat of a disease or condition, 4) perceived barriers, or beliefs about the impediments to performing a particular health behavior, and 5) perceived self-efficacy or the belief that one is able to successfully perform a particular health behavior and produce desired results. Perceptions of susceptibility and severity influence a broader construct of perceived threat, which in turn influences behaviors. In addition, cues to action, or personal and environmental stimuli that trigger behaviors, are said to influence individual behaviors according to the HBM.

Perceptions of the benefits of performing a behavior (e.g., taking medication) are shaped by one's understanding of HTN and the behaviors that can influence HTN outcomes. Visualizations of medication adherence and BP information attempt to enhance understanding about the benefits of adherence depicting the correlation between adherence and BP control (i.e., high adherence leads to controlled BP). Data visualizations can also serve as cues to action by providing information about missed doses of medication. This hypothesized relationship is shown in Figure 2.1.

Research has linked constructs of the HBM to medication adherence among patients with HTN.[16,17] In one cross-sectional study of 671 rural-dwelling Iranians with hypertension, individuals with high levels of perceived susceptibility, severity, and benefits had better medication adherence than those with low to moderate perceived susceptibility, severity, and benefits.[16] In another cross-sectional study of 232 Chinese hypertensive patients, higher perceived susceptibility, cues to action, and self-efficacy, and lower perceived barriers were associated with better medication adherence.[17] In addition, while not explicitly measured as perceived severity or perceived benefits, one study of 514 HTN patients showed that patients who believed in the necessity of a medication were more likely to be compliant.[50]

Figure 2.1 Hypothesized influence of visualization comprehension on concepts of the Health Belief Model*



*Gray boxes indicate theoretical constructs that could be affected by visualization comprehension.

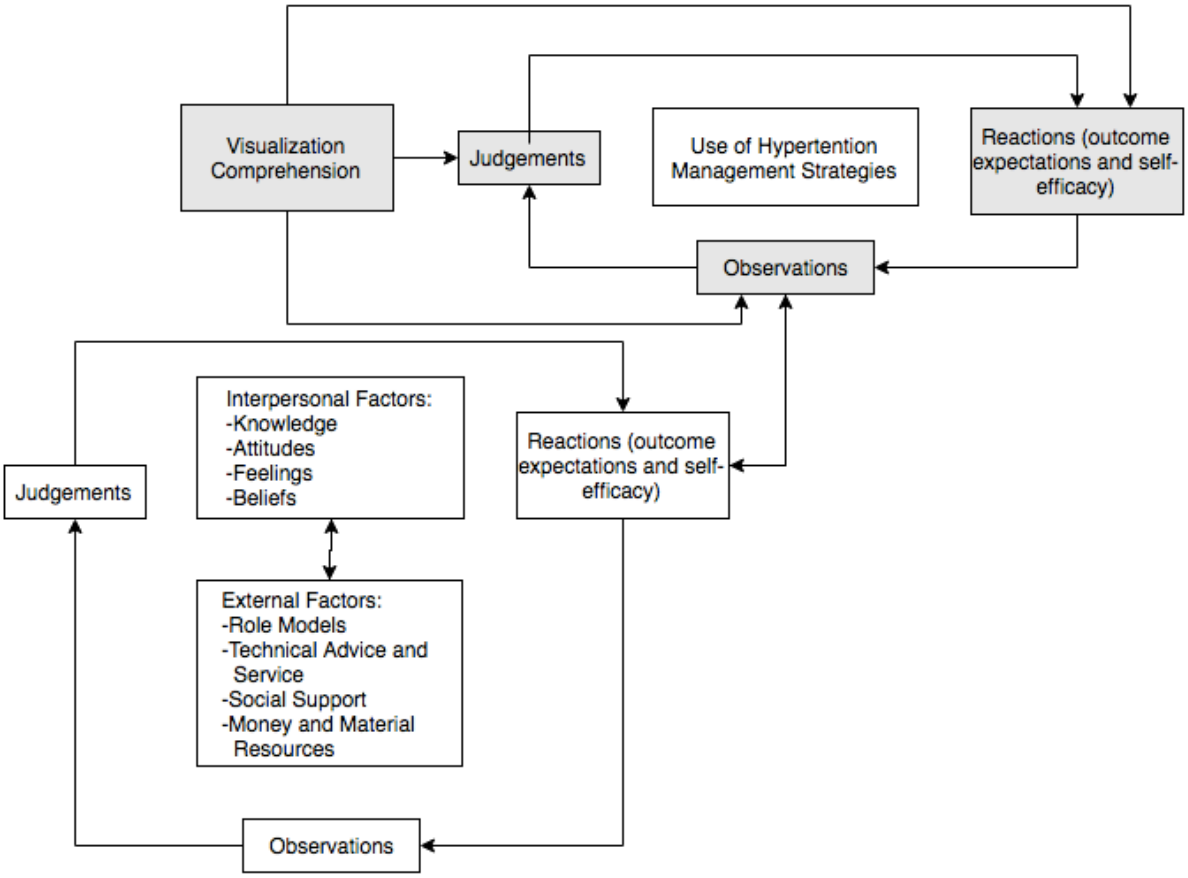
2.4.2 Social Cognitive Theory

Social Cognitive Theory (SCT) posits that people interact with their environments in a reciprocal manner, or that people both influence and are influenced by their environments.[18] Several variables affect the interaction between individuals or groups and their environments, including: 1) outcome expectations, or beliefs about the consequences of behavior choices, 2) self-efficacy or the extent to which one believes one has the ability to perform specific behaviors, 3) observational learning or learning from or modeling new behaviors of others, 4) incentive motivation or the use of rewards or punishments to influence behavior, 5) facilitation, or the use of resources to make behaviors easier to perform, and 6) self-regulation or one's ability to influence one's behavior through self-monitoring, goal-setting, feedback, self-reward, and self-instruction.

As it relates to the comprehension of visualizations of medication adherence and BP information, understanding such information is an important component of outcome expectations and self-regulation. Understanding how behaviors influence outcomes (e.g., adhering to medication improves BP control) can affect what outcomes one can expect from a behavior. Thus, improving one's understanding of a visualization that displays the correlation between adhering to medication and controlling BP can influence patients' expectations of what specific outcomes are associated with a behavior. For example, patients relying on their own physical experiences to determine the effectiveness of a medication might improve their understanding that medication adherence improves BP control when that relationship is visualized in a graph.

Clark and colleagues' model of the self-regulation of chronic diseases, based in SCT,[18] suggests self-regulation of chronic conditions occurs through a process of reciprocal determinism, where outcome expectations (i.e., perceptions about the consequences of a behavior associated with managing one's condition) are made based on judgments (i.e., decisions made about one's illness), which are based on observations (i.e., actively monitoring changes in one's condition).[19] The observations made during this disease self-management process then influence and are also influenced by the outcome expectations produced through a similar reciprocal determinism whereby outcome expectations, observations, and judgments are made in the context of interpersonal and external factors. This hypothesized process is shown in Figure 2.2. Comprehension of medication adherence and BP information visualizations is also an important component of self-regulation in that making accurate observations during self-monitoring of one's condition requires an understanding of the current condition (e.g., BP level) and the factors influencing the condition (e.g., medication adherence).

Figure 2.2 Hypothesized influence of visualization comprehension on concepts of self-regulation of hypertension management behaviors*



*Gray boxes indicate theoretical constructs that could be affected by visualization comprehension.

Components of self-regulation have been used in interventions for chronic health conditions, including obesity, diabetes, heart disease, arthritis, and asthma.[51] In a review of self-monitoring interventions, all 35 interventions provided feedback to patients about their self-monitoring behaviors.[51] Unfortunately, the effectiveness of each intervention on improving health outcomes (e.g., medication adherence or BP) was not assessed. Previous studies have linked SCT to improved medication adherence.[52] In a meta-analysis of SCT-based interventions designed to improve medication adherence, an overall significant effect size (.350, $p<.001$) for improving medication adherence was found among 18 total treatment versus control group comparisons.[52] Studies linking concepts of SCT to HTN self-management are limited, although self-regulating behaviors have been linked to one's understanding of HTN and the factors that influence elevated BP.[53]

Improving comprehension of information visualizations for medication adherence and BP may play an important role in improving medication adherence and BP control. It is likely that several factors shape health behaviors and more distal health outcomes are influenced themselves through improved comprehension. It is reasonable to suspect that improving one's understanding of information about the correlation between medication adherence and blood pressure control leads to improved observations, outcome expectations, and judgments about one's condition (i.e., seeing the consequences of behaviors and adjusting perceptions of future likely outcomes of a behavior), and more accurate perceptions of benefits to treating one's condition (i.e., seeing how medication adherence leads to controlled BP), and cues to action (e.g., seeing when a medication dose was missed).

2.5 Health Literacy

The U.S. Department of Health and Human Services defines health literacy as “the ability to obtain, process, and understand basic health information and services to make appropriate health decisions.”[54] Over a third of adults lack sufficient health literacy to perform common tasks such as understanding prescription drug label directions or making simple calculations from a chart.[54] Some minority groups are disproportionately affected with poor health literacy with 24% of Blacks and 41% of Hispanics having below basic health literacy compared to just 9% of Whites.[54] In addition, age and education are associated with health literacy in that those with less education and the elderly (60 and older) have lower health literacy.[55] However, when accounting for cognitive ability (as measured as verbal working memory or one’s ability to store and manipulate verbal information simultaneously), the association of age and education with health literacy is reduced. This suggests the importance for future hypertension-related health interventions to focus on the cognitive aspects of information comprehension.[55] Several studies have shown an association between health literacy and antihypertensive medication adherence[8–10] and BP control[9,56–60] among patients with hypertension. In addition, evidence suggests that health literacy is a mediating factor between demographic characteristics (e.g., financial status, race, and education) and health information recall (e.g., remembering instructions from a physician, and remembering names of prescribed medications),[61,62] which is important in hypertension self-management.

2.6 Numeracy and Graph Literacy

An individual's ability to interpret health-related information (such as medication adherence and BP information) extends beyond health literacy. Numeracy is a person's ability to comprehend and use numbers. Graph literacy is the ability to process and understand information conveyed in two-dimensional images, often charts, graphs, diagrams, or maps. Both numeracy and graph literacy are important patient characteristics to consider when developing information visualizations intended to help patients manage their hypertension. Patients with high numeracy tend to better understand,[63] remember, and use quantitative information when making health-related decisions, whereas their lower-numerate counterparts tend to rely on non-quantitative information, such as narratives and emotions.[64–66] Furthermore, studies suggest that among older adults, health literacy and numeracy independently affect poor health performance.[67] In addition, graph literacy and numeracy have been shown to be moderately correlated (r=.37),[68] which further supports the notion that patients with high health literacy and low numeracy may be less likely to rely on numeric charts and graphs for managing their hypertension.

2.7 Hypertension Knowledge

In addition to literacy and numeracy, insufficient HTN knowledge, defined as the understanding of the meaning, treatments, seriousness, and management behaviors of HTN, may negatively affect visualization comprehension. Specifically, low HTN knowledge may affect: 1) a patient's ability to comprehend medication adherence and BP information visualizations since familiarity with the content presented in a visualization has been shown to influence their understanding of the visualization,[69] and 2) a patient's ability to make health-related and medication related decisions,[70–73] which is understandable considering health literacy mediates the relationship between education and hypertension knowledge.[74] There are no known studies that have directly linked numeracy and graph literacy to HTN knowledge.

2.8 Assessing Health Literacy

There are several validated scales for assessing health literacy among the general English-speaking adult population.[75–81] However, there are limitations for each assessment that affect the appropriateness of the use of each scale given the context in which it is to be administered (e.g., number of items, timing, administration mode, population in which it was validated, domains assessed). Table 2.2 summarizes important considerations for validated health literacy scales with an administration time of five minutes or less from the Health Literacy Tool Shed.[82]

Table 2.2 Validated health literacy assessments (<5 minutes) (for English-speaking adults ages 18 to 64)

Scale	Domains Assessed	Items	Length (minutes)	Mode(s)
Brief Health Literacy Screener[75]	Information Seeking	3	1.5	Face-to-face
Health Literacy Skills Instrument - Short Form (HLSI-SF)[76]	Numeracy, Information Seeking, Communication, Prose	10	5	Face-to-face, self-administered, online
Medical Term Recognition Test (METER)[77]	Prose	40	2	Face-to-face, Paper and Pencil
Newest Vital Sign (NVS)[78]	Prose, Numeracy	6	3	Face-to-face
Rapid Estimate of Adult Literacy in Medicine (REALM)[79,80]	Prose	125	2.5	Face-to-face, Phone
Single Item Screener (SILS)[81]	Prose	1	1	Face-to-face

2.9 Health Literacy and Visual Short-term Memory

There is no known research that specifically assesses the relationship between literacy and visual-short term memory (i.e., one's ability to store and recall visual information seconds or minutes later). However, health literacy has been shown to be strongly correlated with related cognitive abilities, including working memory, processing speed, and inductive reasoning.[83] It is possible that a link exists between health literacy and visual short-term memory, especially in the context of understanding health information in a graph or chart. If such a link exists, designing information visualizations to reduce demands on visual short-term memory may particularly benefit low health literacy populations.

2.10 Visual Short-term Memory

Tversky and Schiano (1989) first demonstrated that both cognitive and perceptual factors (i.e., how objects are understood to be presented) should be considered in visualization design.[84] In a series of experiments, participants were presented with a visualization of a distribution curve plotted on unlabeled x and y axes, asked to study the visualization for 5 seconds, and then draw the curved line from memory. Participant drawings were rated on a 5-point Likert scale (1= drawing much more asymmetric than the stimulus to 5=very much more symmetric) by three independent raters to provide an objective measure of symmetry. Results indicated that memory skews toward symmetry, suggesting that cognitive limitations exist that distort our recall of visual stimuli. In another set of experiments, Carswell et al (1993) tested the extent to which trend reversals, or points in a line graph where direction of the line reverses, affect ability to recall information about a simple line graph.[85] Results indicated that as the number of trend reversals increased, memory limitations prevented participants from making global assessments about an overall trend, and information recall was limited significantly more to specific localized data points or sets of data points instead.[85] In other words, overall trends of line graphs were more difficult to assess as the number of changes in the direction of the trend line increased, and participants tended to focus on specific points or more local areas of the trend line rather than overall trends as a result. This suggests graphs displaying BP information should limit the number of data points because several trend reversals in BP may decrease one's ability to detect an overall trend.

Visual short-term memory (VSTM) is a subsystem that performs under the general working memory, which is the central executive system that allows for complex tasks (e.g., comprehension, reasoning, and learning) to be completed while keeping other necessary information to complete such tasks in mind.[86] The brain uses VSTM to complete brief tasks requiring the processing of visuospatial information, such as interpreting the meaning of a graph or chart.[87] Experiments in VSTM are often performed by measuring reaction times and accuracy of locating targets, which can be pre-identified (known) or unknown.[88–91] Early investigations into VSTM sought to understand whether VSTM functioned under a general working memory framework, or whether the task of processing visuospatial information is conducted under a specialized visuospatial store where visual information is separate from other information stimuli such as audio.[88]

Logie and colleagues conducted two separate experiments to assess how inserting arithmetic, visual, and verbal secondary tasks within a visuospatial main task influenced visuospatial information recall.[88] Participants were asked to recall verbal or visuospatial information, but were instructed to complete secondary tasks concurrently that were either arithmetic (e.g., calculations), visual (e.g., repeating the movements of a square in a 4x4 matrix), or verbal (e.g., repeating a series of words) in nature. Results indicated support for a specialized visual short-term memory system as the interference, or disruption of memory, caused by interpolated visual secondary tasks, was more prominent among participants completing visual span tasks, and less prominent among participants completing verbal tasks.[88] The converse was found for verbal task and the interference introduced by interpolated verbal and visuospatial secondary tasks. Furthermore, inserted arithmetic secondary tasks also presented a small but significant interference in verbal and visuospatial recall tasks.[88] These findings support earlier assumptions that VSTM functions under a separate visuospatial information-processing store. Support for a separate visuospatial information-processing store is important as it suggests visualization design has implications for performing tasks (e.g., self-monitoring BP and medication adherence) that use visual information. In addition, while the effect is smaller than concurrent visuospatial tasks, concurrent arithmetic tasks limit the functionality of VSTM. This finding is particularly important for visualizations in medication adherence and BP monitoring as concurrent arithmetic and visuospatial information processing tasks are necessary to understand the relationship between changes in medication adherence and possible resultant fluctuations in BP.

Previous research has shown that up to four objects can be reliably stored in VSTM and accurately recalled moments later.[90,92,93] However, in regard to visualizations, this capacity decreases as 1) the number of different features (e.g., lines, colors, shapes) increases, and 2) the amount of information encoded in each feature (e.g., several data points encoded in a line) increases.[94,95] These findings suggest that when designing information visualizations for monitoring medication adherence and BP, the complexity of the visualization should be considered as the user expected to interpret such visualizations will have cognitive limitations in regard to VSTM. Moreover, the organization of objects in a visualization affects the capacity to store the information encoded in those objects in VSTM.[91] In a series of experiments assessing the effects of object configuration (e.g., objects' spatial orientation to one another and grouping of objects with similar characteristics) on VSTM, Jiang et al (2000) demonstrated that changes in the surrounding objects limits recall of information of a predetermined known object (i.e., target). This suggests that relational information (how one object appears relative to another) is an important component of how information about visual objects is stored in VSTM.[91]

Together, these findings regarding the capacity and limitations of VSTM lend themselves to the notion that encoding medication adherence and BP information in two separate visualizations (versus a single visualization) may place undue demands on VSTM when the task at hand is to infer a causal relationship between the information encoded, namely that changes in a behavior (medication adherence) result in changes in a physiological outcome (BP control). In the context of these experiments, demands on VSTM are introduced by interference or probes, which are a stimulus generated to disrupt focus on a visual object(s).[88,91] As Jiang and colleagues demonstrated, interference or probes in the form of configuration changes impaired peoples' abilities to detect an object's visuospatial location, color, and shape.[91] To minimize these demands in the context of visualizations of medication adherence and BP information, the visual configuration of such information should be organized in a manner that streamlines presentation. One approach to streamlining the visual presentation of such information is to condense the information from two separate visualizations into one. In doing so, it can be reasonably hypothesized that comprehension of the information encoded in the visualization will increase because the information is presented in a manner that facilitates information storage and processing.

It is important to note limitations of short-term memory for the recall of numbers. There are limits to the recall of double and triple-digit numbers, especially when the number includes three unique digits (e.g., 777 versus 539).[96] This is particularly relevant as values of BP can take both a simple and more complex form (e.g., 120/80 mmHg versus 136/92 mmHg). While the focus of reducing demands on VSTM is important for design considerations of visualizations for BP information, the added demand of recalling several potentially complex numbers is another consideration. Unfortunately, no known research has examined how VSTM capacity is related to complex numeric information encoded in visual objects.

2.11 Mobile Health and Wearable Technology for Medication Adherence and Hypertension Self-monitoring

In 2018, 77% of adults in the U.S. owned a smartphone.[21] This is in contrast to 35% of adults that owned a smartphone in 2011.[21] Although smartphone adoption is high among all demographics, it is higher among younger, more educated individuals with higher income.[97]

In a 2016 consumer report conducted by Accenture, 21% of U.S. consumers use wearable technology for health tracking and 33% use mobile or tablet apps for health tracking.[98] Furthermore, 77% of U.S. consumers and 85% of physicians agree that using wearable technology helps patients engage in their health.[98] In 2015, a Pew survey found that 62% of smartphone owners use their phone to look up health information.[99] Additionally, in 2016, it was estimated that 27% of U.S. patients with a known heart condition or risk use wearable health tracking devices to monitor their condition.[100] Mobile-based interventions are increasingly capable of addressing barriers to medication non-adherence.[101] Furthermore, among patients with hypertension, mobile self-monitoring of BP and medication adherence have been shown to improve BP control.[102–104] Among the mobile-based BP self-monitoring interventions, technologies for intervention have included the use of personal digital assistants (PDA),[105] smartphone apps,[106] text messages,[107,108] and Bluetooth monitoring devices connecting to smartphones for transmission.[103,109,110] Several BP self-monitoring interventions have also included some form of digital interface for viewing BP results, either directly on the device or through a web portal.[103,105,107–114] In addition, several emerging cutting-edge technologies for self-monitoring HTN are currently being developed and tested, including wireless or Bluetooth-enabled BP cuffs and non-invasive wireless and wearable sensors for measuring BP that are embedded in an ultra-thin adhesive patch.[115,116]

Reviews of mobile apps for medication adherence have shown that a vast majority of existing apps rely of a small set of behavior change techniques such as medication reminders or prompts.[117,118] In a 2016 review of 166 mobile apps for medication adherence, behavior change techniques present in the apps range from 0 to 7 with an average of 2.77.[118] Among the most commonly used techniques were action planning and prompts/cues (e.g., alarms or reminders to take medication) (96%), self-monitoring (e.g., noting missed doses of medication) (37%), and behavior feedback (e.g., graphs or charts that display adherence levels) (36%). Although the techniques used in mobile apps to improve medication adherence are limited, some evidence suggests simple medication reminders improve outcomes for hypertension patients.[102] One study of urban-dwelling hypertension patients prescribed at least 2 antihypertensive medications found medication adherence (measured as proportion of days covered and the Morisky Medication Adherence Scale[119]) and BP control improved following a 3-month use of a medication reminder mobile app.[102]

Mobile apps for medication self-management may also have visual elements that accompany a behavior change technique, such as charts and graphs to track adherence over time. In a 2014 review of 424 mobile applications supporting medication self-management, Bailey et al found that nearly 18% of apps used visual aids.[26] Such visual aids can take several forms, including graphs that chart adherence over time, or photos of pills to help identify a medication. After reviewing the existing literature, it is unclear the extent to which mobile apps for medication adherence rely, at least in part on visual aids to communicate feedback about medication adherence behaviors. However, existing evidence suggests visual aids may not be used commonly.

To further understand how visualizations are used in medication adherence and BP monitoring, I searched both the Apple App and Google Play App stores for medication tracking and BP monitoring apps. I then evaluated the visualizations of the top ten search results (determined by the order in which they appeared in the search results) for both types of apps. Results of this analysis are shown in Table 2.3. The most widely-used mobile apps for “medication tracking” use a dichotomized “yes” or “no” presentation of adherence and often utilize color-codes (e.g., red for non-adherence and green for adherence), symbols (e.g., ☑ versus ☒), a list or calendar view, or percent adherence.

The most widely-used mobile apps for “blood pressure tracking” use two-line graphs to simultaneously chart trends in systolic and diastolic BP over a certain length of time and are color-coded. Color-coding schemes generally use red to indicate high BP, green to indicate well-controlled BP, and some include yellow to indicate BP moderately elevated BP. Taken together, comprehending these three pieces of information, 1) medication adherence, 2) SBP, and 3) DBP, in a way that facilitates a patient’s ability to make causal inferences regarding medication adherence and its physiological outcome (i.e., BP), can potentially be accomplished by utilizing a user-centered design approach, and designing visualizations that reduce demands on visual short-term memory.

The review of visualization approaches presented in Table 2.3 demonstrate the complexity involved for displaying medication adherence and BP in a way that may present excessive demands on visual short-term memory. None of the apps showed both medication adherence and BP information. It is important to show both adherence and BP information because both are closely related and critical for self-monitoring HTN.[23] Furthermore, a common reason patients with HTN stop taking their medication within the first year of their initial prescription is because they do not necessarily feel the benefits of their medication.[4] Thus, visualizing how medication adherence is associated with a positive physiologic effect (e.g. better BP control) may facilitate one's understanding of the benefits of their medication, and ultimately lead to improved adherence.

Table 2.3 Visualizations methods in medication tracking (n=20) blood pressure monitoring apps (n=20)

	Use of Symbols n (%)	Numeric Value n (%)	Line Graph n (%)	Color-coded n (%)	Other Charts n (%)	Calendar View n (%)	List View n (%)
Medication Adherence	5 (25)	5 (25)	-	11(55)	5 (25)	7 (35)	20 (100)
Blood Pressure	2 (10)	20 (100)	18 (90)	16 (80)	12 (60)	4 (20)	-

2.12 Guidelines and Best Practices for Information Visualizations

Guidelines and best practices for visualizing patient data are driven largely by considerations for health literacy, numeracy, and graph literacy.[120] There are no known best practices for visualizing either medication adherence or BP information; however, best practices do exist for visualizing the type of data that underlies such information.[20,121,122] Specifically, there are best practices to visualize dichotomized (medication adherence) and continuous variables (blood pressure) over time.[121] Table 2.4 presents visualization best practices and guidelines related to the display of medication adherence and BP information using data visualizations. Best practices for communicating information using lists, charts, and graphs for individuals with low health literacy suggests that lists are best for monitoring information over time.[123] The use of lists is preferred because individuals with low health literacy have a difficult time making inferences from the graph. For monitoring medication adherence and BP over time, it is unknown what, if any, type(s) of visualizations might facilitate a person's ability to make inferences (e.g., derive trends about the effect medication adherence might have on BP levels). In addition to the known best practices and guidelines, extant research in visual perception and visualization preferences in certain contexts can further guide the design of visualizations.

Table 2.4 Data visualization standards and best practices related to medication adherence and BP data visualizations

Fitting the visualization type to the data (e.g., continuous longitudinal data fitted to a line graph)
Appropriate color palettes given the data type (e.g., binary opposites), and target audience (e.g., color blind)
Use of culturally recognizable symbols (e.g., U.S., English-speaking audience)
Use of context-appropriate symbols (e.g., HTN management)
Use of whitespace (e.g., limit cluttering of objects that may alter perception and hinder comprehension)
Adjusting X and Y axes to appropriately communicate meaning changes (e.g., changes in direction or slope of BP levels)
Appropriate font sizes
Appropriate line thickness
Appropriate and intuitive axes orientation
Use of axes tick marks
Use of chart/graph legend

2.12.1 Visualization Perceptions and Preferences

Data often are visually communicated using multiple types of visualizations (e.g., charts, graphs, and tables). While considering best practices and guidelines for displaying certain types of data, target audience preferences and the underlying message being communicated should be considered as these are often not captured in best practice guidelines. In a survey of undergraduate students (n=161), participants were shown 9 visualization types (scatterplot, a simple bar chart, a 3D volume bar chart displaying a perspective of looking up from the x-axis plane, a 3D volume bar chart displaying a perspective of looking down onto the x-axis plane, an area line graph with a shaded region below the line, a simple graph, a 3D surface line graph, and a 3D pie chart) depicting a hypothetical data set consisting of 9 data points with six trend reversals (points in a line graph where direction of the line reverses).[124] Participants were then given six data visualization objectives, and asked to identify the most appropriate visualization type for communicating patterns, gist, details, trends, contrast between data points, and creating a memorable visualization (participants were told a memorable visualization would be one that they would be expected to retain and recall information about at a later time after being presented with other visualizations). Results indicated simple line graphs were preferred for communicating the gist, trends, and contrast between data points, and shaded line graphs were preferred for communicating information that was memorable.[124] These results are consistent with recognized best practices,[20,121] and align with recent research that found line graphs are easiest to understand for patients viewing their own personal data,[125] which further support the use of line graphs to communicate longitudinal BP information to the patient. Research has also shown that perceptual organization of information depicting interactions (e.g., from factorial research designs) in graphs and charts influences comprehension.[126] In a series of experiments, researchers found that simple line graphs are not sufficient in themselves for communicating variable interactions. By employing the more effective aspects of certain chart types promote comprehension of more complex (e.g., color-coding, axis orientation, and vertical lines to indicate y-axis values), results indicated that improving comprehension of a visualization requires careful consideration of the data and the user. Specifically, the selection of graphical objects for displaying data (e.g., line versus bar) is not trivial as clutter can hinder comprehension, as can user unfamiliarity with the organization of the visualization.[126] However, it remains unknown how such considerations pertain to patients with HTN, and whether shaded line graphs to show BP and medication adherence or a simple line graph accompanied by symbols to show medication adherence information are preferred for communicating BP and medication adherence information concurrently.

As it relates to distinguishing between different colors or different shapes, discerning between colors is faster than discerning between shapes and letters.[127] For visualizations of medication adherence, these findings suggest perceptually different colors may be the optimal way of communicating adherence versus non-adherence. However, these perceptually different colors could take multiple forms while still accomplishing the primary task of communicating differences. One study conducted a series of experiments to assess which color and shape palettes maximize perceptual distance.[128] Using color and shape palettes from the commercial visualization tool Tableau, the palettes were reordered based on study results (see Figure 2.3) to display perceptually distant pairs of shapes and colors. From left to right, the first pair shows the two shapes (or colors) that are most perceptually distant, and the following two shapes (or colors) are the pair that is most perceptually distant from the pair before.[128]

Figure 2.3 Reordered Tableau shape and color palettes to show perceptual distance[128]

Lastly, while visualization design should be driven in large part by research in visual perceptions and existing guidelines and best practices, the subjective element of aesthetic preference is an important consideration in the visualization design process. In one study of seven different types of visualizations, participants (n=285) were asked to first rate the aesthetic quality of each visualization, then performed a task which consisted of interpreting the information contained in the visualization and answering two questions to determine the accuracy and efficiency (i.e., time to perform each task) of their answer.[129] In that study, the higher participants rated the aesthetic quality of a visualization, the more accurate their responses. However, the relationship between subjective aesthetic quality and efficiency showed mixed results where some higher-rated visualizations resulted in longer times to complete the task. The authors suggest this is perhaps explained by the willingness to thoroughly evaluate an aesthetically-pleasing visualization without completely abandoning the task altogether as accuracy did not decrease as time to task increased.[129]

2.12.2 Visualization Design and Task Performance

Visualization design is known to influence task performance, or one's ability to successfully complete an action involving the use of a visualization, such as interpreting a graph or chart.[130] Horoz and Whitney (2012) assessed how varying visual feature type (color vs. motion), visualization layout, and variety of visual elements (e.g. the number of different colors) affects people's abilities to: 1) find a pre-specified known object (i.e., a known target), 2) detect abnormalities within a visualization (an unknown oddball object), and 3) obtain a gist representation of the visualization.[130] Ability to identify a pre-specified known target was significantly better when objects were grouped according to color (versus randomly dispersed), and when objects were in motion. However, increasing the variety of objects surrounding the target did not diminish ability to identify the known target. When identifying an unknown oddball object (e.g., an object that stands out among other objects), ability to identify the oddball object diminished as the variety of objects increased. When tasked to obtain a gist representation (as measured by perceived variety in a visualization), participants were significantly less able to identify which visualization had more variety as the variety of colors of features increased. However, when similar features in a visualization were grouped (versus randomly dispersed), the ability to understand a gist representation was significantly better.[130] These results suggest that grouping displays of information when possible is better for conveying the gist of a visualization, and visualization design should aim to reduce variety within a visualization unless the goal of the visualization is to communicate an outlier. As it relates to visualizing medication adherence and BP, these findings support a visualization design that combines medication adherence and BP information into a minimal number of features (e.g., color-coding BP trend lines based on adherence), and does so in a single visualization as opposed to two separate visualizations.

2.13 Hypertension-related Information Visualization Comprehension

Several validated hypertension knowledge scales exist, which suggest that there are key sub-dimensions of hypertension knowledge,[13,14,131–134] some of which may correlate with aspects of comprehension of hypertension-related information visualizations. Among these scales is the Hypertension Knowledge-level Scale (HK-LS). The HK-LS developed by Erkoc et al (2012) measures hypertension knowledge along six domains: hypertension definition, treatment, drug compliance, lifestyle, diet, and complications.[13] There are no known validated scales for assessing comprehension of information visualizations for BP and medication adherence.

As it relates to the comprehension of the hypertension-related information visualizations presented in this study, the HK-LS provides theoretical support for a unidimensional solution for comprehension of hypertension-related information visualizations, namely the comprehension of the correlation between medication adherence and BP control. However, it is possible that key sub-dimensions exist, namely comprehension of 1) BP-related aspects of the correlation between medication adherence and BP control, and 2) medication adherence-related aspects of the correlation between medication adherence and BP control. These hypothesized constructs of hypertension-related information visualization comprehension are theoretically linked to three sub-domains of the HK-LS, specifically: 1) hypertension definition (the comprehension of systolic and diastolic BP), 2) drug compliance (medication adherence), and 3) medical treatment (the causal link between medication adherence and BP control). The remaining domains of the HK-LS (lifestyle, diet, and complications) are not considered aspects of comprehension communicated in the information visualizations that are the focus of this study.

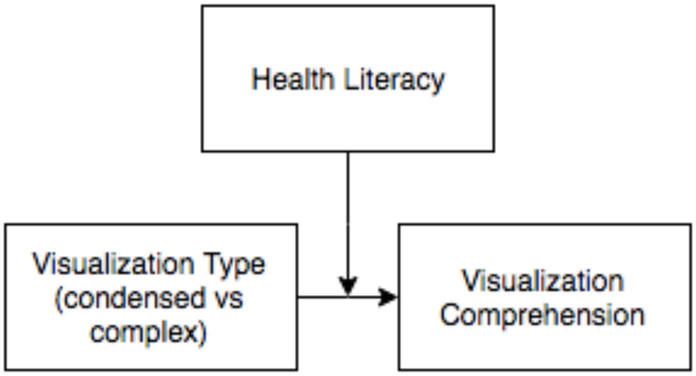
2.14 Developing A Conceptual Framework to Address Research Gaps

In summary, I identified the following research gaps: 1) patient preferences for and understanding of condensed visualizations that simultaneously display medication adherence and BP data have not been documented, 2) it is unknown whether condensed data visualizations that combine medication adherence and BP data result in improved patient comprehension of such information, and 3) there is not a validated scale to assess patient comprehension of medication adherence and BP control visualizations.

The growing use of technologies for health monitoring and management (e.g., mobile apps and wearable health monitoring devices) suggests information visualizations may likely be a particularly important aspect of HTN self-monitoring, specifically visualizations for medication adherence and BP information. As it relates to mobile-based health interventions that rely in part on the visual communication of medication adherence and BP control, the comprehension of such visual information has important cognitive aspects to consider. For instance, one’s ability to perform a visual task, such as understanding the meaning of charts and graphs, is dependent in part on the capacity to interpret several pieces of information, then recall it moments later and synthesize information into knowledge. This suggests that guidelines and best practices for information visualization design and the limitations of VSTM should be considered when designing visualizations for medication adherence and BP information. While adhering to such guidelines, best practices, and current understanding of VSTM limitations, there is still considerable latitude for design possibilities. This research gap suggests a need to both assess: 1) patient preferences for medication adherence and BP information visualization design, and 2) whether patients understand such visualizations once preferences are implemented in the design. Aim 1 addresses these two research gaps.

Existing mobile apps for monitoring medication adherence and BP suggest there are common ways of visualizing such information. However, given guidelines and best practices for visualization design and known limitations of VSTM, it is unclear whether these common visualization techniques optimize patient comprehension of the information they seek to convey. For instance, based on extant research, it can be reasonably inferred that condensing visualizations for medication adherence and BP information from two separate visualizations to one single visualization could reduce demands on VSTM. Furthermore, it is unknown if condensed visualizations designed to adhere to such guidelines and best practices while considering known limitations in VSTM will improve the comprehension of medication adherence and BP information. Moreover, the role of health literacy in medication adherence and BP information visualization comprehension is unknown. Links between health literacy and medication adherence and BP control among patients with HTN, and information recall, suggest there may be a mediating effect between visualization design and comprehension in that individuals with lower health literacy may see a greater benefit (i.e., increased comprehension) with visualizations designed specifically to optimize comprehension. Figure 2.4 presents the hypothesized conceptual model displaying the effect of visualization type on visualization comprehension, and the moderating effect of health literacy on this relationship. Aim 2 addresses these research gaps.

Figure 2.4 Conceptual model



Lastly, there is no known validated scale for assessing the comprehension of medication adherence and BP information visualizations. Aim 3 addresses this research gap by developing and assessing the reliability and validity of a 6-item hypertension-related information visualization comprehension scale.

CHAPTER 3: RESEARCH AIMS AND HYPOTHESES

The overall goal of this research is to determine the best approach for visually presenting patient medication adherence and blood pressure (BP) data on a mobile device or patient portal in ways that optimize patient comprehension of such data. In Chapter 2, I reviewed the literature related to hypertension and the self-monitoring of medication adherence and BP, the role of mobile health in self-monitoring medication adherence and BP, and aspects of visual short-term memory (VSTM) and visualization design in regard to data visualizations for medication adherence and BP. As part of the literature review, I identified three major research gaps for which I have developed three specific aims. Each specific aim and its associated research question and hypotheses (when warranted) are presented below.

Manuscript #1 (Aim 1) presents user assessment data that describe patient preferences for data visualizations that display medication adherence and BP data and describe how patients prefer to incorporate such visualizations into their HTN self-monitoring behaviors. Since there are no existing studies documenting how patients prefer to view condensed data visualizations, using cognitive interview data, Manuscript #2 (Aim 1) explores patient understanding of three newly-developed visualizations that condense the visual display of medication adherence and BP data. Using data collected from a randomized experiment, manuscript #3 (Aim 2) assesses whether condensed visualizations for medication adherence and BP data improve patient comprehension of such data when compared with visualizations that present adherence and BP data separately. Manuscript #3 also explores whether health literacy moderates the relationship between condensed visualizations and visualization comprehension. Aim 3, which is not part of a manuscript, involves documenting the psychometric properties of a newly-developed 6-item data visualization comprehension scale.

Specific Aim 1: To assess a) patient preferences for data visualizations that display medication adherence and BP data and document how patients use visualizations to self-monitor their HTN, b) patient preferences for visualizations that condense the display of BP and adherence information, and c) patient understanding of key features of visualizations that display BP and adherence information.

RQ_1: What are patient preferences for displaying data visualizations for medication adherence and BP?

RQ_2: What are patient preferences for visualizations that condense BP and adherence data?

RQ_3: Once patient preferences are incorporated into visualizations, do patients correctly interpret key features of visualizations for displaying medication adherence and BP data?

Specific Aim 2: To conduct a randomized experiment to assess whether visualizations that condense the display of information improve patient comprehension of BP and adherence data and evaluate whether health literacy moderates the relationship between visualization type and patients' comprehension of BP and adherence data.

RQ_4: Do condensed visualizations of medication adherence and BP data improve patient comprehension of such information compared to separate visualizations?

H_4: Patients viewing the condensed visualization of medication adherence and BP will have better comprehension of BP and adherence information than patients viewing visualizations displaying medication adherence and BP information separately.

RQ_5: Does health literacy moderate the relationship between visualization type (condensed display versus separate display) and patient comprehension of BP and adherence data?

H_5: Health literacy will moderate the relationship between visualization type and comprehension such that among participants with low health literacy, the difference in comprehension will be greater between the treatment (i.e., condensed visualization) and control (i.e. separate visualizations for medication adherence and BP) groups when compared to the difference in comprehension among participants with high health literacy.

Specific Aim 3: To assess the validity and reliability of a newly-developed 6-item scale to assess patient comprehension of data visualizations.

RQ_6: Does the 6-item visualization comprehension scale sufficiently capture a unidimensional latent construct of comprehension of the correlation between medication adherence and BP control, or a two-factor solution of the correlation between medication adherence and BP control (separate latent factors for adherence-focused comprehension and BP-focused comprehension)?

RQ_7: Does the 6-item comprehension scale converge with related constructs (construct validity)?

H_7: HTN knowledge will be positively and significantly associated with higher scores on the comprehension scale.

RQ_8: Does the 6-item comprehension scale have acceptable internal consistency for each subscale?

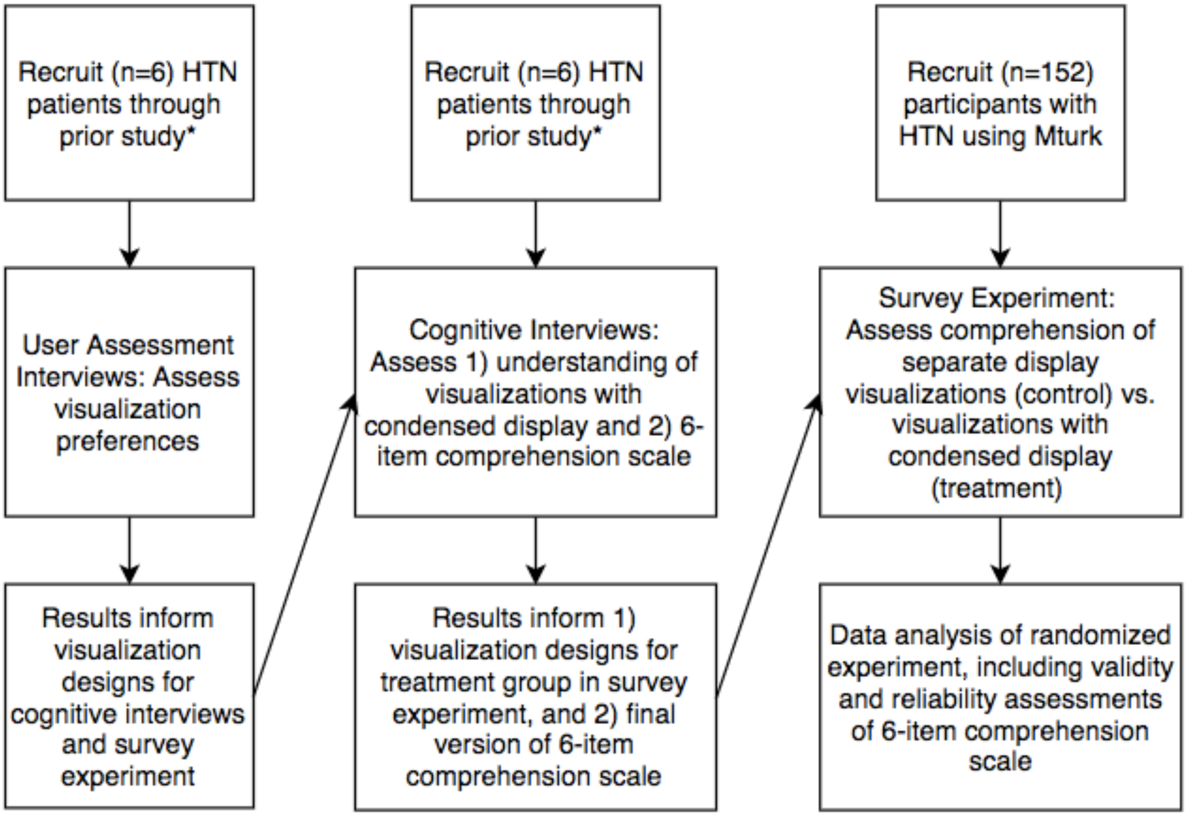
H_8: The comprehension scale will have acceptable internal consistency, indicated by a $\rho_{KR2} \geq .70$.

CHAPTER 4: METHODS

4.1 Study Overview

I collected primary data to accomplish my specific aims. For Aim 1, I conducted user assessment and cognitive interviews to assess patient preferences for and understanding of data visualizations for blood pressure (BP) and medication adherence. I also assessed face validity of a 6-item scale for assessing comprehension of data visualizations for BP and medication adherence. For Aim 2, I conducted a randomized experiment to assess patient comprehension of visualizations for BP and medication adherence. For Aim 3, I used data from the randomized experiment to assess the validity and reliability of a 6-item comprehension scale. This chapter includes a description of: the overall study (4.1); the process for developing visualizations (4.2); Aim 1 methods, including participant recruitment, eligibility, and user assessment and cognitive interview data collection and analytic procedures (4.3); Aim 2 methods, including participant recruitment, eligibility, measures, and data collection and analytic procedures (4.4); and Aim 3 methods and analytic procedures, including exploratory and confirmatory factor analysis and reliability assessments (4.5).

Figure 4.1 Key stages and process flow of study



*Recruitment from previous studies are described in sections 4.3.1.1 and 4.3.1.2

4.2 Development of Visualizations

4.2.1 Incorporating Best Practices and Guidelines

Best practices and guidelines for information visualization design allows for multiple approaches for some key features (i.e., design aspects), including visualization type, color palettes, symbols, labels, and positioning of objects. For certain information types and the intended visualizations' audience, the most appropriate approach to these design aspects should be evaluated based on preferences and understanding. To prepare for Aim 1, I developed several versions of data visualizations displaying two weeks of longitudinal information for medication adherence and BP based on best practices and guidelines for visualizing numeric information.[20,120–122,135] Developing several versions of visualizations allowed participants to see different options and communicate their preferences. Guidelines and best practices informed several aspects of the visualizations, including the following:

- appropriate chart type given the data type (e.g., longitudinal BP data fitted to a line graph);
- selection of possible color palettes for drawing contrast where necessary;
- the use of culturally recognizable (i.e., U.S.) and context appropriate (i.e., HTN management) symbols for communicating positive and negative meaning;
- the use of white space, adjusting the scales of x and y axes of line graphs to appropriately communicate meaningful changes in BP via changes in line slope;
- appropriate label font sizes;
- appropriate line thickness for trend lines;
- axis orientation;
- the use of tick marks; and
- the use of a chart legend.

Certain key features of visualizations can vary in appearance while still adhering to accepted guidelines, and user preference is important in understanding more precisely how each feature should be presented. In addition, addressing demands on VSTM by condensing the display of medication adherence and BP information into one data visualization can take multiple forms, including color-coding medication adherence by coloring the BP trend lines using a perceptually distant color scheme (e.g., blue indicating adherence and orange indicating non-adherence), perceptually distant color-coding to shade areas below BP trend lines to indicate medication adherence (see example in Figure 4.2), using symbols within a line graph to indicate medication adherence, or a combination of these.

Figure 4.2 Example of perceptually distant color-coding

4.2.2 Iterative Results-driven Visualization Design

An iterative results-driven visualization design process was used throughout the study. Aim 1 addresses design preferences using user assessment interviews. Results from these interviews informed the design of three visualizations that I developed in order to assess whether participants understand visualizations that incorporate their design preferences. I tested participant understanding of these three visualizations during the Aim 1 cognitive interviews. Finally, results from the cognitive interviews informed the refinement and development of the final versions of visualizations that were used for the treatment group in the randomized experiment in Aim 2. The methods for Aim 1 describe this visualization development process and how these newly developed visualizations were used throughout this study.

4.2.3 Information Assumptions for Visualization Designs

Medication adherence and BP data used for all visualizations were based on known parameters concerning the pharmacology of Lisinopril[136] and standard definitions of HTN.[30] Lisinopril is the most commonly used antihypertensive drug and is prescribed to approximately 20% of the hypertensive population.[34] The antihypertensive effect of Lisinopril starts to rapidly drop off after 24 hours, which suggests two consecutive missed doses for individuals taking Lisinopril once daily could result in elevated BP levels.[136] All visualizations in this study depict medication adherence and BP information over a two-week (14-day) period for taking Lisinopril once daily. Only one medication (Lisinopril) was depicted in visualizations that convey medication adherence information. Information prefaced visualizations that specified that the depicted medication is a BP medication and that it is prescribed once daily. For the Aim 2 randomized experiment, condensed visualizations (treatment) were compared to separate BP and adherence visualizations (control). The visualizations showed the following four medication adherence and BP combinations: 1) high medication adherence and adequate BP control (HC), 2) high medication adherence and inadequate BP control (HU), 3) low medication adherence and adequate BP control (LC), and 4) low medication adherence and inadequate BP control (LU). In the visualizations, controlled BP was presented as BP that is controlled for 100% of days over the 14-day period and uncontrolled BP was presented as elevated BP resulting from 50% adherence (i.e., missed medication for 7 days). Similarly, low medication adherence was presented as 50% adherence (i.e., medications only taken 7 of the 14 days), and high medication adherence was presented as 100% adherence (i.e., the medication was taken every day over the 14-day period).

For the low adherence/uncontrolled BP visualization type, days of elevated BP was shown when non-adherence occurs for 2 or more consecutive days, and was shown starting on the second day of non-adherence. This approach closely mimics the loss of the antihypertensive effect of Lisinopril after 24 hours. The visualizations depicted elevated BP levels until a medication was taken again. For the low adherence/uncontrolled BP and low adherence/controlled BP visualization types, days of non-adherence were selected using a random number generator in R (randomly choosing 7 days, or 50% of non-adherence). For the high adherence/uncontrolled BP visualization type, days of elevated BP were selected using a random number generator in R (randomly choosing 7 days of elevated BP). For Aim 1, elevated BP was presented as randomly chosen numbers between 140 and 210 mmHg systolic BP (SBP) and 90 and 110 mmHg diastolic BP (DBP) using a random number generator in R. Controlled BP was presented as a randomly chosen number between 120 and 140 mmHg (SBP) and 80 and 90 mmHg (DBP).

In November of 2017 new BP guidelines were released by the American College of Cardiology and the American Heart Association, which define HTN as SBP > 120 mmHg or DBP > 80 DBP.[1] To reflect these new guidelines, Aim 2 presented elevated as randomly chosen numbers between 121 and 210 mmHg SBP and 81 and 110 mmHg DBP using a random number generator in R. Controlled BP was presented as a randomly chosen number between 90 and 120 mmHg (SBP) and 60 and 80 mmHg (DBP).

4.3 Aim 1 Methods

Aim 1 consists of: 1) one-on-one user assessment interviews to assess patient preferences for data visualizations communicating blood pressure and medication adherence information, and 2) cognitive interviews to assess understanding of data visualizations for blood pressure and medication adherence.

> ***Specific Aim 1:*** *Assess a) patient preferences for data visualizations that display medication adherence and BP data and document how patients use visualizations to self-monitor their HTN, b) patient preferences for visualizations that condense the display of BP and adherence information, and c) patient understanding of key features of visualizations that display BP and adherence information.*

4.3.1 Aim 1 Participant Recruitment

4.3.1.1 Participant Recruitment for User Assessment Interviews

Participants for the one-on-one user assessment interviews in Aim 1 (n=6) were purposefully recruited based on gender (3 males and 3 females), race/ethnicity (3 White, 3 non-White, and at least 1 Hispanic), health literacy (at least 2 participants with low health literacy), and education (at least 2 with a high school diploma or less and at least 2 college graduates). Participants were recruited from an existing pool of adult HTN patients who participated in a previous study entitled “Developing and testing an electronic health record-based strategy for the routine assessment of medication self-management skills among primary care patients with complex drug regimens” *(MeDS II),* that assessed the use of a patient portal to measure and monitor patient medication use in primary care. All participants from the MeDS II study received healthcare from the Internal Medicine Clinic (IMC) in the UNC Health

Care System. Participants from the MeDS II study who agreed to be re-contacted for future studies were contacted. These participants were called by the PI (Adam Sage) to assess interest in participation and further screened for eligibility. Participants were screened by phone for eligibility (described in section 4.3.2).

4.3.1.2 Cognitive Interview Participant Recruitment

Participants for the cognitive interviews in Aim 1 (n=6) were purposefully recruited based on gender (3 males and 3 females), race/ethnicity (3 White, 3 non-White, and at least 1 Hispanic), health literacy (at least 2 participants with low health literacy), and education (at least 2 with a high school diploma or less and at least 2 college graduates). Thematic saturation was achieved with six participants. All participants for the cognitive interviews were recruited from the MeDS II study. These participants were called by the PI (Adam Sage) to assess interest in participation and to further screen for eligibility.

4.3.2 Aim 1 Eligibility Criteria

Eligible participants for the Aim 1 user assessment and cognitive interviews met the following criteria: 1) were able to speak and write English, 2) had a self-reported diagnosis of HTN, 3) had a self-reported prescription medication to treat HTN, 4) owned a smartphone, and 5) were over the age of 18. Participants were excluded if they had any vision or cognitive impairments that precluded study participation or informed consent. User assessment interview participants were not eligible to participate in the cognitive interviews.

4.3.3 User Assessment Data Collection Procedures

A trained interviewer (Adam Sage) conducted in-person user assessment interviews (n=6) until thematic saturation was met to assess preferences of key features of visualizations for medication adherence and BP information, and preferences for approaches to condensing the display of medication adherence and BP information. Interviews took place in a private setting. Interviews lasted approximately 30 minutes. First, participants read a study fact sheet, which described the study's procedures, and then provided written consent. Each participant was provided a paper copy of all visualizations discussed during the interview. A semi-structured interview guide was used (see Appendix A for user assessment interview protocol); interview procedures are described in more detail below. Each interview was audio recorded using a digital audio-recorder. Audio recordings were analyzed by two coders (Adam Sage and Aditi Dhamanaskar). This study was approved by the UNC Institutional Review Board.

First, participants were presented with a color palette with 5 perceptually distant pairs based on previous research in perceptions of color differences.[128] (see Figure 4.3) and asked to choose which pair best represents something positive and negative, such as taking medication and missing a dose of medication. Participants were then asked to explain why they chose those colors, which color represents something positive and which represents something negative, and if there were different colors not shown that they would have preferred. Next participants were presented with seven pairs of perceptually distant symbols based on previous research in perceptions of shape differences.[128] and more culturally recognizable symbols (see Figure 4.4), and asked to choose which pair best represents something positive and negative, such as taking medication and missing a dose of medication. Participants were then asked to explain why they chose those symbols, and if there were different symbols not shown that they would have preferred. Next, participants were shown a graph with labeled BP points on a line graph, and a graph without labeled BP points (see Figures 4.5 and 4.6). Participants were then asked which graph they preferred and why. Next, participants were presented with four graphs: 1) a graph with horizontal reference lines, 2) a graph with vertical reference lines, 3) a graph with a grid for reference, and 4) a graph with shaded regions indicating the range for controlled BP (see Figures 4.7 through 4.10). Next, participants were asked if any of the following label terms were confusing: Blood Pressure Level, Date, Systolic Blood Pressure, Diastolic Blood Pressure, and Taken/Missed Medication. Participants were also asked if there were any other terms they would use in place of those presented. Participants were then presented with two charts to show medication adherence: a list and calendar view. Participants were asked which chart they preferred and why. For each visualization presented throughout the interview, participants were also asked to explain what they liked and disliked about each variation of each key feature display. Participants were also asked to identify confusing aspects about each visualization they saw throughout the interview. Participants were encouraged to use the paper visualizations to mark their preferences or confusing aspects.

Figure 4.3 Perceptually distant color pairs

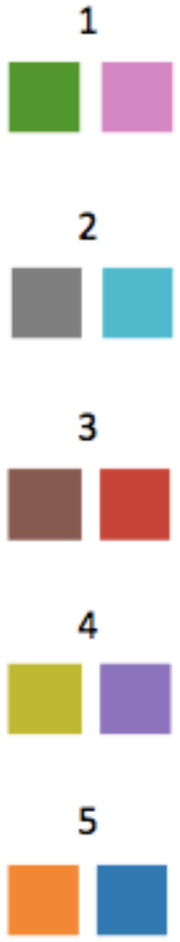


Figure 4.4 Perceptually distant symbol pair

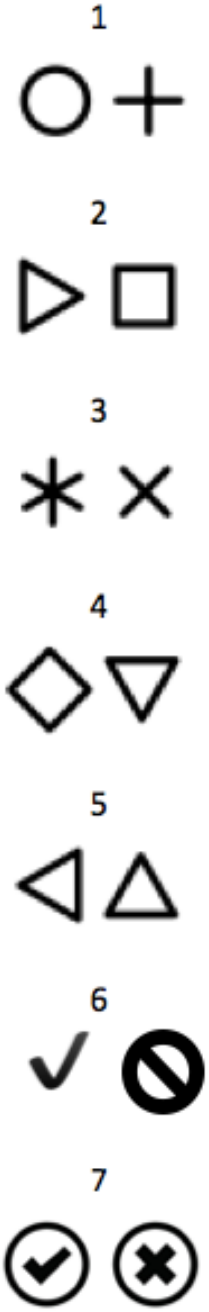


Figure 4.5 Graph without labeled data points

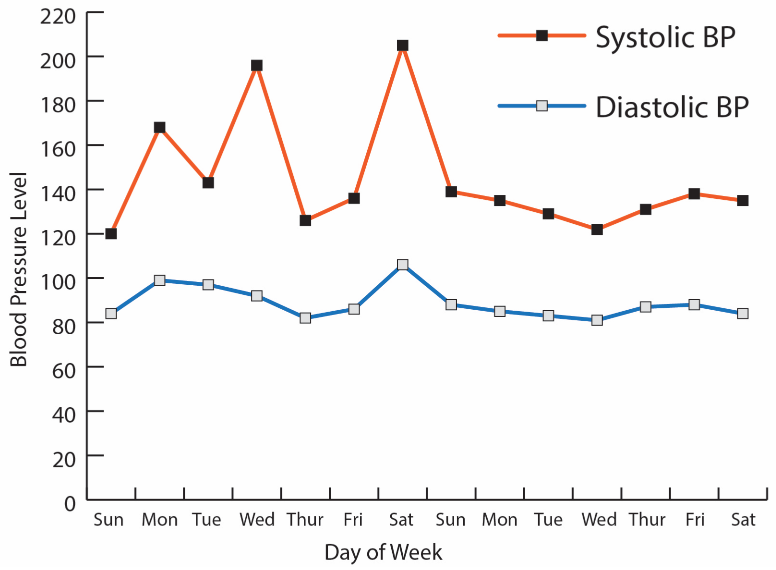


Figure 4.6 Graph with labeled data points

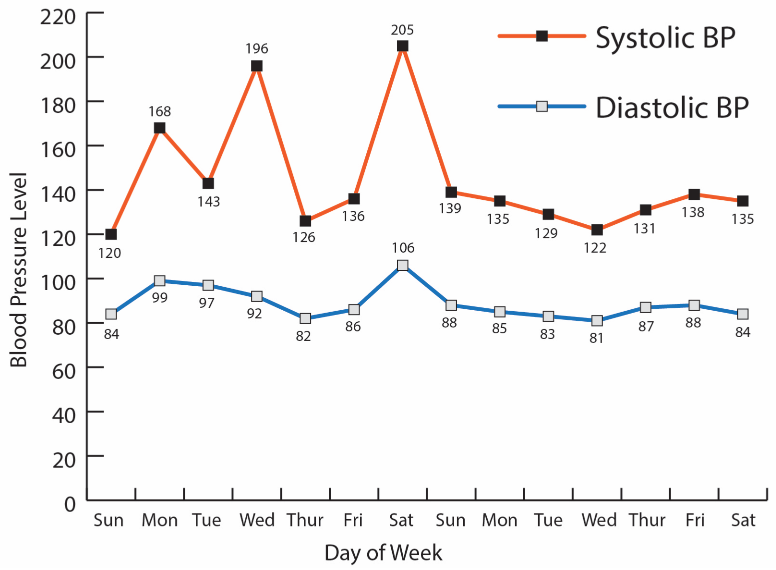


Figure 4.7 Graph with horizontal reference lines

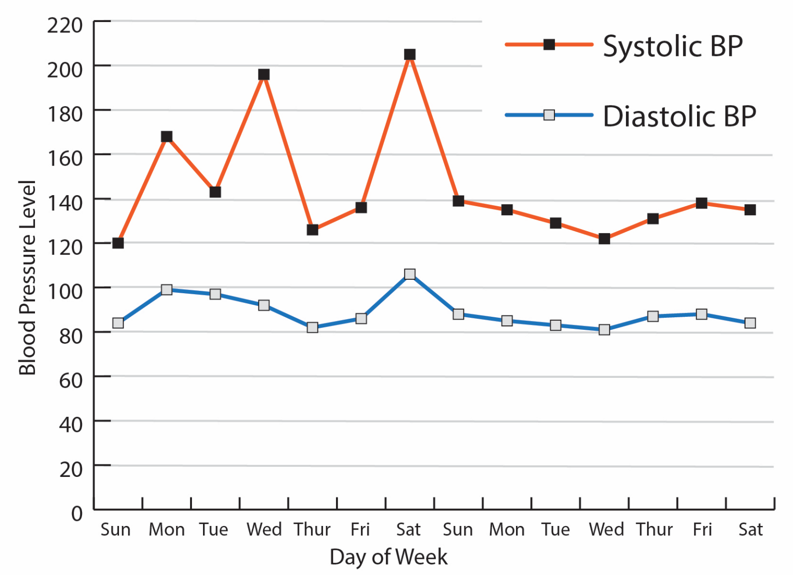


Figure 4.8 Graph with vertical reference lines

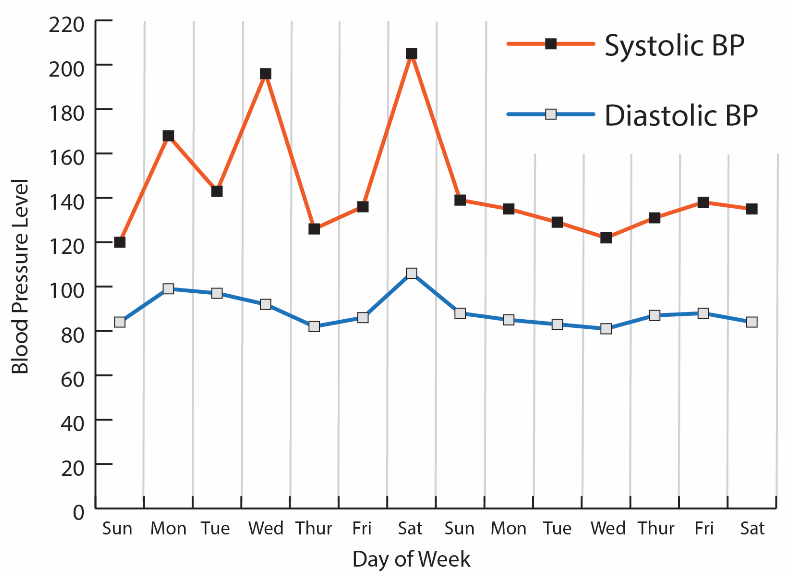


Figure 4.9 Graph with reference gridlines

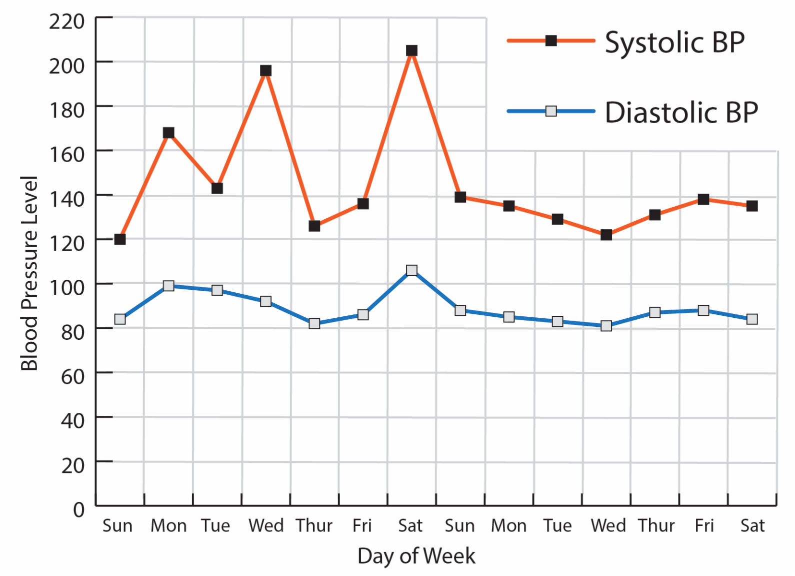
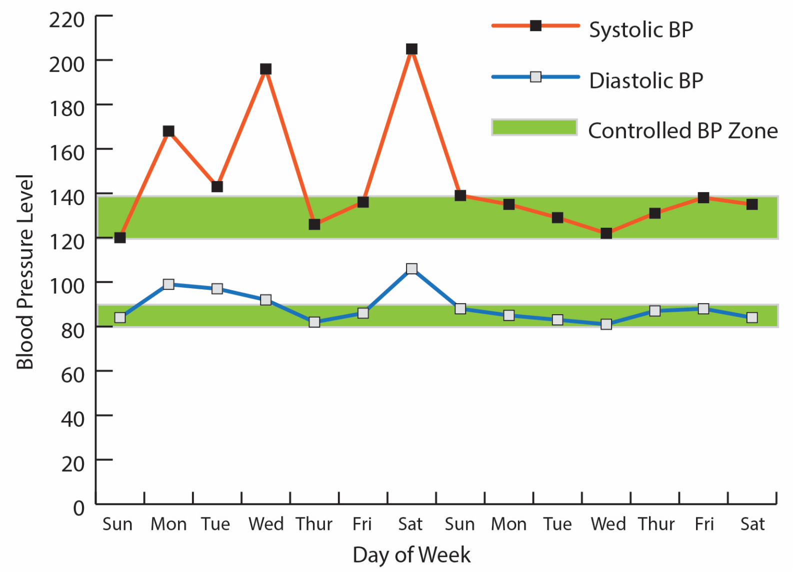


Figure 4.10 Graph with shaded regions indicating the range for controlled BP



Next, participants were presented with three types of visualizations that condense the display of medication adherence and BP information by 1) color-coding medication adherence on lines for SBP and DBP (shown in Figure 4.11), and 2) using shaded regions under lines for DBP and SBP (shown in Figure 4.12), and 3) using symbols to communicate medication adherence for each day that appear on and below the lines indicating DBP and SBP (shown in Figures 4.13 through 4.15). Participants were asked to rank each visualization by preference. Participants were also asked to explain their preferences and identify any confusing aspects about each visualization. Next, participants were shown three versions of the visualization with symbols that varied position of the symbols within the graph (shown in Figure 4.13 through 4.15) and asked which version they prefer and why. Participants were encouraged to use the paper visualizations to mark confusing aspects. The interview protocol in Appendix A outlines questions asked during these interviews. User assessment interviews were conducted until saturation was achieved and no additional insights were provided from participants. Each participant was given a $25 cash incentive after the interview.

Figure 4.11 Graph using color-coded lines to show medication adherence

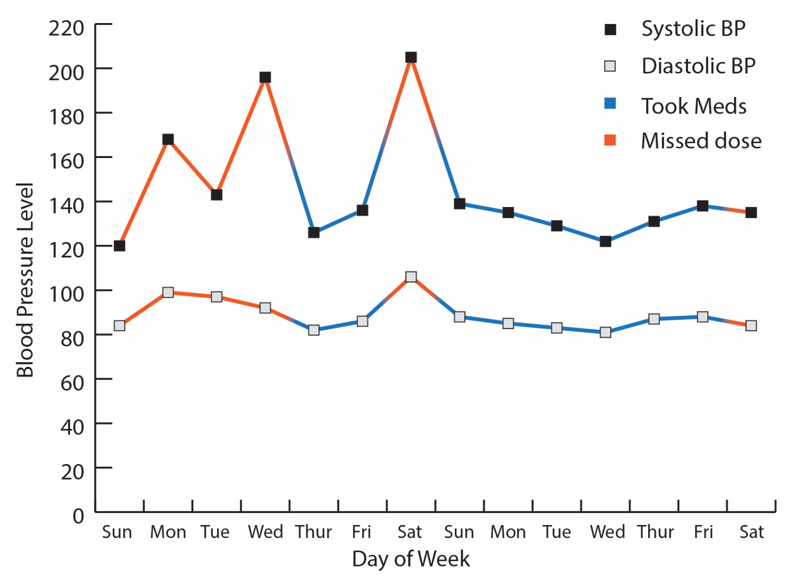


Figure 4.12 Graph using shaded region to show medication adherence

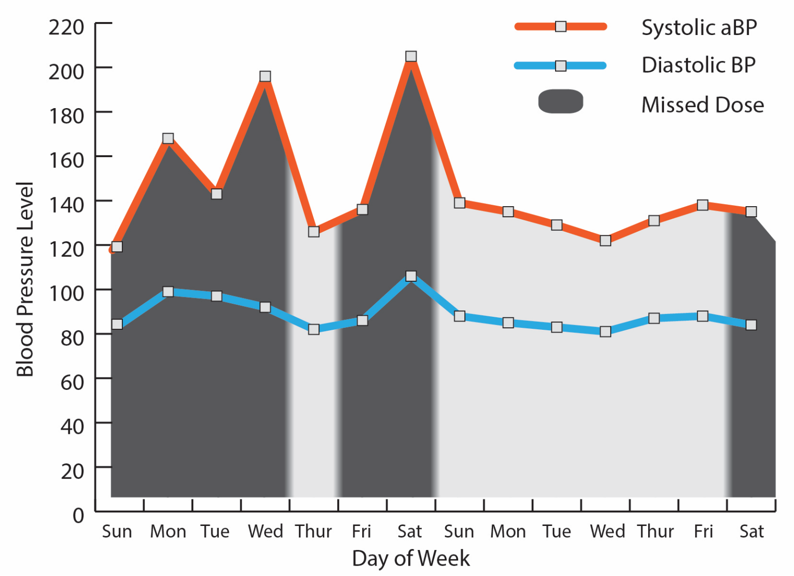


Figure 4.13 Graph using symbols on the line to show medication adherence

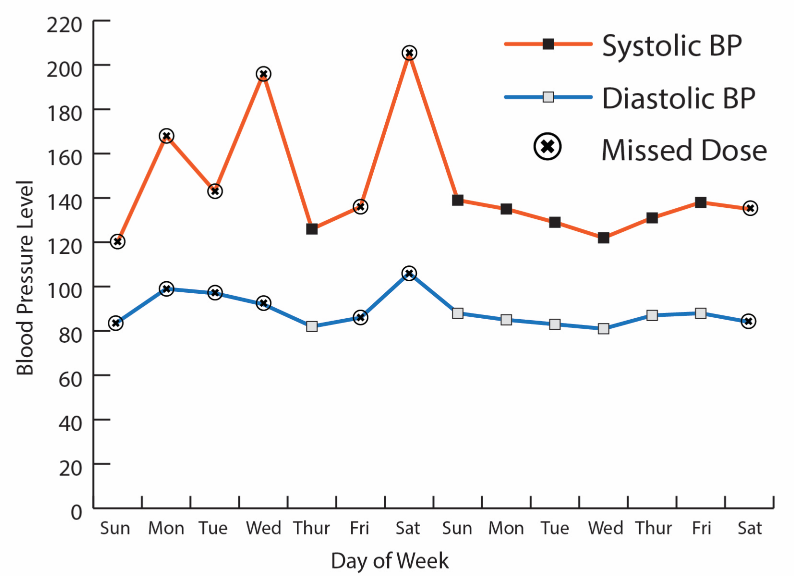


Figure 4.14 Graph using symbols below the line to show medication adherence

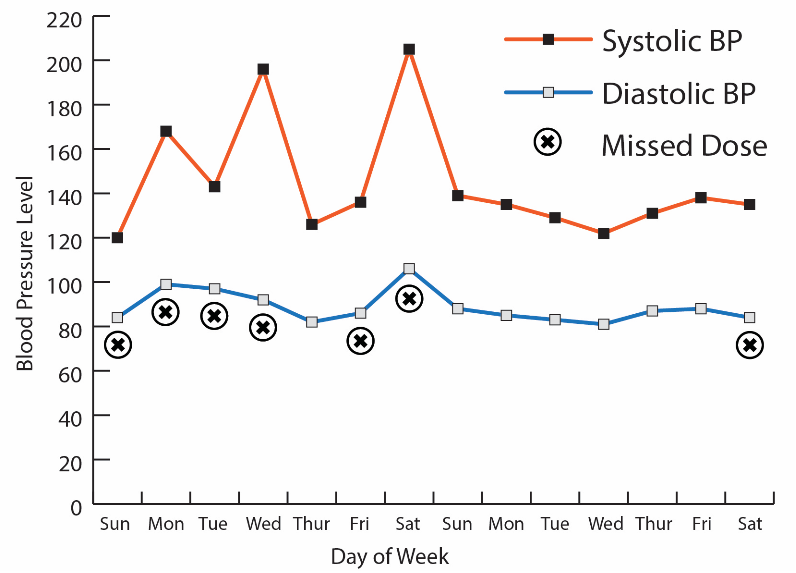
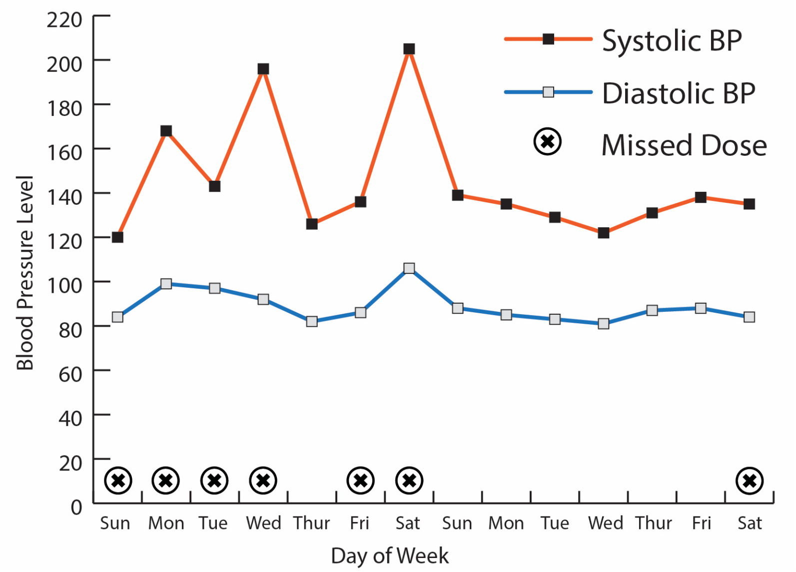


Figure 4.15 Graph using symbols along the x-axis to show medication adherence



4.3.4 User Assessment Interview Analyses

User assessment interviews were audio recorded and were analyzed according to a codebook, and results were recorded in an Excel template. A codebook was developed to categorize participant responses to visualization features (e.g., each different color palette or chart type for displaying medication adherence information) into the following categories: 1) positive reactions (e.g., liked, preferred) 2) negative reactions (e.g., disliked, not preferred) and 3) confusing (e.g., uncertain of the feature's meaning), and 4) unsure (e.g., a neutral reaction, neither liked or disliked).[137] In addition, suggestions for improvement for each visualization feature were coded into themes that emerged during interviews. For each feature, reactions (positive or negative) were coded and tallied to calculate frequencies, and preferences were determined by the overall percentage of positive responses. Results from the interview analysis were used to inform the development of three visualizations condensing the display of medication adherence and BP information used for cognitive interviews.

Two coders (Adam Sage and a research assistant) analyzed all audio recordings, and kappa scores were calculated to assess inter-coder reliability. Disagreements in categorization were discussed between the coding team to settle coding discrepancies.

4.3.5 Cognitive Interview Data Collection Procedures

Using results from the user assessment interviews, three visualizations (see Appendix B) were developed that condensed the display of medication adherence and BP information. A trained cognitive interviewer (Adam Sage) conducted cognitive interviews (n=6) to assess participants' understanding of each visualization. Cognitive interviews took place in a private setting. Each cognitive interview lasted approximately 35 minutes and was audio-recorded for analysis. First, participants were read a study fact sheet, which described the study's procedures, and participants provided written consent. A walk-through method[138] was used where participants were asked to answer several questions (see Cognitive Interview Protocol in Appendix B) about the information conveyed in each visualization. For each type of response (whether a feature was correctly or incorrectly understood), the interviewer probed for insights into aspects of the feature that facilitated or impeded understanding. For each visualization, participants were asked to identify 1) each day that a HTN medication was taken, 2) each day a HTN medication was not taken, 3) each day BP was controlled, 4) each day BP was uncontrolled, 5) which axis represented BP, 6) which axis represented day of week, 7) the meaning of axes' tick marks 8) the meaning of colors associated with any color-coding, 9) the meaning of any symbols, and 10) the meaning of any labels (i.e., terminology). Cognitive interviews were conducted until saturation was achieved and no additional insights were provided from participants. This portion of the cognitive interviews was expected to last approximately 25 minutes.

Following visualization assessments, an assessment of the 6-item comprehension scale was conducted, as described below. Using a walk-through method,[138] participant's understanding of each item of the scale was assessed using probes to explain what the question was asking and whether any words or phrases were confusing. Appropriateness of the response options was also assessed to determine the potential for floor or ceiling effects. The cognitive interview protocol was developed based on best practices for cognitive interviews (see Cognitive Interview Protocol found in Appendix B).[138] This portion of the cognitive interview lasted approximately 10 minutes. Each cognitive interview participant was given a $25 cash incentive for his/her participation.

4.3.6 Cognitive Interview Analysis

Cognitive interviews were audio recorded and analyzed according to a codebook, and results were recorded in an Excel template. A codebook was developed to categorize whether participants understood visualizations that condensed the display of medication adherence and BP information. The following categories were used to assess participant responses to the interviewer’s questions: 1) correctly understood feature (i.e., provided a correct response to the researcher’s question) and 2) incorrectly understood feature (i.e., provided an incorrect response to the researcher’s question). In addition, factors that facilitated or impeded participants’ ability to understand each feature were analyzed.

Two coders (Adam Sage and Aditi Dhamanaskar) analyzed all audio recordings, and kappa scores were calculated to assess inter-coder reliability. Disagreements in categorization were discussed between the coding team to settle coding discrepancies. Results from the cognitive interviews informed the design of the condensed (treatment group) visualizations in Aim 2. Based on the preferences for condensed visualizations assessed in the user assessment interviews and the understanding of the condensed visualizations in the cognitive interviews, the best overall performing condensed visualization type was used in Aim 2. Additionally, these results were discussed with the full study team to reach consensus on which visualization to use in Aim 2.

4.4 Aim 2 Methods

To accomplish Aim 2, I conducted a randomized experiment to assess whether visualizations that condense the display of medication adherence and BP information improve visualization comprehension versus separate visualizations for medication adherence and BP information.

> ***Specific Aim 2:*** *Conduct a randomized experiment to assess whether visualizations that condense the display of information improve patient comprehension of BP and adherence data and evaluate whether health literacy moderates the relationship between visualization type and patients' comprehension of BP and adherence data.*

4.4.1 Aim 2 Participant Recruitment

Participants for Aim 2 were recruited using Amazon's Mechanical Turk (www.mturk.com).[139] Mechanical Turk (Mturk) allows researchers to recruit study participants by providing incentives for completing small tasks called Human Intelligence Tasks (HITs), such as taking a short survey. Participants were paid a pre-specified amount for their time. First, participants were screened for eligibility, (described in 4.4.2), and completed the Health Literacy Skills Instrument-Short Form (HLSI-SF), described in 4.4.5.2.[76] All participants received a $0.50 incentive for completing the short screening instrument. The screening instrument was left open until the needed sample size was met (n=152) for both the high and low health literacy groups (n=76).

First, potential participants were invited to complete the screening instrument. Individuals were provided with a description of the study, including study eligibility criteria. Participants were then shown a study fact sheet and provided electronic consent prior to completing the screening instrument. Eligible participants were invited to participate in the full study and received a $4 incentive for their participation. Eligible participants were also given a unique identification code that allowed them to participate in the full study. Ineligible participants were thanked for their time and were not invited to participate in the full study.

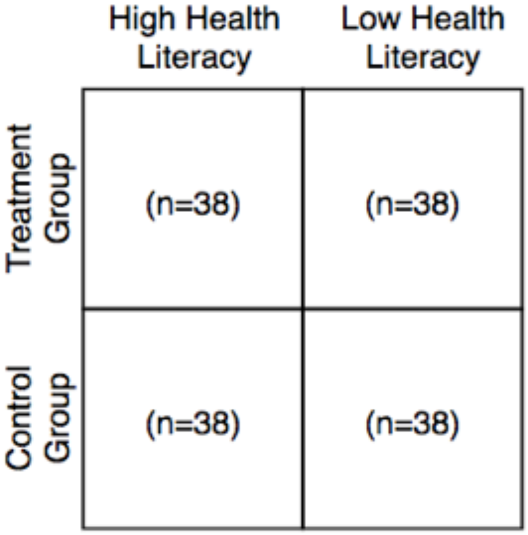
4.4.2 Aim 2 Eligibility Criteria

Eligible participants for Aim 2 of the study met the following criteria: 1) were 18 years or older, 2) were English-speaking, 3) were able to read and write English, 4) had a self-reported diagnosis of HTN, 5) self-reported being currently prescribed at least one antihypertensive medication, 6) had internet access at any location (e.g., home, phone, public library), and 7) owned a smartphone. Participants were excluded if they reported having severe vision or cognitive impairments. All participants were screened for eligibility using an online screening questionnaire that preceded the online survey (described in 4.4.1).

4.4.3 Sample Size and Power Calculation

The sample size was calculated to detect the moderating effect of health literacy on visualization comprehension (main dependent variable). For this study, the HLSI-SF was categorized as low or high, low health literacy being an HLSI-SF score of 0-6 (inadequate), and high health literacy being an HLSI-SF score of 7-10 (adequate). Guidelines for the HLSI-10 suggest these cutoff scores, and it was expected that approximately 63% of participants would have adequate health literacy, and 37% would have less than adequate health literacy.[76] By categorizing health literacy as low versus high, moderation was assessed as differences between comprehension of low and high health literacy individuals among the treatment and control groups, for a total of four distinct groups (see in Figure 4.16). The sample size was calculated to detect a medium effect size for the main effects (.45) in comprehension and a medium to large effect size for the interaction between visualization type and health literacy with 80% power (two-tailed alpha = .025). Using these assumptions, the sample size for each group was calculated, which resulted in 38 subjects per group, or a total of 152 participants.[140]

Figure 4.16 Sample size group allocation



	High Health Literacy	Low Health Literacy
Treatment Group	(n=38)	(n=38)
Control Group	(n=38)	(n=38)

4.4.4 Experimental Design

The online survey was administered using an online survey program called Qualtrics. Participants were randomized using Qualtrics' built-in randomizer that randomly assigned participants to one of two groups: 1) a treatment group consisting of four visualizations with a condensed display of medication adherence and BP information (see Appendix C), or 2) a control group consisting of four sets of visualizations for medication adherence and BP that use conventional techniques for displaying medication adherence and BP information in separate visualizations (see

Appendix C). Qualtrics' built-in randomizer allows for blocks (i.e., groups of questions) to be randomly assigned to participants. Visualizations for the treatment and control groups were placed into two blocks, and participants were randomly assigned one of the blocks. The order of presentation of the four visualizations was also randomized within each block. As part of an online Qualtrics survey, each participant was shown the visualizations for either the treatment or control group and asked to evaluate a set of four visualizations depicting all possible combinations of high or low adherence and controlled or uncontrolled BP (LU, HU, LC, HC). For each visualization, the participant answered 6 comprehension questions.

4.4.5 Measures

All measures and their response options are described in Table 4.1. The survey included an assessment of hypertension knowledge, health literacy, visualization comprehension, participant characteristics, and participant demographic information. See Appendix C for a complete version of the survey instrument.

4.4.5.1 Hypertension Knowledge

The Hypertension Knowledge-level Scale (HK-LS) is a reliable (Cronbach's alpha = .82) and validated 22-item correct/incorrect assessment of six dimensions of HTN knowledge, including hypertension definition, treatment, drug compliance, lifestyle, diet, and complications.[13]

The HK-LS was first used among a sample of 457 adults in Turkey. To develop the HK-LS, the authors consulted the cardiology literature and treatment guidelines to create a 52-item scale. This original 52-item scale was assessed for face validity, and content validity was assessed by having a panel of nine experts rank how essential each item was for HTN knowledge. Following the review by the nine panel experts, twelve items were excluded and two sub-domains were dropped. Ten individuals with no medical or research backgrounds were also asked to assess the items in terms of language and clarity.

The HK-LS was found to be reliable after a retest of 417 respondents from the original sample. Construct validity was assessed through principal components analysis. Single-item domains and items with low factor loadings (<0.49) were excluded (n=13). Analysis for internal consistency resulted in the exclusion of 5 items and 2 domains. For the remaining six domains (definition, medical treatment, drug compliance, lifestyle, diet, complications) consisting of 22 items, Cronbach's alpha for the entire scale was 0.82, and alphas for individual domains ranged from poor (0.59) to good (0.92).

Discriminant validity was assessed by first looking at scores for individuals with a history of hypertension, of which scores were significantly higher. In addition, sub-domain scores for medical treatment and complications were significantly higher for those with a history of hypertension. The HK-LS was later successfully used to measure hypertension knowledge among Jordanians[141] using English and Arabic, as well as by Greeks.[142] These studies demonstrate that when translated correctly, the HK-LS can be applied cross-culturally.

The final version of the HK-LS is a 22-item scale, which consists of a mixture of correct (n=13) and incorrect (n=9) statements regarding treatment and complications of hypertension (e.g., "Individuals with increased blood pressure take their medication only when they feel ill"), drug compliance attitudes and behaviors (e.g., “If individuals with increased blood pressure change their lifestyles, there is no need for treatment”), diet (e.g., “The best meat for individuals with increased blood pressure is red meat”), and lifestyle (“Individuals with increased blood pressure can drink alcoholic beverages”). Responses were scored by the total number of statements correctly indicated as true or false. Possible scores range from 0 to 22, with higher scores indicating higher HTN knowledge.

4.4.5.2 Health Literacy

To assess health literacy, patients completed the Health Literacy Skills Assessment Short Form (HLSI-SF).[76] The HLSI-SF is a validated 10-item questionnaire that assesses four domains of health literacy skills: 1) print literacy (reading and writing), 2) numeracy skills, 3) oral literacy skills (listening), and 4) information seeking skills (navigation of the Internet and a facilities map). Scores for the HLSI-SF were calculated by adding the number of correct items. Patients correctly answering 7 or more questions were considered to have adequate health literacy. The HLSI-SF is a short version of the 25-item HSLI. Establishing validity and reliability of the 25-item HSLI included consulting an expert panel regarding the definition of health literacy, important concepts, and the measurement process, cognitive interviews, confirmatory factor analysis, comparisons of means between demographic characteristics and self-reported skills, and correlations with scores on the s-TOFHLA. Confirmatory factor analysis demonstrated good model fit (CFI=0.95, TLI=0.98, and RMSEA=0.03), with factor loadings across the four domains as follows: print-prose (0.98), print-quantitative (0.95), oral (0.85), and Internet (0.81). Higher health literacy scores were found among those with higher education and who were married, and lower scores were found among black (vs. white), retired or disabled (vs. employed), and those with poorer self-reported abilities of understanding the information in the assessment. Correlations between health literacy domains and the S-TOFHLA were highest for print prose (r=0.47), print-document (r=0.45), and print-quantitative skill areas (r=0.41). Correlations between Internet search and oral literacy domains were lower than for the print-related domains; however, this is likely because these domains require fewer reading skills.

During the scale development process for the HLSI-SF, the 10 best performing items were selected using the following *a priori* guidelines: 1) only including items with high factor loadings and Item Response Theory (IRT) slopes, 2) items with correct responses close to 0 or 100%, 3) items with a variety of IRT thresholds and percentage correct to be inclusive of a wide range of health literacy ability levels, 4) excluding items with a high rate of missing data, don't know responses, or confusing and/or irrelevant, and 5) excluding items that do not demonstrate slope-related Differential Item Functioning (DIF). In addition, experts reviewed the wording of selected items to ensure content validity by including items that captured all 5 components of health literacy (print-prose, print-document, print-quantitative, oral, and internet).

Confirmatory factor analysis of the HLSI-SF demonstrated internal consistency, with all individual factors except for one with a factor loading greater than 0.4. The HLSI-SF demonstrated acceptable internal consistency (Cronbach's α = .70). Lastly, the HLSI-SF had a small to moderate correlation with the S-TOFHLA (r=.36), as expected, demonstrating construct validity.

4.4.5.3 Visualization Comprehension

There are no known existing comprehension scales that assess comprehension of data visualizations for medication adherence and BP. To address this gap, I developed and validated a new comprehension scale. Visualizations for medication adherence and BP require comprehension of multiple pieces of information, specifically 1) comprehension of medication adherence information, 2) comprehension of BP information, and 3) comprehension of the implied connection between medication adherence and BP control. In order to improve the measurement of an abstract phenomenon, such as comprehension, multiple questions were developed to assess the phenonmenon.[143,144] Benefits of multi-item scales include more detailed measurement of a concept than a single question and a better measurement of what a set of items have in common.[145] In other words, multi-item scales allow for more nuanced measures of a concept versus a broad measure (e.g., measuring comprehension of more specific components of a visualization) and a better way of measuring an underlying idea or construct than a single question. Thus, multi-item scales are less prone to measurement error and tend to have better reliability than single-item measures.

The HK-LS[13] provides theoretical support that two separate hypertension-related constructs exist in the information visualizations in this study, namely the comprehension of: 1) BP-focused information and 2) medication adherence-focused information. These two hypothesized constructs of hypertension-relation information are closely linked with three subdomains of the HK-LS, specifically 1) hypertension definition (the comprehension of SBP and DBP), 2) drug compliance (medication adherence), and 3) medical treatment (the causal link between medication adherence and BP control). To capture these, a 6-item comprehension scale with multiple items for each construct was developed and reliability and validity were assessed using the techniques described in section 4.5. This scale included six questions that assessed understanding of the correlation between adherence and BP control. Multiple choice questions consisted of correct/incorrect answers. Comprehension scores were calculated as a proportion of correct answers by summing correct answers (0 to 6). Higher scores indicated higher comprehension.

4.4.5.4 Participant Characteristics and Demographic Variables

Table 4.1 Participant characteristics and demographic variables

Variable Type	**Variable Name**	**Description**
Main Outcome	Visualization Comprehension of Each Scenario	6-items (true/false, correct/incorrect) assessing understanding of the correlation between medication adherence and BP control (6 items). Continuous variable scored as proportion correct.
Moderating Variable	Health Literacy	Health Literacy Skills Instrument Short Form (HLSI-SF).[76] 10-items scored as number of items correct (0-10), and coded as low (0-6) and high (7-10).
Control Variables	Patient Characteristics	• Number of currently prescribed medications (count), • Number of currently prescribed hypertension medications (count), • Comorbid conditions (Charlson Comorbidity Index),[146] • Frequency of medication self-monitoring (never, rarely, sometimes, very often, always), • Frequency of BP self-monitoring (never, rarely, sometimes, very often, always), • Smartphone ownership (yes/no), • Wearable health tracking device ownership (yes/no), • Health management app use (yes/no), • Healthcare coverage (private, Medicaid, Medicare, employer-sponsored)
	Hypertension Knowledge	Hypertension Knowledge Scale. 22-item true/false. Scored as sum of correct responses.[13]
	Patient Demographics	• Age (years), • Race (White, Black, Asian, Other-specify), • Ethnicity (Hispanic, non-Hispanic), • Gender (Male, Female), • Education (elementary, some high school, high school graduate, some college or technical school, college graduate, graduate degree, refused), • Income (less than $10,000, $10,000 to $19,999, $20,000 to $29,999, $30,000 to $39,999, $40,000 to $49,999, $50,000 to $99,999, $100,000 or more, refused, don’t know)

Participant characteristics and demographic variables are described in Table 4.1. Participant characteristics assessed include number of all currently prescribed medications (count), currently prescribed HTN medications, comorbidity (calculated using the Charlson Comorbidity Index, which is a sum of weighted scores,1 through 6, assigned to 19 self-reported diseases),[146] frequency of medication and BP self-monitoring (never, rarely, sometimes, very often, always), smartphone ownership (yes/no), wearable device ownership (yes/no), health app use (yes/no), and healthcare coverage (private, Medicaid, Medicare, employer-sponsored). Measures of participant demographic characteristics included age (years), race (White, Black or African American, Asian, Native American or Pacific Islander, Other-specify), ethnicity (Hispanic, non-Hispanic), gender (Male, Female), education (elementary, some high school, high school graduate, some college or technical school, college graduate, graduate degree, refused), and income (less than $10,000, $10,000 to $19,999, $20,000 to $29,999, $30,000 to $39,999, $40,000 to $49,999, $50,000 to $99,999, $100,000 or more, refused, don’t know).

4.4.6 Statistical Analysis

4.4.6.1 Data Quality and Missing Data

Data quality was assessed using a validation check during the survey, which asked each participant to provide an answer to a simple statement (e.g., “Please select ‘Strongly Agree’ below.”), and by assessing survey completion timing data. For the screening instrument, completion times more than 1 standard deviation (5 minutes and 1 second) below the average time to complete (8 minutes and 53 seconds) were not invited to participate in the full study because it is unlikely valid responses could occur in less than 3 minutes and 53 seconds considering the instrument consisted of 2 minutes and 13 seconds of multimedia (i.e., an audio and video clip) necessary for completing questions. For the full survey, completion times less than 5 minutes were not included in analysis because such a short completion time would suggest the participant did not read and appropriately respond to survey questions.

While the survey was designed to limit respondent burden, missing data from some participants occurred. To minimize this, pop-up reminders were used to alert participants when a question was missing a response. Missing data were addressed using mean imputation, where missing values were replaced by a calculated value equal to the mean of available cases for each item. This method allows the sample size to be maintained, however, it may lead to underestimated standard deviation and variance estimates.[147] This method is preferred over casewise deletion because casewise deletion reduces power by lowering the overall sample size. In addition, limited project resources do not allow for oversampling. There is no established cutoff from the literature for an acceptable proportion of missing data that does not bias statistical inference. In particular, there is no established cutoff for determining whether missing values should be imputed versus deletion of the entire case (i.e., casewise deletion). The effect of missing data on statistical inference is driven by several factors, including the pattern of missing data (e.g., missing at random, missing completely at random, missing not at random), and the type of missing data (e.g., control variables versus the main outcome variable).[148] For all study variables, a cutoff for missing measures was set at 25% before a case was deleted. In addition, a cutoff of 25% of missing data for the comprehension measures was also applied. Any imputed data were noted as a limitation of the study that may bias parameter estimates.

4.4.6.2 Descriptive Statistics

Descriptive statistics for all variables were calculated to characterize the sample. Frequencies and percentages were calculated for race, gender, education, income, frequency of medication and BP self-monitoring, smartphone and wearable health tracking device ownership, health app usage, and healthcare coverage, and health literacy. Means and standard deviations were calculated for health literacy, HTN knowledge, visualization comprehension, number of currently prescribed HTN medications, comorbidities, and age.

4.4.6.3 Experiment Analysis

Differences in comprehension between the treatment and control groups were assessed using multiple regression. Because comprehension was assessed for four separate combinations of medication adherence and BP control (LU, HU, LC, HC), a repeated measures model was assessed using the Proc Mixed procedure in SAS Version 9.4 (SAS Institute, Inc. Cary, NC, USA), which accounts for within-subject correlations by including a within-subject covariance structure as part of the overall model residual. A treatment*health literacy interaction term was used to assess the moderating effect of health literacy. A visualization type variable was also included to assess differences in comprehension between different visualization types. A treatment*visualization type interaction term was included to assess the magnitude of influence of each visualization type on comprehension. To assess which control variables to include, backwards step-wise multiple regression was used. First, all variables except the independent variables (the experimental condition and health literacy) and interactions (treatment*health literacy and treatment*visualization type) were included in a regression and evaluated individually to assess whether each met inclusion criteria ($p \leq .05$). Those variables that met inclusion criteria were then included in a multiple regression with the independent variables and interaction terms. Multicollinearity was assessed using the variance inflation factor (VIF). All analyses used an a priori significance level of alpha=.05. Because comprehension was assessed for four separate scenarios (high/low medication adherence and controlled/uncontrolled BP control), a Bonferroni alpha correction was made if the treatment*visualization type interaction was significant (alpha=.05/4). Interaction terms that were not significant were excluded from the model.

Full model: $Y= \alpha + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_1X_2 + \beta_5X_1X_3 + \beta_iX_i + \boldsymbol{\varepsilon}$

where:

Y = visualization comprehension

α = control group mean for comprehension holding controls constant

β_1 = parameter estimate for treatment group

β_2 = parameter estimate for health literacy

β_3 = parameter estimate for visualization type

β_4 = parameter estimate for treatment*health literacy interaction

β_5 = parameter estimate for treatment*visualization type interaction

β_i = parameter estimate for control variables (participant characteristics, participant demographics, HTN knowledge)

X_1 = experimental group (0 = control, 1 = treatment)

X_2 = health literacy (0 = low, 1 = high)

X_3 = Visualization Type (LU, HU, LC, HC)

X_i = control variables (participant characteristics, participant demographics, HTN knowledge)

ε = residuals including within-subject covariance

4.5 Aim 3 Methods

Aim 3 assessed the validity and reliability of the 6-item comprehension scale using exploratory and confirmatory factor analysis and Kruder-Richardson-20.[149]

Specific Aim 3: *Assess the validity and reliability of a newly-developed 6-item scale to assess patient comprehension of data visualizations.*

4.5.1 Exploratory and Confirmatory Factor Analysis of the 6-item Comprehension Scale

It was hypothesized that an underlying unidimensional solution exists for comprehension of visualizations for medication adherence and BP information. However, I assessed whether an underlying two-factor solution exists (for medication adherence-focused and BP-focused comprehension of the correlation between medication adherence and BP control). These two possible factors, or latent constructs (L_1 and L_2), were measured using six separate indicators, or questions (Z_1 through Z_6) described below and in Figure 4.17. As Figure 4.18 shows, it was assumed that a two-factor solution would fall under a superorder construct of visualization comprehension:

Figure 4.17 Path diagrams for the hypothesized unidimensional solution for visualization comprehension

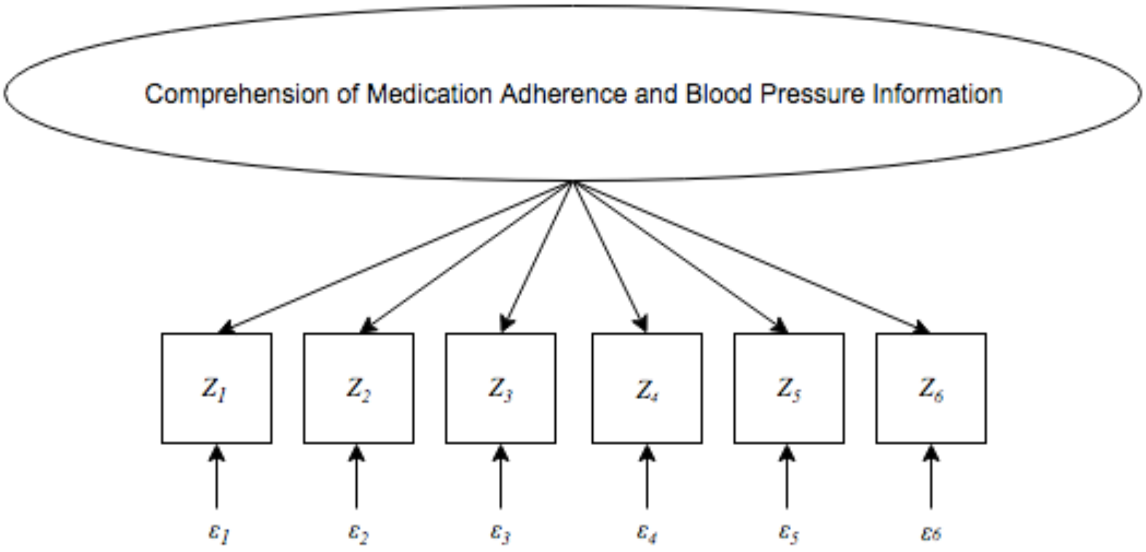
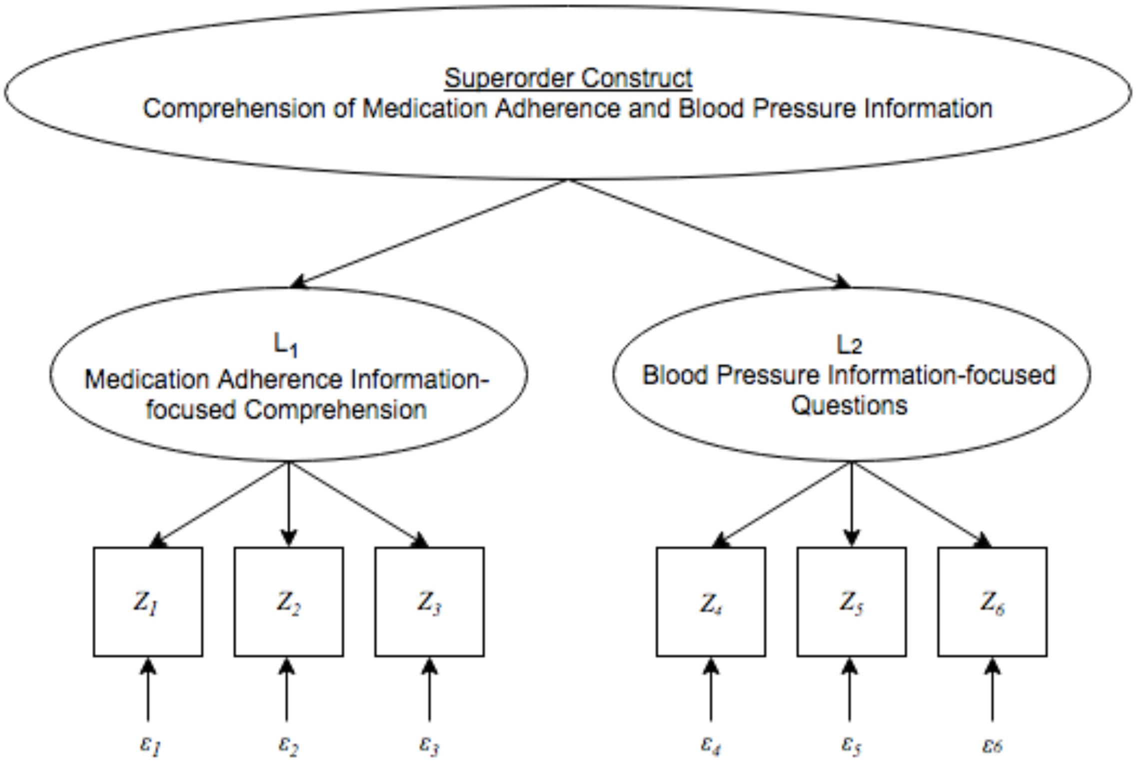


Figure 4.18 Path diagram for alternative 2-factor solution for visualization comprehension



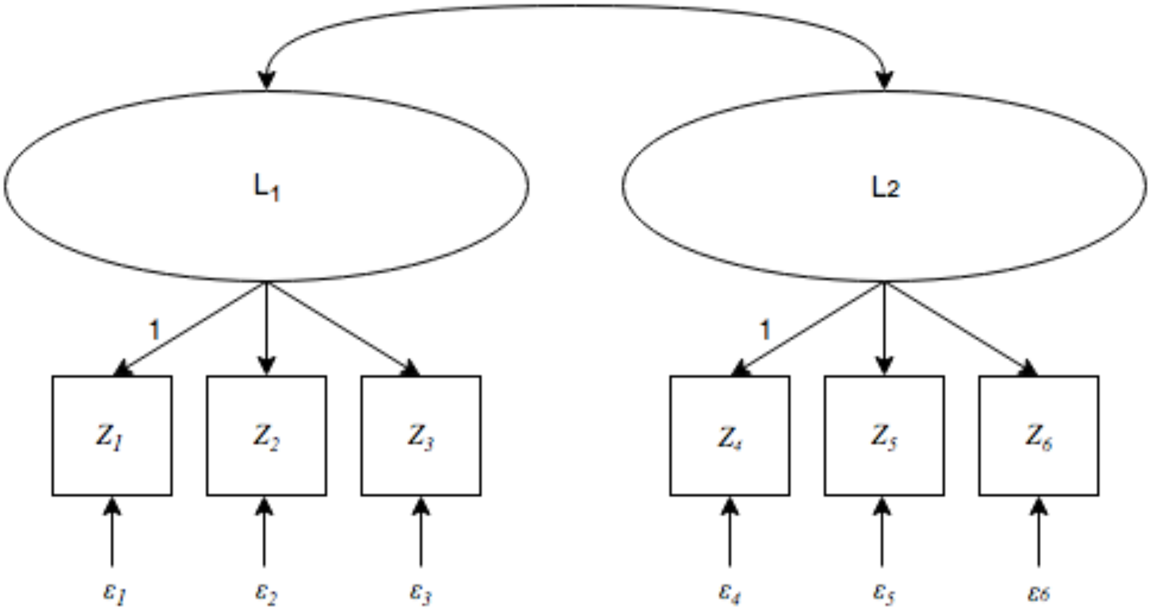
First, exploratory factor analyses using principal component analysis (PCA) with promax rotations were conducted for the LU and HU visualization comprehension measures.[150] Parallel analysis was also conducted to further validate the number of underlying factors of the 6-item scale. Next, confirmatory factor analysis was performed to assess dimensionality of the comprehension scale and to evaluate model fit for the LC and HC visualization comprehension measures. First, to assess dimensionality, two nested model comparisons were made using chi-square difference tests to assess the correlations between L_1 and L_2. A chi-squared test statistic with a $p<.05$ threshold was used to determine if the correlation between the latent variables significantly differed from 1, which would confirm a two-factor solution (i.e., more than one dimension). To evaluate goodness of fit for each model, a chi-square test statistic, Tucker-Lewis Index (TLI),[151] Incremental Fit Index (IFI),[152] Relative Non-centrality Index (RNI),[153,154] Root Mean Square Error of Approximation (RMSEA),[155] and Bayesian Information Criterion (BIC),[156] were calculated. A priori criteria for determining a good fit are as follows: χ^2 $p > .05$, TLI $> .9$ and ≤ 1.0, IFI $> .9$ and ≤ 1.0, RNI $> .9$ and ≤ 1.0, RMSEA ≥ 0 and $< .1$, and BIC < 0. Exploratory factor analysis was performed using SAS software version 9.4 (SAS Institute, Inc. Cary, NC, USA) and confirmatory factor analysis was performed using Lavaan in R.[157]

4.5.1.1 Model Identification

Both the unidimensional and two-factor models are identified. The hypothesized unidimensional model consists of six indicators. For the two-factor solution, each latent variable consists of three indicators. The path diagram in Figure

4.19 shows the relationship of the latent variables, the indicators, and the errors to one another. As shown in Figure 4.19, Z_1 and Z_4 are scaled to 1. The two-factor model is identified per the three-indicator rule in that it has the following characteristics: 1) each latent variable has 3 indicators, 2) there is only one non-zero element in each row of $\boldsymbol{\Lambda}$ (i.e., each indicator variable is linked to only one latent variable and no other indicator variables), and 3) $\boldsymbol{\Sigma_{\varepsilon\varepsilon}}$ is diagonal (i.e., the errors of the indicators can only correlate with themselves and not one another).[158] These criteria are illustrated in the path diagrams and equations shown in Figure 4.19.

Figure 4.19 Path diagrams and equations for Λ and Σεε for the 6-item comprehension scale



$$\mathbf{\Lambda} = \begin{bmatrix} 1 & 0 \\ \Lambda_{21} & 0 \\ \Lambda_{31} & 0 \\ 0 & 1 \\ 0 & \Lambda_{52} \\ 0 & \Lambda_{62} \end{bmatrix}$$

$$\mathbf{\Sigma}_{\varepsilon\varepsilon} = \begin{bmatrix} \Sigma_{\varepsilon_1\varepsilon_1} & & & & & \\ 0 & \Sigma_{\varepsilon_2\varepsilon_2} & & & & \\ 0 & 0 & \Sigma_{\varepsilon_3\varepsilon_3} & & & \\ 0 & 0 & 0 & \Sigma_{\varepsilon_4\varepsilon_4} & & \\ 0 & 0 & 0 & 0 & \Sigma_{\varepsilon_5\varepsilon_5} & \\ 0 & 0 & 0 & 0 & 0 & \Sigma_{\varepsilon_6\varepsilon_6} \end{bmatrix}$$

To assess model fit for each individual latent variable for the two-factor solution, an additional constraint was put on each model by adding an estimated factor loading from the full unidimensional model because each individual latent variable model with only three indicators is exactly identified.

4.5.1.2 Correlated Errors

Figure 4.19 depicts a path diagram that shows the hypothesized relationship between the indicators, their errors, and the latent variables. No correlation between the errors of the indicators is modeled because it is assumed that the respective underlying latent variable captures all association between the indicators, however latent variables are allowed to freely correlate because it is assumed there is an underlying superorder factor of overall information visualization comprehension.

4.5.2 Convergent Validity

Convergent validity was assessed by analyzing correlations between HK-LS (hypertension knowledge) scores and comprehension scores, and high correlations suggested convergent validity.

4.5.3 Scale Reliability

For each subscale, Kuder-Richardson Formula 20 (KR-20) was calculated.[149] A cut-off of $\rho_{KR20} > .70$ was used, which is the lower bound of acceptable reliability for a scale.[149] For $\rho_{KR2} < .70$, each item was correlated with the total score for the subscale, and low correlations (approaching zero) were removed.[159] Model fit and KR-20 were then reassessed on the newly-specified model.

CHAPTER 5: USER ASSESSMENTS OF HYPERTENSION-RELATED INFORMATION VISUALIZATIONS FOR SELF-MONITORING MEDICATION ADHERENCE AND BLOOD PRESSURE

5.1 Overview

Background: Technology-based hypertension self-management tools (e.g., mobile apps, text messages, Bluetooth-connected devices) have been shown to improve patients' blood pressure control. Although many self-management technologies rely on the visualization of patient data to provide feedback, no known research has assessed patient preferences for visualizing information related to hypertension self-management, including feedback on changes in blood pressure and medication adherence.

Objective. To assess: 1) the current state of information visualizations used in mobile apps for monitoring blood pressure and medication adherence; and 2) patient preferences for hypertension-related information visualizations for medication adherence and blood pressure monitoring, including whether they prefer separate or condensed visualizations for these data.

Methods. Semi-structured interviews were conducted with a purposive sample of adults who self-reported taking at least one medication for hypertension and owned a smartphone (n=6). Participants viewed and evaluated several information visualizations displaying medication adherence and blood pressure information and provided preferences for visualization features. Interviews were audio-recorded, and preferences were coded by two coders, who reached

consensus on patient preferences for the following features: 1) labels, 2) terminology, 3) reference lines, 4) indicators of medication adherence, 5) perceptually distant color and symbol pairs, and 6) displaying medication adherence as a calendar versus list view.

Results. Two participants had low health literacy. Participants preferred culturally recognizable and context appropriate symbols, such as a “✓” to indicate something positive and X’s to indicate something negative. They also preferred blue/orange color pairs for indicating medication adherence, labeled blood pressure data points, and reference indicators of a “normal” blood pressure zone. For visualizations showing condensed blood pressure and medication adherence information, participants preferred using symbols with a line graph versus color coding blood pressure lines or using shaded regions. For visualizations that displayed only medication adherence, participants preferred a calendar view as opposed to a list view.

Conclusions. Regardless of health literacy level, participants’ preferences for adherence and blood pressure visualizations were quite similar. Apps that include blood pressure and adherence visualizations should incorporate patient preferences.

5.2 Introduction

Hypertension (HTN), or high blood pressure (BP), affects approximately 70 million (29%) adults in the U.S. and is associated with $46 billion in health care costs, medication costs, and missed days of work.[2,29] It is projected that by 2030, 41.4% of adults in the U.S. will have HTN.[29] What makes HTN particularly dangerous, and why it is referred to as a “silent killer,” is that patients often overlook symptoms of high BP or are asymptomatic, which makes self-monitoring (personal tracking of one's own BP levels) of BP essential.

Medication non-adherence among patients with HTN is important because it has direct negative impacts on health outcomes, increases mortality, and contributes to $290 billion in costs to the U.S. health care system each year.[3] It is estimated that approximately 45% of patients prescribed at least one anti-hypertensive medication discontinue medications within a year of initial prescription.[4] Among patients with HTN, determinants of non-adherence include demographic factors such as age[5–7] and race,[6,8] as well as health literacy. [8–10] Specifically, several studies have shown positive associations between health literacy and antihypertensive medication adherence[8–10] and BP control[9,56–60] among patients with hypertension.

5.2.1 Technology and hypertension self-management

In 2018, 77% of adults in the U.S. owned a smartphone,[21] and 27% of U.S. patients with a known heart condition or risk used wearable health tracking devices to monitor their condition.[100] Mobile-based interventions are increasingly capable of addressing barriers to medication non-adherence.[101] Among patients with HTN, mobile self-monitoring of BP and medication adherence have been shown to improve BP control.[102–104] Mobile-based BP self-monitoring interventions include the use of personal digital assistants (PDA),[105] smartphone apps,[106] text messages,[107,108] and Bluetooth monitoring devices connected to smartphones.[103,109,110] Several BP self-monitoring interventions have also included some form of digital interface for viewing BP results, either directly on a device or through a web portal.[103,105,107–114] In a 2014 review of 424 mobile applications supporting medication self-management, Bailey et al found that nearly 18% of apps used visual aids.[26] Such visual aids can take several forms, including graphs that chart adherence over time or photos of pills to help identify a medication. In addition, several emerging cutting-edge technologies for self-monitoring HTN are being developed and tested, including wireless or Bluetooth-enabled BP cuffs and non-invasive wireless and wearable sensors for measuring BP that are embedded in an ultra-thin adhesive patch.[115,116]

5.2.2 Data Visualizations for Hypertension Self-management

An important component of many technology-based HTN self-management tools are the visualization of patient data, namely tracking medication adherence and changes in BP. It is important that the design of such visualizations adhere to guidelines and best practices for visualizing patient data and give consideration to prior research in the effectiveness of successfully communicating data to the patient. Guidelines and best practices for visualizing patient data are driven largely by considerations for health literacy, numeracy, and graph literacy.[120] Although there are no known best practices for specifically visualizing either medication adherence or BP information, best practices exist for visualizing the type of data that underlie such information.[20,121,122] Specifically, there are best practices to visualize dichotomized and continuous variables over time.[121] Although best practices for communicating information using lists, charts, and graphs for individuals with low health literacy suggests that lists are best for monitoring information over time,[123] it is unknown what, if any, type(s) of visualizations might facilitate a patient's ability to make sense of patient data intended to illustrate the relationship between medication adherence and BP over time, (e.g., derive trends about the effect that medication adherence might have on BP levels).

While visualization design should be driven in large part by research in visual perceptions and existing guidelines and best practices, the subjective element of aesthetic preference is also an important consideration. Aesthetic preference has been related to how accurate and quickly one can retrieve information from a visualization, further underscoring its importance in the context of BP monitoring.[129] Furthermore, assessing preference is important as the same information can be visualized in multiple ways (e.g., color-coding versus symbols). For instance, line graphs have been shown to be preferred for communicating gist, trends, and contrast between data points, while shaded line graphs are often preferred for communicating information to be retained for longer periods of time.[124] So while the use of line graphs may be the easiest to understand for patients viewing their own personal data,[125] adding features (e.g., colors and symbols) in certain contexts may require patient preference assessments.

The purpose of this study is to describe the current state of visualization of BP and medication adherence data for HTN apps and assess user preferences for data visualizations for medication adherence and BP tracking over time. First, we searched the Apple and Google Play app stores for the top 10 blood pressure tracking apps and the top 10 medication tracking apps, and assessed the visualizations used in these apps to present blood pressure and medication adherence information. We then employed a user-centered approach[137] to assess user preferences for specific data visualization features, such as reference markers, colors, symbols, and terminology.

5.3 Methods

5.3.1 Participant Recruitment

Six participants were recruited from an existing pool of adult HTN patients who participated in a prior study that tested an electronic health record-based strategy for the routine assessment of medication self-management skills among primary care patients with complex drug regimens. These participants were initially recruited from an internal medicine clinic in North Carolina at an academic medical center. For this study, participants were purposively recruited based on gender (3 males and 3 females), race/ethnicity (3 White, 3 non-White, and at least 1 Hispanic), health literacy (at least 2 participants with less than adequate health literacy as assessed via the Rapid Estimate of Adult Literacy in Medicine[79]), and education (at least 2 with a high school diploma or less and at least 2 college graduates). Eligible participants were over 18 years of age, spoke and read English, had a self-reported diagnosis of HTN, were prescribed at least one medication to treat their HTN, and owned a smartphone. A total of 10 individuals were contacted, two of which were not interested in participating, and two of which had unresolved scheduling conflicts. All participants provided written consent.

5.3.2 Data Visualization Design

For our first objective, to understand how visualizations are currently used in medication adherence and BP monitoring and better understand what visualizations characteristics warrant further investigations into preferences, we searched both the Apple App and Google Play App stores for the top 10 medication tracking and BP monitoring apps (i.e., the top ten results in each store). The top 10 were determined by the order in which they appeared in the search results. The apps were then evaluated for the following characteristics of their visualizations: the use of symbols, using numeric values (e.g., percent adherence, mmHg), line graphs, color-coding, a calendar view, a list view, and the use of other charts (e.g., bar charts, scatterplots).

For our second objective, visualizations used in the semi-structured interviews were based on known parameters concerning the pharmacology of Lisinopril[136] and standard definitions of HTN.[30] Lisinopril is the most commonly used antihypertensive drug, and is prescribed to approximately 20% of the hypertensive population.[34] The antihypertensive effect of Lisinopril starts to rapidly drop-off after 24 hours, which suggests two consecutive missed doses for individuals taking Lisinopril once daily could result in elevated BP levels.[136] All visualizations depicted medication adherence and BP information over a two-week (14-day) period using the following criteria:

- Low medication adherence was shown as 50% adherence (i.e., medications only taken 7 of the 14 days)
- Days of nonadherence were randomly chosen using a random number generator
- All BP levels were chosen using a random number generator
- Elevated systolic BP was presented as between 140 and 210 mmHg
- Elevated diastolic BP was presented as between 90 and 100 mmHg
- Controlled systolic BP was presented as between 100 and 120 mmHg
- Controlled diastolic BP was presented as between and 70 and 80 mmHg

5.3.3 Data Collection Procedure and Measures

In-person semi-structured user assessment interviews were conducted to assess preferences of key features of visualizations for medication adherence and BP information, and preferences for approaches to condense the display of medication adherence and BP information into a single visualization. Participants were provided paper copies of all visualizations discussed during the interview (see Appendix A for all visualizations used). Each interview was audio recorded using a digital audio-recorder, and audio recordings were analyzed by two coders (AS and AD), along with any supplemental notes taken during the interview. Interviews lasted approximately 30 minutes, and participants were given $25 cash as an incentive. All participants provided written informed consent. This study was approved by the UNC Institutional Review Board.

Prior to commencing the user assessment interviews, participants reported their age in years, gender, race (White, Black, Other-specified) and ethnicity (Hispanic, non-Hispanic), whether they had hypertension, whether they took medication to control their high blood pressure, and whether they owned a smartphone. Participants were also administered the Rapid Estimate of Adult Literacy in Medicine (REALM),[79] which is an in-person health literacy assessment that determines how many of 66 health-related terms are pronounced correctly. Correctly pronounced words for the REALM are summed to produce a score, and scores less than 61 are considered less than adequate.

During the interview, participants were first presented with a color palette with 5 perceptually distant pairs based on previous research in perceptions of color differences,[128] and asked to choose which pair best represents something positive and negative, such as taking medication and missing a dose of medication, and if there are different colors not shown that they would prefer. Participants were then asked which pair they preferred and to explain why they chose that color pair. The same procedure was repeated to assess patient preferences for perceptually distant symbols and the preferred symbol pair.

To assess the terminology used with the visualizations, we asked participants if they understood the following words and phrases: “blood pressure level,” “systolic BP,” “diastolic BP,” “day of week,” “taken medication,” “missed dose,” “medication,” and “controlled BP zone.” We also asked if there were any other words or phrases they would use instead. If participants did not understand a word or phrase, we explained the meaning and asked what they would call what was described. Participants were also asked if any of the following label terms appearing on the graphs were confusing: Blood Pressure Level, Day of Week, Systolic BP, Diastolic BP, and Taken Medication/Missed Dose, and Controlled/Normal BP Zone. They were then asked if there were any other terms they would use in place of those presented. Figures 5.1 and 5.2 present how these terms were displayed on visualizations.

Figure 5.1 Line graph with controlled BP zone

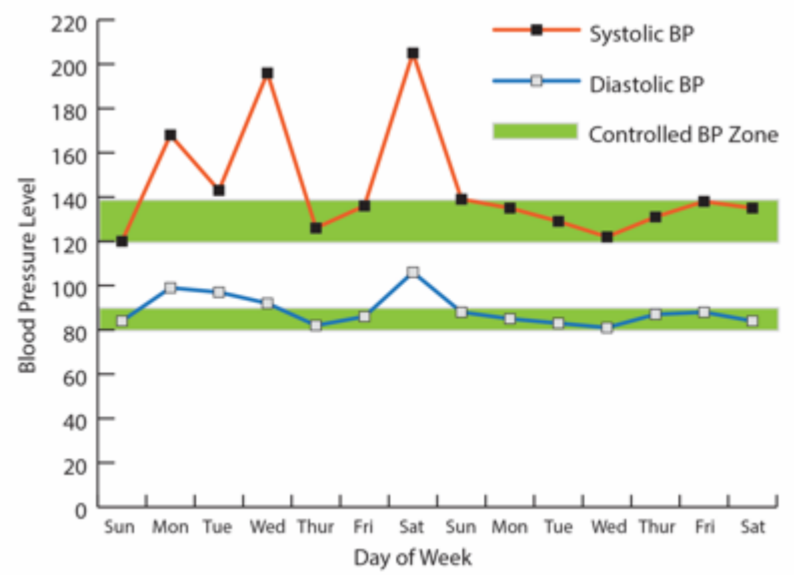
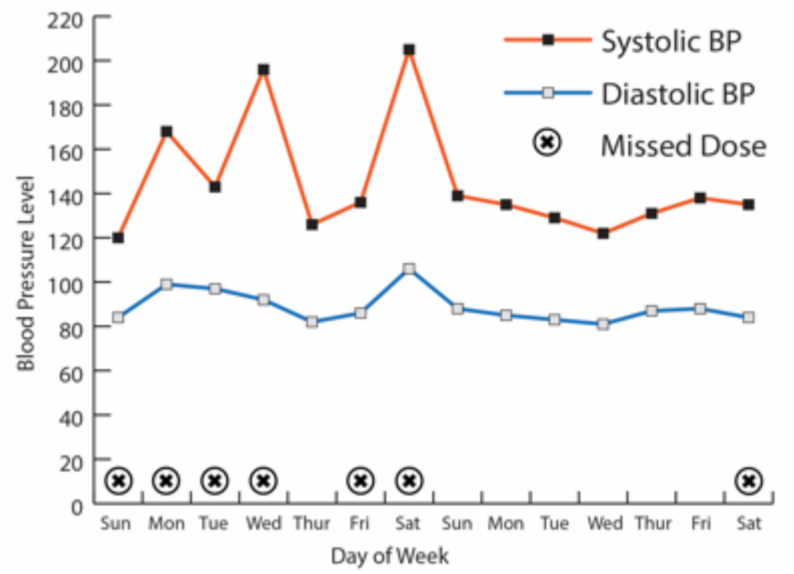


Figure 5.2 Line graph with symbols indicating medication adherence



Next, participants were shown a series of graphs and their preferences for labeled values, reference lines, and shaded “Normal BP Zones” (shown in Figure 5.1). Participants were then asked which graphs they preferred and why. Throughout the interviews, responses were probed for confusing aspects of the visualizations.

To assess preferences for visualizations that condense the display of medication adherence and BP information, participants were shown three types of visualizations: 1) color-coded BP lines to indicate medication adherence/non-adherence (Figure 5.3), 2) the use of shaded regions under lines to indicate medication adherence/non-adherence (Figure 5.4), and 2) the use of symbols to show medication non-adherence for each missed dose that appeared on or below the BP lines (see example in Figure 5.2). Participants then ranked each visualization by preference, explained their preferences, and identified any confusing aspects about each visualization. Participants also were shown three versions of the visualization using symbols that vary the position of the symbols within the graph (for example, Figure 5.2 shows symbols placed along the X-axis), and asked which version they preferred and why.

Figure 5.3 Line graph with color-coded lines indicating medication adherence

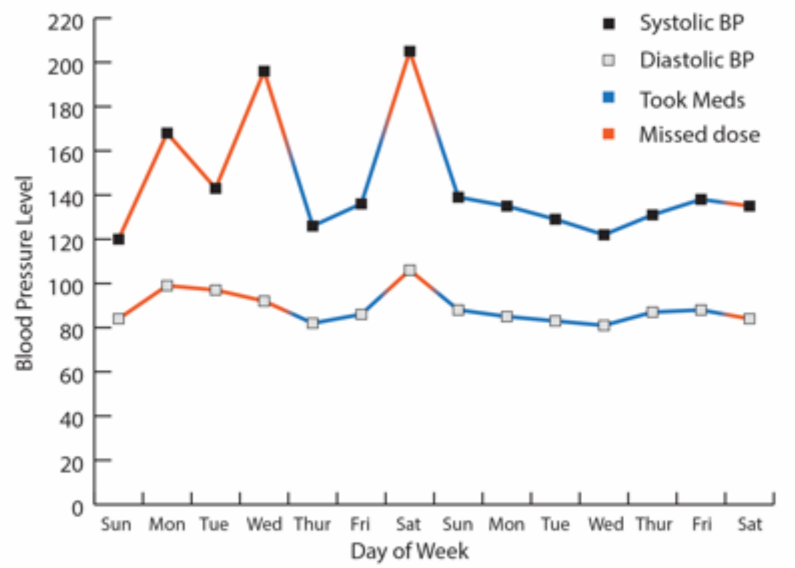
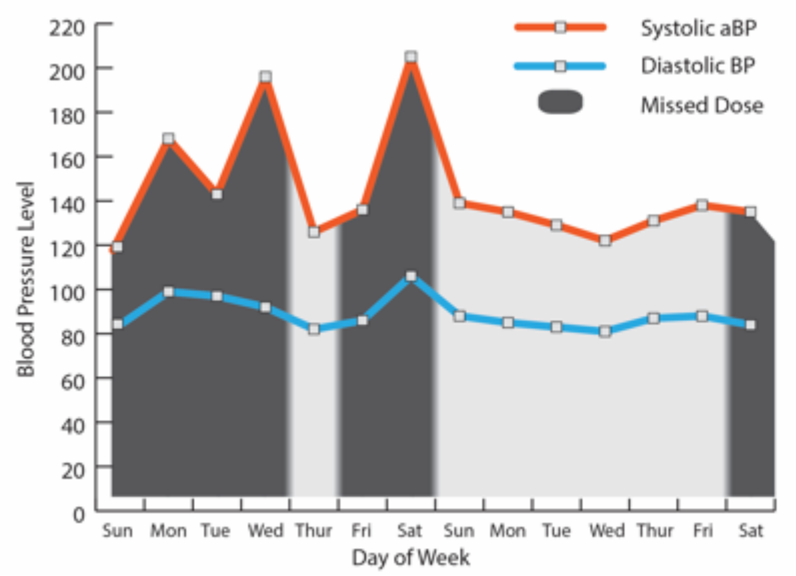


Figure 5.4 Line graph with shaded region to show medication adherence



Finally, participants were asked if they preferred a calendar versus list view to track medication adherence.

5.3.4 Data Analysis

Interviews were audio-recorded to facilitate coding and analysis. Unique IDs were assigned to each participant to de-identify responses. Two independent coders (AS and AD) listened to the audio-recorded interviews and coded responses to questions assessing preference. Both coders coded all six interviews. Cohen's Kappa was calculated to assess inter-coder reliability.[160] Disagreements in categorization were discussed between the coding team and resolved.

Participant responses to visualizations/features were coded as 1) positive reactions (e.g., liked, preferred) 2) negative reactions (e.g., disliked, not preferred), or and 3) unsure (e.g., a neutral reaction, neither liked or disliked).[137] Confusing aspects (e.g., unsure of the feature's meaning) were also noted. In addition, suggestions for improvement for each visualization feature were coded into themes as they emerged. For each feature, reactions (positive or negative) were coded and tallied to calculate frequencies, and preferences were determined as the percentage of participants with a positive reaction.

5.4 Results

5.4.1 Common Data Visualizations in Existing Apps

Results of the Apple and Google Play app store searches are shown in Table 5.1. All apps that were reviewed were unique; there were no duplicative apps between the Apple and Google Play app stores. The most widely-used mobile apps for “medication tracking” used a dichotomized “yes” or “no” presentation of adherence and often utilize color-codes (e.g., red for non-adherence and green for adherence), symbols (e.g., ☑ versus ☒), a list or calendar view, or percent adherence. The most widely-used mobile apps for “blood pressure tracking” use two-line graphs to simultaneously chart trends in systolic and diastolic BP over a certain length of time and are color-coded. Color-coding schemes generally use red to indicate high BP, green to indicate well-controlled BP, and some include yellow to indicate moderately elevated BP.

Table 5.1 Visualizations methods in medication tracking (n=20) blood pressure monitoring apps (n=20)

	Use of Symbols n (%)	Numeric Value n (%)	Line Graph n (%)	Color-coded n (%)	Other Charts n (%)	Calendar View n (%)	List View n (%)
Medication Adherence	5 (25)	5 (25)	-	11(55)	5 (25)	7 (35)	20 (100)
Blood Pressure	2 (10)	20 (100)	18 (90)	16 (80)	12 (60)	4 (20)	-

5.4.2 Sample Characteristics

Table 5.2 summarizes characteristics of the study participants. The sample included 3 males and 3 females, with an average age of 55.7 years. Three participants were white, 2 were black, and 1 was Hispanic. Two participants had a college degree or more, 2 had some college, and 2 had a high school diploma or less. Two participants had less than adequate health literacy as measured via the REALM.[79]

Table 5.2 Sample characteristics

Characteristics (N=6)	n (%)/Mean (SD)
Age, *Mean (SD)*	55.7 (10.8)
Male	3 (50)
Race/ethnicity	
Non-Hispanic White	3 (50)
Non-Hispanic Black	2 (33)
Hispanic	1 (17)
Less than adequate health literacy (REALM)	2 (33)
Education	
College	2 (33)
Some College	2 (33)
High School or less	2 (33)

5.4.3 Visualization Preferences

Table 5.3 summarizes visualization preferences. All participants (n=6) preferred labeled data points. Using a shared “Normal BP Zone” for reference was preferred by most participants (n=5). All participants (n=6) preferred the use of symbols for visualizations that condense the display of BP and medication adherence information into one graph. There was some disagreement as to the best location to place symbols, with three participants preferring the X-axis (n=3). When visualizations just presented medication adherence (no blood pressure data), all participants (n=6) preferred a calendar view. Table 5.4 presents the inter-coder reliability scores, which ranged from substantial (κ =.76) to perfect agreement (κ = 1).[161]

Table 5.3 Visualization preferences

	n (%)
Labeled data point	
Preferred labeled data points	6 (100)
Reference Lines	
Preferred horizontal reference lines	1 (17)
Preferred vertical reference lines	1 (17)
Preferred grid reference lines	4 (67)
Found the “Normal BP Zone” helpful	5 (83)
Medication Adherence Indicators on Graph	
Prefer color-coded line	-
Prefer shaded region	-
Prefer symbols	6 (100)
Symbol Location	
Prefer symbols on line	2 (33)
Prefer symbols close to line	1 (17)
Prefer symbols next to X axis	3 (50)
Medication Adherence Only	
Preference for Calendar View	6 (100)
Preference for List View	-

Table 5.4 Inter-coder reliability scores for coding on patient preferences

	Kappa
Preferences for colors	1
Preferences for symbols	0.76
Preferences for labeled data points	1
Preferences for reference lines	1
Preferences for normal BP zone	1
Preferences for condensed display	1
Preferences for symbol location	1
Preferences for terminology	0.86
Preferences for calendar vs. list view	1

5.4.4 Label Preferences

All participants (n=6) preferred labeled data points compared to no labels. As one participant noted *“there’s no guessing what the number is” (White, Male, 57)*. However, as one participant noted, labeling specific values is not necessary if the objective of the graph is to highlight abnormal BP because spikes in values were generally noticeable, and reference lines and shaded normal BP zones were more helpful in determining abnormal values. *“I think [Figure 5.1] is better for people who aren’t interested in the absolute numbers but summarizing ‘am I doing the best thing for my health.’ I look at this [Figure 5.1] and immediately know there’s something happening on these days and I would prefer to be here [normal BP zone]” (White, Male, 69).*

5.4.5 Reference Line Preferences

Most participants (n=4) preferred a reference gridline, and nearly all (n=5) participants found the green shaded region that indicated a controlled or normal BP zone helpful (Figure 5.1). In response to the gridlines, one participant noted *“you* *know exactly where things are" (White, Male 57)*; however, both individuals with low health literacy described the gridlines as "too much." Describing the usefulness of the green shaded region for controlled or normal BP, one participant noted *"it immediately tells you to pay attention… there's something going on here" (White, Male, 69).*

5.4.6 Shading, Color-coding, and Symbols for Medication Adherence

When combining medication adherence information on a line graph for BP, all participants (n=6) preferred the graph with the shaded region (Figure 5.4) over the color-coded line (Figure 5.3). As one participant noted *"The multiple colors is confusing" (Black, Female, 38).* However, all participants (n=6) preferred the graph that used symbols more than the graph with the shaded region and the graph that used color-coded lines. Referring to both graphs, one participant noted *"It's too much" (Hispanic, Female, 56).*

There was some disagreement regarding the optimal placement of symbols on the graph. Half of the participants (n=3) preferred the symbols at the bottom of the graph, closer to the day of week axis, a third of participants (n=2) preferred the symbols on the line, and one participant (n=1) preferred the symbols below the line (Figure 5.2).

5.4.7 Calendar versus List View for Medication Adherence

All participants (n=6) preferred a calendar view for medication adherence when compared to a list view. Participants noted a list view as confusing and required more effort. As one participant noted *"[the calendar] is easier because I know what day it is, [the list] I have to search" (White, Male, 57).*

5.4.8 Terminology

Most participants understood all of the terminology on the visualizations. Most participants (n=4) said they would call systolic and diastolic BP either “upper and lower,” “top and bottom,” or “high and low” numbers. During the second interview, a participant with low health literacy was unsure about the phrase “controlled BP zone.” When it was explained, the participant responded, *“I would call this normal blood pressure” (Black, Female, 38).* Thus, after the second interview, the phrase “normal BP zone” was used for all remaining interviews and was understood by all four remaining participants.

5.4.9 Perceptually Distant Color Preferences

Table 5.5 shows results for perceptually distant color preferences, including positive and negative associations for each color pair, and the overall preferred color pair. Two-thirds of the participants (n=4) preferred the blue/orange color pair, while a third (n=2) preferred the pink/green color pair. A few participants commented on the blue/orange pair, with one participant noted they were “*distinct colors” (Hispanic, Female, 56)*, and another noting *“when it comes to colors, it sticks out more” (Black, Female, 38)*. The positive/negative association with the blue/orange color pair was split, with half (n=3) associating blue with positive, and half (n=3) associating orange with positive. However, when asked about the blue/gray color pair, all participants associated a lighter blue with positive. One-third of participants (n=2) suggested a more culturally recognizable color pair of green/red, one participant noting *"The green is good. If you had green and red that would be perfect” (White, Male, 57).* These preferences did not differ by health literacy level. It is worth noting that despite being culturally associated with positive/negative meanings, we did not use a red/green color pair in order to better ensure results are more likely to be applicable for those with red/green colorblindness.

Table 5.5 Perceptually distant color preferences and positive/negative associations

	Positive n (%)	Negative n (%)	Preferred Pair n (%)
🟩	4 (66)	2 (33)	2 (33)
🟪	2 (33)	4 (66)	
⬛	-	6 (100)	-
🟦	6 (100)	-	
🟫	2 (33)	4 (66)	-
🟥	4 (66)	2 (33)	
🟨	2 (33)	4 (66)	-
🟪	4 (66)	2 (33)	
🟧	3 (50)	3 (50)	4 (66)
🟦	3 (50)	3 (50)	

5.4.10 Perceptually Distant Symbol Preferences

Table 5.6 shows results for perceptually distant symbol preferences, including positive and negative associations for each symbol pair, and the overall preferred symbol pair. All participants (n=6) preferred the “✓”/”X” symbol pair, and nearly all participants (n=5) made a positive association with the “✓” and a negative association with the “X.” It is possible the one participant associating the “✓” with negative and the “X” with positive was confused, as this participant had less than adequate health literacy.

Table 5.6 Perceptually distant symbol preferences and positive/negative associations

	Positive n (%)	Negative n (%)	Preferred Pair n (%)
○	-	6 (100)	-
+	6 (100)	-	
▷	3 (50)	2 (33)*	-
□	2 (33)*	3 (30)*	
✱	5 (83)	1 (17)	-
✕	1 (17)	5 (83)	
◇	2 (33)*	2 (33)*	-
▽	2 (33)*	2 (33)*	
◁	-	4 (66)*	-
△	4 (66)*	-	
✓	5 (83)	1 (17)	-
⊘	1 (17)	5 (83)	
✓⃝	5 (83)	1 (17)	6 (100)
⊗	1 (17)	5 (83)	

*Missing values are “don’t know” responses

5.4.11 Other Preferences and Suggestions

When asked which features they would combine, most participants (n=4) mentioned the use of symbols with the green normal BP zone. Some participants (n=2) also suggested colors for the normal BP zone be a lighter shade.

5.5 Discussion

There are no known studies that assess preferences for information visualizations displaying blood pressure and medication adherence information over time. While guidelines and best practices provide a path for designing more effective visualizations, particularly for individuals with less than adequate health literacy, there remains flexibility to incorporate patient preferences for some visualization features. This study seeks to address this gap in the literature by assessing patient preferences for visualization features in order to develop visualizations that optimize a patient's ability to understand the information that is communicated, and ultimately improve comprehension of the inferred relationship between medication adherence and BP control (i.e., that improved medication adherence improves blood pressure control).

From the perspective of health behavior theory, improving comprehension of information visualizations for medication adherence and BP may play an important role in improving medication adherence and BP control. It is reasonable to suspect that improving one's understanding of information about the correlation between medication adherence and blood pressure control leads to improved observations, more accurate perceptions of benefits to treating one's condition (i.e., seeing how medication adherence leads to controlled BP), and cues to action (e.g., seeing when a medication dose was missed).[19]

The primary focus of these user assessments was ascertaining feedback on aspects of visualization features that are not explicitly described in guidelines and best practices in order to design visualizations that can be better understood by their intended audience (i.e., patients with HTN). Our results suggest that for visualizations that condense the display of medication adherence and BP information into a single visualization, the use of culturally recognizable symbols (✓'s and X's) is preferred over other techniques of indicating adherence. In addition, labeling individual BP values, using reference lines, and indicating the region of normal BP were preferred features. However, combining all desired features will likely clutter the visualization, and future research should assess which of these features most improve patient understanding of the visualization.

Health literacy may also play a role in preference and should be considered when designing visualizations for patients with HTN. In this study, a grid format for reference lines was preferred by four of six participants; however, the two that did not prefer the grid had low health literacy and noted that it was "too much." Participants provided alternative terminology for both systolic (upper, top, high) and diastolic (lower, bottom, low) BP, as well as controlled BP (normal). While a visualization can provide clues to what the top and bottom number are via layout and legend, it may be beneficial to place alternative terms in parentheses or consider replacing altogether. Lastly, when looking at preferences for tracking medication adherence alone, participants preferred a calendar view over a list view, which is contrary to how available mobile apps for tracking medication adherence currently visually present such information.

Finally, our results both align and conflict with current visualization methods used in medication and blood pressure tracking apps. Our results showed that patients prefer numeric labels for blood pressure graphs, and all blood pressure monitoring apps we reviewed (n=20) had this visualization characteristic. For medication adherence, only 25% of apps we reviewed (n=5) used symbols for showing medication adherence, whereas all participant (n=6) in our study preferred the use of symbols. Similarly, all participants in our study preferred to track medication only using a calendar view versus a list view, but in our review of medication tracking apps, only 35% of apps (n=7) used a calendar view, and all of the apps (n=20) used a list view.

This research has several limitations. A convenience sampling method was used to purposively sample individuals with HTN in order to ensure representation from males, females, racially and ethnically-diverse participants, participants with adequate and less than adequate health literacy, and individuals with a wide range of education. However, these participants may not be representative of the broader population of individuals with hypertension that may rely on information visualizations to manage their HTN. For the purpose of this study and the stage in the visualization design process, the sampling method and interview process was sufficient to obtain data on visualization feature preference. Also, we achieved saturation in visualization preferences with 6 participants whereby a majority of participants preferred a particular feature over other features. Because these visualizations were hypothetical, it is possible that real blood pressure and medication adherence data may be interpreted differently than hypothetical data. In addition, all visualizations were presented to participants on paper, although the intended use of these visualizations is on mobile devices. It is possible that the medium on which visualizations are seen affects interpretation, particularly as it relates to size and white space.

Future studies should use real data collected in apps to assess whether HTN patient preferences differ when viewing their own data. Visualizations were also limited to two-weeks. Patient preferences may differ when viewing BP and adherence information over longer periods of time. For instance, graphs depicting shorter or longer periods of time may benefit from labeling BP values, the use of color-coded lines to show adherence, or how the X-axis is labeled (e.g., day of week).

5.6 Conclusion

This study is an important step in developing useful and useable data visualizations for self-managing hypertension. Adhering to data visualization design standards and best practices and ensuring adequate and appropriate usability testing throughout all stages of the visualization design is important. The results from this study will be incorporated into data visualizations that will then be assessed in cognitive interviews to ensure optimal understanding of the concepts communicated. Ultimately, visualization techniques for condensing the display of medication adherence information and BP into a single visualization will be tested to assess whether such techniques can improve the comprehension of the inferred relationship between medication adherence and BP control. Our results suggest patient preferences for visualizations do not entirely align with current visualization techniques used in blood pressure and medication tracking apps, and this research hopes to address that discrepancy.

CHAPTER 6: PATIENT UNDERSTANDING OF HYPERTENSION-RELATED INFORMATION VISUALIZATIONS WITH A CONDENSED DISPLAY OF MEDICATION ADHERENCE AND BLOOD PRESSURE INFORMATION

6.1 Overview

Background: Mobile apps and Bluetooth-connected devices for self-monitoring hypertension have been shown to improve patients' blood pressure control. Although many self-management technologies rely on the visualization of patient data to provide feedback, and prior research has shown how patient preferences can be incorporated into visualizations condensing the display of medication adherence and blood pressure information into a single graph, no known research has assessed how well patients understand such condensed visualizations.

Objective. To assess patient understanding of information contained in visualizations that condense the display of medication adherence and blood pressure levels into a single graph.

Methods. Cognitive interviews were conducted with a purposive sample of six adults who self-reported taking at least one medication for hypertension and owned a smartphone. Participants were purposively sampled based on their gender, race, and health literacy levels as measured by the Rapid Estimate of Adult Literacy in Medicine (REALM). Participants viewed three separate information visualizations that condensed the display of medication adherence and blood pressure information into a single graph. Interviews were audio-recorded and patient understanding of information was coded by two coders. Patients' ability to understand the following aspects of the graph were coded: 1) labels, 2) terminology, 3) reference lines, 4) indicators of medication adherence, 5) perceptually distant color and symbol pairs, and 6) displaying medication adherence as a calendar versus list view.

Results. Two of six participants had low health literacy. Participants had the most difficulty understanding visualizations that used horizontal reference lines and number labels for blood pressure data points. Participants were able to best understand visualizations with a shaded region indicating a normal blood pressure zone. Some participants had difficulty initially understanding the meaning of symbols that represented medication non-adherence, such as "✓" and "X". One participant relied on changes in blood pressure rather than symbols to determine medication adherence.

Conclusions. For the most part, patients can understand visualizations that condense the display of medication adherence and blood pressure information into a single graph. Visualizations that condense blood pressure and adherence information should use a shaded region to indicate a normal blood pressure zone and use symbols with perceptually distant colors to indicate medication adherence. This may lead to improved comprehension of the inferred relationship between adhering to medication and controlling blood pressure.

6.2 Introduction

Hypertension (HTN), or high blood pressure (BP), affects approximately 70 million (29%) adults in the U.S. and is associated with $46 billion in health care costs, medication costs, and missed days of work.[2,29] Patients with HTN often overlook symptoms of high BP or are asymptomatic, which makes HTN particularly dangerous, since high BP is associated with heart attack, stroke, heart failure, and kidney disease.[29] To make patients more aware of uncontrolled BP, self-monitoring (personal tracking of one's own BP levels) and adherence to antihypertensive medications is encouraged.

Medication non-adherence costs to the U.S. health care system each year are estimated to be $290 billion.[3] Patients with HTN contribute to those costs; approximately 45% of patients prescribed at least one anti-hypertensive medication discontinue medications within a year of initial prescription.[4] Determinants of non-adherence among patients with HTN include demographic factors such as age[5–7] and race.[6,8] In addition, several studies have shown an association between health literacy and antihypertensive medication adherence[8–10] and BP control[9,56–60] among patients with HTN.

6.2.1 Technology and Hypertension Self-management

The use of technology in HTN self-management, including monitoring BP and medication adherence, has been shown to improve BP control[38,102–104]. Self-monitoring technologies will likely become more important as 41.4% of adults in the U.S. are projected to have HTN by 2030.[29] In addition, 77% of adults in the U.S. currently own a smartphone,[21] and 27% of U.S. patients with a known heart condition or risk use wearable health tracking devices to monitor their condition.[100] Technology-based BP self-monitoring interventions often include some form of digital interface, either directly on a device or through a web portal,[103,105,107–114] which facilitates viewing of one's own health data. Viewing one's own health data in real-time is a growing reality for self-monitoring HTN as emerging technologies, including wireless or Bluetooth-enabled BP cuffs and non-invasive wireless and wearable sensors for measuring BP that are embedded in an ultra-thin adhesive patch,[115,116] are developed and tested.

6.2.2 Visualization Comprehension

The effectiveness of visualizations for health management relies in large part on one's ability to comprehend the information in the visualization; thus, improving comprehension of information visualizations for medication adherence and BP may play an important role in disease self-regulation.[19] It is reasonable to suspect that improving one's understanding of information about the correlation between medication adherence and BP control leads to improved observations, outcome expectations, and judgments about one's condition (i.e., seeing the consequences of behaviors and adjusting perceptions of future likely outcomes of a behavior).[19]

One's ability to comprehend a visualization is likely affected by visualization design. For example, one's ability to comprehend visualizations for BP and medication adherence may be affected by limitations of visual short-term memory (VSTM). The brain uses VSTM to complete brief tasks requiring the processing of visuospatial information, such as interpreting the meaning of a graph or chart.[87] Research has shown that there are limitations to VSTM, and that only four objects can be reliably stored in VSTM and accurately recalled moments later.[90,92,93] However, in regard to visualizations, this capacity decreases as: 1) the number of different features (e.g., lines, colors, shapes) increases; and 2) the amount of information encoded in each feature (e.g., several data points encoded in a line) increases.[94,95]

These findings regarding the capacity and limitations of VSTM lend themselves to the notion that encoding medication adherence and BP information in two separate visualizations (versus a single visualization) may place undue demands on VSTM when the task at hand is to infer a causal relationship between the information encoded, namely that changes in a behavior (medication adherence) result in changes in a physiological outcome (BP control).

6.2.3 Data Visualizations for Hypertension Self-management

Visualizing patient data, such as medication adherence and BP over time, are important components of technologies for monitoring HTN. However, in a review of current medication and BP tracking apps, patient preferences often do not align with commonly-used visualization techniques.[162] In a previous study assessing preferences for visualization characteristics, patients with HTN preferred culturally recognizable and context appropriate symbols, such as a "✓" to indicate something positive and X's to indicate something negative.[162] Patients also preferred blue/orange color pairs for indicating medication adherence, labeled BP data points, horizontal reference lines, and reference indicators of a "normal" BP zone. When presented with three types of visualizations that condensed the display of BP and medication adherence information, participants preferred using symbols with a line graph versus color coding BP lines or using shaded regions.

While some aspects of data visualization design, such as the use of line graphs, may be easier to understand for patients viewing their own data,[125] it is unknown how adding features (e.g., colors and symbols) in certain contexts affects understanding. The purpose of the current study is to assess patient understanding of three visualizations that combine medication adherence and BP information into a single graph. These three visualizations were developed using results from a previous study assessing patient preferences for visualization characteristics,[162] while also adhering to best practices for visualizing the type of data that underlie the visualizations of interest.[20,121,122] Using cognitive interviews, we examined patient understanding of several individual characteristics of visualizations, including: 1) what lines represent systolic BP and diastolic BP; 2) the meaning of colors, symbols, numbers, and terminology used in the graphs; 3) the meaning of horizontal (time) and vertical (BP) axes; 4) the meaning of tick marks for the horizontal and vertical axes; 5) what days medication was taken/missed, and 6) what days showed high or uncontrolled BP.

6.3 Methods

6.3.1 Participant Recruitment

Six participants were recruited from an existing pool of adult HTN patients who participated in a prior study that tested an electronic health record-based strategy for the routine assessment of medication self-management skills among primary care patients with complex drug regimens. These participants were initially recruited from an internal medicine clinic in North Carolina at an academic medical center. For this study, participants were purposively recruited based on gender (3 males and 3 females), race/ethnicity (3 White, 3 non-White, and at least 1 Hispanic), health literacy (at least 2 participants with less than adequate health literacy as assessed via the REALM[79]), and education (at least 2 with a high school diploma or less and at least 2 college graduates). Eligible participants were over 18 years of age, spoke and read English, had a self-reported diagnosis of HTN, were prescribed at least one medication to treat their HTN, and owned a smartphone. Participants from a related previous study were not eligible to participate in this study.[162] A total of 8 individuals were contacted, 2 of which were unable to resolve scheduling conflicts. All participants provided written informed consent.

6.3.2 Data Visualization Design

Three visualizations were developed after assessing preferences for certain visualization characteristics.[162] Preferences from these assessments were incorporated into visualizations, and three different approaches to referencing BP values were used: 1) graph 1 with horizontal reference lines (Figure 6.1), 2) graph 2 with shaded normal BP zone (Figure 6.2), and 3) graph 3 with labeled BP data points (Figure 6.3). Other preferences incorporated into all three visualizations included X's to indicate a missed dose, orange and blue lines to differentiate systolic and diastolic BP, respectively, and tick marks at intervals of 20 mmHg and for each day of the week.

Visualizations used in the cognitive interviews were based on known parameters concerning the pharmacology of Lisinopril[136] and standard definitions of HTN.[30] Lisinopril is the most commonly used antihypertensive drug, and is prescribed to approximately 20% of the hypertensive population.[34] The antihypertensive effect of Lisinopril starts to rapidly drop-off after 24 hours, which suggests two consecutive missed doses for individuals taking Lisinopril once daily could result in elevated BP levels.[136] All visualizations depicted medication adherence and BP information over a two-week (14-day) period. All three visualizations showed uncontrolled BP resulting from 50% adherence (i.e., medications only taken 7 of the 14 days). Elevated BP was presented as randomly chosen numbers between 140 and 210 mmHg (systolic BP) and 90 and 100 mmHg (diastolic BP). Controlled BP was presented as a randomly chosen number between 100 and 120 mmHg (SBP) and 70 and 80 mmHg (DBP).

Figure 6.1 Graph 1 with horizontal reference lines

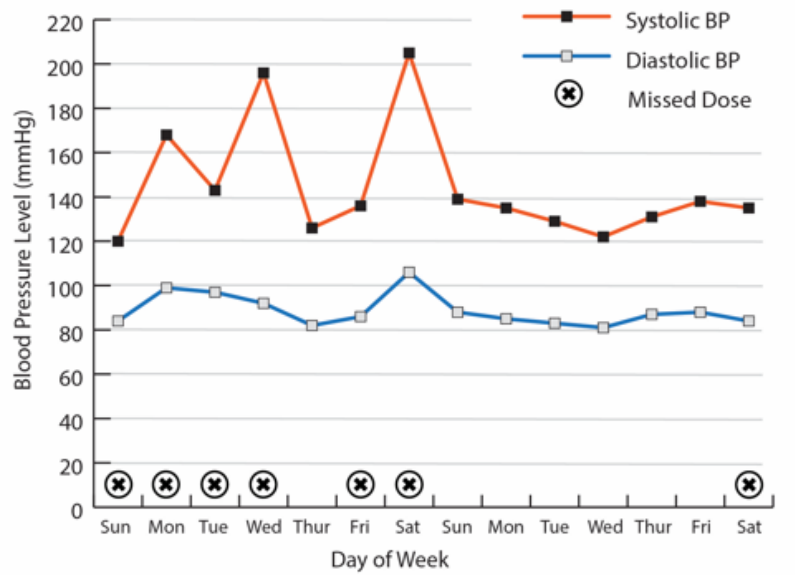


Figure 6.2 Graph 2 with shaded normal BP zone

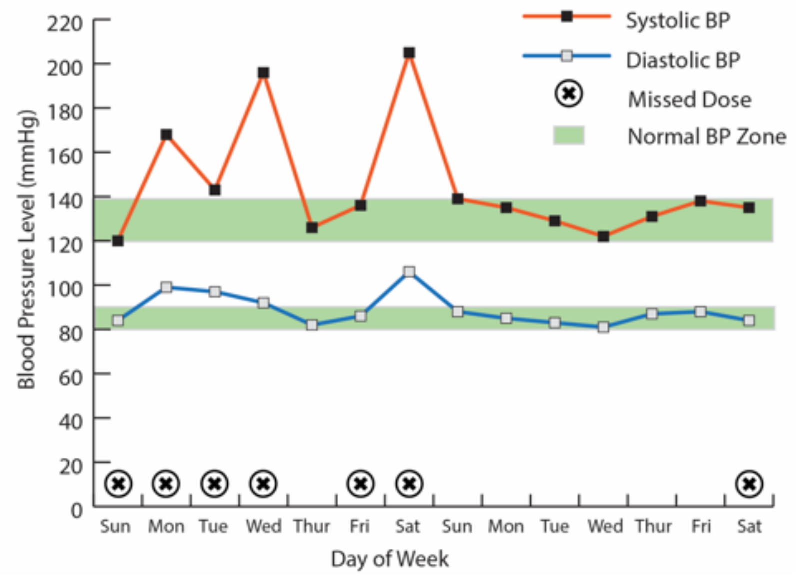
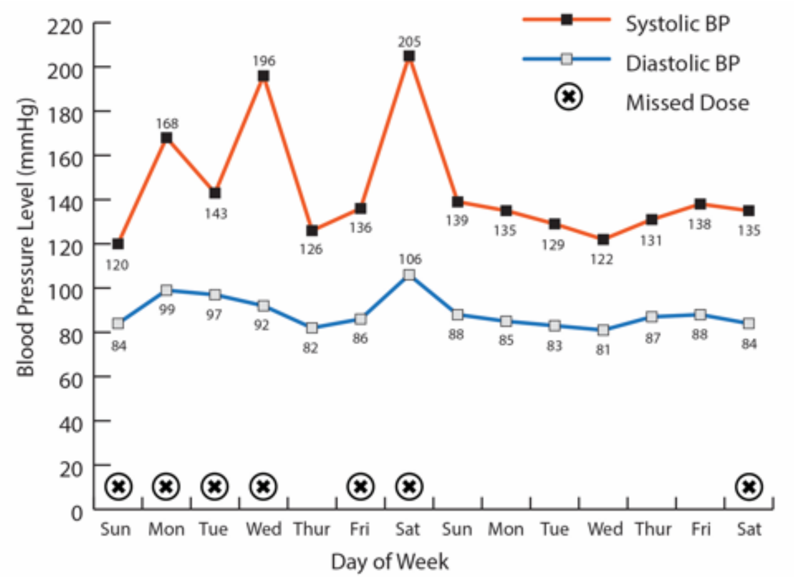


Figure 6.3 Graph 3 with labeled BP data points



6.3.3 Data Collection Procedure and Measures

During an in-person cognitive interview (see Appendix B for cognitive interview protocol), participants were provided paper copies of all three condensed visualizations. Each interview was audio recorded using a digital audio-recorder, and audio recordings were analyzed by two coders (AS and AD), along with any supplemental notes taken during the interview. Interviews lasted approximately 30 minutes, and participants were given $25 cash as an incentive. This study was approved by the UNC Institutional Review Board.

Prior to commencing the cognitive interviews, participants were asked their age in years, gender, race (White, Black, Other-specified) and ethnicity (Hispanic, non-Hispanic), whether they had HTN, whether they took medication to control their high BP, and whether they owned a smartphone.

During the interview, participants were presented with three visualizations on paper. To minimize the influence of learning effects on our results, each of the three visualizations was presented so that the order in which it was assessed by participants as either first, second, or third would occur equally throughout the study. Participants were then asked questions to assess understanding of four aspects of each visualization: 1) the meaning of colors, symbols, and labels; 2) the meaning of terminology used in the visualizations; 3) the meaning of the horizontal and vertical axes and the tick marks separating BP values (mmHg) and days of the week; 4) medication adherence, and 5) BP levels.

To assess the understanding of the meaning of colors, symbols, and labels, participants were first asked to describe what the top and bottom lines on the graph represent and how they knew this. Next, participants were asked to describe the meaning of the symbol representing a missed dose and how they knew this. Participants were then asked to describe the meaning of the different colors shown throughout the graph (i.e., red line for systolic BP, blue line for diastolic BP, and green shaded regions for normal BP zone). Finally, for the visualization with numeric labels for each BP data point, participants were asked what those numbers represent.

To assess the understanding of the meaning of terminology used throughout the visualizations, participants were asked to provide their own short definition to describe each of the following words or phrases: blood pressure level, systolic BP, diastolic BP, day of week, missed dose, and normal BP zone. Next, participants were asked to explain what the horizontal and vertical axes represent, and what the purpose of the tick marks were for each axis. Finally, to assess understanding of medication adherence and BP, participants were asked to first identify the days of week where medication was not taken and then asked to identify days of the week that showed high BP levels. Participants were reminded that normal or controlled BP was a systolic BP level between 120 and 140 mmHg, and a diastolic BP level between 80 and 90 mmHg.

6.3.4 Data Analysis

Interviews were audio-recorded to facilitate coding and analysis. Unique IDs were assigned to each participant to de-identify responses. Two independent coders (AS and AD) listened to the audio-recorded interviews and coded responses to questions assessing understanding. Both coders coded all six interviews. Cohen's Kappa was calculated to determine inter-coder reliability.[160] Disagreements in categorization were discussed between the coding team and resolved.

The following categories were used to code participants' understanding: 1) correctly understood feature (i.e., provided a correct response to the researcher's question) and 2) incorrectly understood feature (i.e., provided an incorrect response to the researcher's question). In addition, factors that facilitated or impeded participants' ability to understand each feature were noted to provide context to responses.

6.4 Results

6.4.1 Sample Characteristics and Adolescent Technology Use

Table 6.1 summarizes characteristics of the study participants. The sample included 3 males and 3 females, with an average age of 57.2 years. Three participants were white, 1 was black, and 2 were Hispanic. Two participants had a college degree or more, 2 had some college, and 2 had a high school diploma or less. Two participants had less than adequate health literacy as measured via the Rapid Estimate of Adult Literacy in Medicine (REALM).[79]

Table 6.1 Sample characteristics

Characteristics (N=6)	**n (%)/Mean(SD)**
Age, *Mean (SD)*	57.2 (10.6)
Male	3 (50)
Race/ethnicity	
Non-Hispanic White	3 (50)
Non-Hispanic Black	1 (17)
Hispanic	1 (17)
Less than adequate health literacy (REALM)	2 (33)
Education	
College	2 (33)
Some College	2 (33)
High School or less	2 (33)

6.4.2 Visualization Understanding

Table 6.2 summarizes the results of the cognitive interviews. Overall, Graph 2 was best understood by participants, and Graph 1 was the least well understood. Table 6.3 presents the inter-coder reliability scores, which ranged from moderate (κ =.52) to perfect agreement (κ = 1).[161]

Table 6.2 Understanding of graph features for graphs 1, 2, and 3

	Graph 1 Horizontal Lines n (%)	Graph 2 Shaded Normal BP Zone n (%)	Graph 3 Labeled BP Data points n (%)
Colors, symbols, and labels			
Understood top and bottom lines	5 (83)	6 (100)	6 (100)
Understood missed dose symbol	6 (100)	6 (100)	5 (83)
Understood meaning of colors	5 (83)	6 (100)	6 (100)
Understood labeled BP data points	n/a	n/a	6 (100)
Axes and tick marks			
Understood horizontal axis	6 (100)	6 (100)	6 (100)
Understood vertical axis	6 (100)	6 (100)	6 (100)
Understood day of week tick marks	5 (83)	6 (100)	6 (100)
Understood BP tick marks	5 (83)	5 (83)	6 (100)
Adherence and BP Information			
Identified days of non-adherence	5 (83)	5 (83)	5 (83)
Identified days of high BP	4 (67)	6 (100)	3 (50)
Total Incorrect	**7**	**2**	**5**

Table 6.3 Inter-coder reliability scores

	Kappa
Understanding of top and bottom lines	1
Understanding of missed dose symbol	1
Understanding meaning of colors	1
Understanding of labeled BP data points	1
Understanding of horizontal axis	1
Understanding of vertical axis	1
Understanding of day of week tick marks	1
Understanding of BP tick marks	1
Understanding of days of non-adherence	1
Understanding of days of high BP	0.52
Understanding of terminology	1

6.4.3 Colors, Symbols, and Labels

For graph 1, all but one participant (n=5) understood that the top and bottom lines represented systolic and diastolic BP, and that the orange line was systolic BP and the blue line was diastolic BP. One participant with high health literacy incorrectly described the top and bottom lines as heart rate and pulse, and was unsure of the meaning of the colors in the graph. All participants (n=6) correctly answered that the symbol for missed dose represented non-adherence. For graph 2, all participants (n=6) understood that the top and bottom lines represented systolic and diastolic BP, that the orange line was systolic BP and the blue line was diastolic BP, and that the symbol for missed dose represented non-adherence. For graph 3, all participants (n=6) understood that the top and bottom lines represented systolic and diastolic BP, that the orange line was systolic BP and the blue line was diastolic BP, and that the labeled data points indicated individual BP values. All but one participant (n=5) understood that the symbol for missed dose represented non-adherence. This participant confused the symbol for missed dose with taking medication. This particular participant was able to resolve their confusion by the 2nd and 3rd graph they viewed, as they only incorrectly answered this question on graph 1. It should also be noted that despite correctly identifying days of non-adherence, one participant, when probed about how they knew which days there was a missed dose, incorrectly explained *“when the blood pressure has the highest reading, they didn’t take their medication” (Hispanic, Male, 65).* This also occurred for graphs 1 and 2, but not for 3, which suggests learning effects occurred.

6.4.4 Terminology

All but one participant (n=5) correctly defined the following words or phrases: blood pressure level, systolic BP, diastolic BP, day of week, missed dose, and normal BP zone. One participant with less than adequate health literacy incorrectly defined blood pressure level as *“there are two different levels,”* and normal BP zone as *“130 over 80” (Black, Female, 63)*. However, patients often have target BP levels different from general guidelines, particularly those with diabetes. It is possible that this was this particular participant’s target BP recommended by their physician; thus, a normal zone may be specific to the patient.

6.4.5 Axes and Tick Marks

For graphs 1, 2, and 3, all participants (n=6) understood the vertical (blood pressure level) and horizontal (day of week) axes. For graph 1, all but one participant (n=5) understood the meaning of the tick marks for both axes. For graph 2, all but one participant (n=5) understood the meaning of the tick marks for the vertical (blood pressure level) axis, and all participants (n=6) understood the meaning of the horizontal (day of week) axis. For graph 3, all participants (n=6) understood the meaning of both axes. All incorrect responses about the axes occurred with only one participant with adequate health literacy, and suggest they learned the meaning over time.

6.4.6 Adherence and Blood Pressure Information

For graphs 1, 2, and 3, all but one participant (n=5) was able to correctly identify days of non-adherence. It should be noted that this incorrect response occurred with the same participant, and the same day of non-adherence was overlooked for each graph. This was also the only question this participant incorrectly answered about all three graphs. For graph 1, two-thirds of participants (n=4), and for graph 3, half of participants (n=3) correctly identified days with high or uncontrolled BP. In contrast, all participants (n=6) correctly identified days with high or uncontrolled BP for graph 2.

6.5 Discussion

There are no known studies that assess understanding of information visualizations that condense the display of BP and medication adherence information over time in a single graph. While guidelines and best practices provide a path for designing such visualizations, it is important to reassess understanding of visualizations when patient preferences are incorporated. This study seeks to do that by assessing condensed visualizations that follow best practices and guidelines, but also include patient preferences for presentation of information. Our overall results indicate that, in general, a diverse group of patients were able to understand the condensed visualizations.

Our results suggest that patients with HTN understand the use of symbols to indicate a missed dose, although adding a symbol to show medication adherence may improve one's ability to distinguish between the two. Patients also understood the meaning of colors, so color-coding perceptually distant symbols with color pairs may facilitate one's recognition of the difference between opposing concepts, such as medication adherence and non-adherence. It is clear from our results that visually dichotomizing controlled versus uncontrolled BP by using a shaded normal BP zone facilitates one's ability to distinguish between controlled and uncontrolled BP. While labeled data points and horizontal reference lines may allow for more granular understanding of specific BP values, our results suggest it is not the most effective approach for communicating controlled versus uncontrolled BP values.

Health literacy may also play a role in understanding visualizations and should be considered when designing visualizations for patients with HTN. In this study, participants with both adequate and inadequate health literacy incorrectly answered several questions. However, one participant with less than adequate health literacy appeared to have difficulty understanding symbols, BP levels, and some terminology. This misunderstanding would likely be avoided with more explicit symbols for showing medication adherence versus non-adherence (e.g., symbols with perceptually distant colors), and by relying on a more simplified visual display of controlled versus uncontrolled BP, such as that shown in Figure 6.2. However, this participant's understanding appeared to improve over time as the participant became more familiar with the visualizations. When designing visualizations for mobile apps, identifying this learning process is important for understanding where the user might benefit from a tutorial, or what is often called a new user experience in user experience research.

Improving a patient's understanding of their own medication adherence and BP patterns is an important step in improving their observations, outcome expectations, and judgments about their health condition. As patients accurately perceive when they took or missed a dose of their medication and what their BP was when they did and did not take their medication, their judgments about their behavior are more likely to improve, (e.g., how medication adherence leads to controlled BP), and consequently are more likely to see a missed dose or elevated BP as a cue to action (to either take their medication as prescribed or to seek medical care). These cues to action could ultimately improve adherence and clinical outcomes for patients.

This research has several limitations. A convenience sampling method was used to purposively sample individuals with HTN in order to ensure representation from males, females, racially and ethnically-diverse participants, participants with adequate and less than adequate health literacy, and individuals with a wide range of education. However, these participants may not be representative of the broader population of individuals with HTN who may rely on information visualizations to manage their HTN. For the purpose of this study and the stage in the visualization design process, the sampling method and interview process was sufficient to obtain data on visualization feature understanding. After six interviews, we were able to sufficiently obtain saturation in our findings, and clearly identify which of the three visualizations was the most understood by participants.

All three visualizations were presented to participants on paper, although the intended use of these visualizations is on mobile devices. It is possible that the medium on which visualizations are seen affects interpretation, particularly as it relates to size and white space. No known studies have specifically examined differences in understanding visualizations on mobile devices versus paper, and future research should assess how presentation mediums or platforms affect visualization understanding.

It is clear that learning effects occurred during our cognitive interviews, and for questions about the meaning of symbols and tick marks on the vertical and horizontal axes, participants' ability to interpret the graphs improved over time. To avoid the influence of this in our results, we ordered the sequence of graphs 1, 2, and 3 so that each graph appeared first, second, or third for two participants. It is also important to note that several aspects of the visualization can change, such as shorter or longer periods of time (e.g. one week or one month), different medication instructions (e.g., two times per day). Patient understanding of information contained in visualizations may change if displayed over long periods of time or with more complex regimens. Similarly, different antihypertensive medications may result in different relationships between medication adherence and BP control, and the relationship between adherence and BP control may be less obvious than what was displayed in the visualizations used in this study. These visualizations were optimized for mobile devices, so visualizations designed for devices with more screen real estate would likely differ. Lastly, we assessed visualizations that condense the display of medication adherence and BP information in a single graph, however it has yet to be assessed whether these types of visualizations improve overall comprehension of the relationship between medication adherence and BP control over displaying such information in separate visualizations.

6.6 Conclusion

This study provides important insights into information visualization techniques that facilitate understanding of medication adherence and BP information for patients with HTN. Participants were able to best understand visualizations that condense the display of BP and medication adherence information using techniques that clearly indicate controlled versus uncontrolled BP and taking or missing a medication dose. This was best accomplished by using a shaded region to indicate a normal BP zone (i.e., dichotomizing BP as controlled versus uncontrolled) and symbols with perceptually distant colors for medication adherence. It is important for the design of information visualizations intended for self-monitoring of one’s condition to take into consideration the needs of the entire patient population, particularly those with low health literacy. The results from this study will be incorporated into data visualizations that will assess whether visualizations that condense the display of medication adherence information and BP information can improve the comprehension of the inferred relationship between medication adherence and BP control when compared to separate visualizations (i.e., a line graph and calendar view).

CHAPTER 7: ASSESSING THE EFFECT OF VISUALIZATION TECHNIQUES ON PATIENT COMPREHENSION OF HYPERTENSION-RELATED INFORMATION

7.1 Overview

Background: Patient use of technology such as smartphones, for self-monitoring hypertension (HTN) has been shown to improve patients' blood pressure (BP) control. Many of these technologies rely on the visualization of patient data to provide feedback on BP control and adherence; however, no known research assesses how visualization techniques influence patient comprehension of data. *Objective.* Our objectives are: 1) to assess if condensing medication adherence and BP information into a single graph versus displaying BP and adherence data separately improves patient comprehension of such information, and 2) assess if health literacy moderates the relationship between viewing condensed versus separate visualizations and comprehension of the information contained in the visualization.

Methods. A randomized survey experiment was conducted with U.S. adults with HTN (n=137). Participants were randomized to view a condensed visualization (treatment group) or separate visualizations of BP and adherence data (control group). Each participant viewed four visualizations depicting different scenarios with various combinations of medication adherence and BP control, then answered a 4-item comprehension scale for each scenario. Multivariate regression analysis was used to assess the effect of visualization type (treatment vs. control) on patient

comprehension. The moderating effect of health literacy on comprehension was also assessed.

Results. The main hypothesized effect was not significant and condensing the display of medication adherence and BP information did not improve comprehension when compared to visualizations providing a separate display of the same information. Health literacy did not moderate the relationship between visualization technique and comprehension, and condensed visualizations did not lead to more improved comprehension among individuals with low health literacy when compared to those with high health literacy. However, greater health literacy (B=0.61, p=.0001) and higher HTN knowledge (B=0.10, p<0.0001) were positively associated with visualization comprehension.

Conclusions. Condensed visualizations that displayed medication adherence on a line graph for blood pressure did not improve patients' ability to comprehend the association between adherence and blood pressure. Visualizations that display medication adherence and BP data should consider characteristics of the intended users, such as health literacy and HTN knowledge, as these variables may affect users' ability to understand the information contained in the visualization.

7.2 Introduction

Hypertension (HTN), or high blood pressure (BP), affects approximately 70 million (29%) adults in the U.S., and is associated with over $46 billion in costs to the U.S. health care system. Hypertension also contributed to over 360,000 deaths in the U.S. in 2013, many of which are a result of a heart attack, stroke, heart failure, or kidney disease.[29] Many of these deaths, however, are avoidable, as common risk factors for HTN are linked to health-related behaviors, including non-adherence to antihypertensive medications and inadequate self-monitoring of BP.[29] Other individual factors including socioeconomic status,[29] body weight,[29] race,[32] ethnicity,[32] age,[32] and sex are also linked to a higher risk of HTN.[29] For those diagnosed with HTN, altering lifestyle behaviors makes it a manageable condition. Unfortunately, only about half (54%) of people with HTN have their condition under control.[29]

Two major contributing factors to wide-spread uncontrolled HTN is lack of adherence to antihypertensive medication and insufficient monitoring of one's condition.[29] In fact, it is estimated that approximately half (45%) of patients with HTN stop taking their medication within the first year.[33] One contributing factor to nonadherence among patients with HTN is a lack of knowledge about their condition,[11,12] Patients with HTN often overlook symptoms of high BP or are asymptomatic and fail to see the benefits of their medication and the consequences of nonadherence. This makes self-monitoring (personal tracking of one's own BP levels) of BP and medication adherence important.

Health literacy is also an important factor in HTN self-management. The U.S. Department of Health and Human Services defines health literacy as "the ability to obtain, process, and understand basic health information and services to make appropriate health decisions."[54] Over a third of adults lack sufficient health literacy to perform common tasks such as understanding prescription drug label directions or making simple calculations from a chart.[54] Several studies have shown a positive association between health literacy and antihypertensive medication adherence[8–10] and BP control[9,56–60] among patients with HTN. In addition to health literacy, more

HTN knowledge, defined as the understanding of the meaning, treatment, seriousness, and management behaviors of HTN, is associated with higher antihypertensive medication adherence.[163]

7.2.1 Technology and Hypertension Self-management

Technologies used for BP self-monitoring interventions (e.g., smartphones or web portals) often include some form of digital interface for viewing personal health data.[103,105,107–114] Many of these technology-based self-manage tools have been shown to improve BP control,[38,102–104] and will likely become more important as both the prevalence of HTN and technology use grow. By 2030, it is projected that 41.4% of adults in the U.S. will have HTN.[29] Currently, 77% of adults in the U.S. own a smartphone,[21] and 27% of U.S. patients with a known heart condition or risk of heart disease use wearable health tracking devices to monitor their condition.[100] Furthermore, emerging technologies, including wireless or Bluetooth-enabled BP cuffs and non-invasive wireless and wearable sensors embedded in ultra-thin adhesive patches that can measure BP,[115,116] are currently being developed and tested. Together, these trends suggest technology will continue to facilitate the real-time monitoring of one’s health.

7.2.2 Visualization Comprehension

Improving visualization comprehension for medication adherence and BP likely improves their effectiveness in communicating patient data by facilitating disease self-management and self-regulating behaviors. By improving comprehension of visualizations for BP and medication adherence, accuracy of observations, outcome expectations, and judgments about one’s condition (i.e., seeing the consequences of behaviors and adjusting perceptions of future likely outcomes of a behavior) may also be improved.[19]

Improving comprehension of visualizations requires certain design considerations. One such consideration is limitations of visual short-term memory (VSTM), a subsystem of general working memory. VSTM serves to store visuospatial information for short periods of time (seconds) to complete cognitive tasks, such as interpreting the meaning of a graph or chart.[86,87] Research suggests only four objects can be reliably stored in VSTM for recall. [90,92,93] However, the ability to recall objects from a visualization is highly contextual. Specifically, when the number of different features (e.g., lines, colors, shapes) increases, or when the amount of information encoded in each feature (e.g., several data points encoded in a line) increases, VSTM capacity decreases.[94,95] Designing visualizations with consideration to limitations of VSTM may improve comprehension. One approach to doing this is encoding medication adherence and BP information in a single visualization (versus separate visualizations).

7.2.3 Data Visualizations for Hypertension Self-management

Previous studies have documented patient preferences for and understanding of visualizations for HTN self-management. Key findings for HTN patients' visualization preferences were: 1) the use of ✓'s to indicate adherence and X's to indicate non-adherence; 2) the use of a shaded region to indicate a normal blood pressure zone; 3) the use of symbols with a line graph (versus color coding BP lines or using shaded regions) when condensing medication adherence and BP information into a single visualization; and 4) the use of a calendar (versus list view) when showing medication adherence information.

Certain techniques for visualizing personal health data have been shown to facilitate understanding of one's own health or condition, such as the use of line graphs for showing longitudinal data.[125] However, it is unknown how certain visuospatial aspects of visualizations for HTN self-management influence patient comprehension of the relationship between medication adherence and BP control. In particular, it is unknown whether condensing medication adherence and BP information into a single visualization improves comprehension of the inferred relationship between adherence and controlled BP (and vice versa). For this study, we hypothesized that condensed visualizations facilitate patient comprehension of BP and adherence information when compared to visualizations that display BP and medication adherence information in separate visualizations. We also hypothesized that the improvement in comprehension of BP and adherence information among individuals with low health literacy who view condensed versus separate visualizations will be significantly greater than their high health literacy counterparts.

7.3 Methods

7.3.1 Participant Recruitment

A convenience sample of participants with self-reported HTN (n=137) were recruited using Amazon's Mechanical Turk (www.mturk.com).[139] Mechanical Turk (Mturk) allows researchers to recruit study participants (Mturk workers) by providing pre-specified payments (i.e., incentives) for completing small tasks called Human Intelligence Tasks (HITs), such as taking a short survey. First, participants were screened for eligibility. Eligible participants were 18 years or older, English-speaking, able to read and write English, had a self-reported diagnosis of HTN, self-reported current prescription for at least one antihypertensive medication, had internet access, and owned a smartphone. Participants were excluded if they reported having severe hearing or vision impairments or did not meet eligibility criteria. All participants received a $0.50 incentive for completing the short screening instrument. Eligible participants were then invited to participate in the full study. Participants for the full study received a $4 incentive for their participation. For both the screening instrument and full study, individuals were provided with a description of the study, including study eligibility criteria, and provided electronic consent. Participants were excluded from analysis if they failed to meet an attention check question during the survey.

7.3.2. Data Visualization Design

A patient-centered approach was used to asses user preferences for the design of the data visualizations used in this study.[162] All visualizations were based on known parameters concerning the pharmacology of Lisinopril[136] and the revised standard definitions of HTN.[30] All visualizations depicted medication adherence and BP information over a two-week (14-day) period. For this study, poor adherence was depicted as a randomly selected (using a random number generator) 7 of the 14 days. High adherence was shown as 100% adherence. Elevated BP was presented as randomly chosen numbers between 120 and 210 mmHg (systolic BP) and 80 and 100 mmHg (diastolic BP). Controlled BP was presented as a randomly chosen number between 100 and 120 mmHg (SBP) and 60 and 80 mmHg (DBP).

7.3.3 Participant Randomization

Data for the survey experiment were collected using an online survey program called Qualtrics. First, eligibility and health literacy were assessed as part of a short screening survey. Health literacy was determined by the 10-item Health

Literacy Survey Instrument-Short Form.[76] A 2x2x4 experiment was used to assess comprehension of visualizations. Using Qualtrics' built-in randomizer, participants with adequate (n=75) and inadequate (n=62) health literacy were randomly assigned to either the treatment group with condensed visualizations (see example in Figure 7.1) or the control group with separate visualizations (see example in Figure 7.2). Each participant viewed four visualization types that displayed various combinations of BP control and medication adherence: 1) low adherence/uncontrolled BP (LU), 2) high adherence/uncontrolled BP (HU), 3) low adherence/controlled BP (LC), and 4) high adherence/controlled BP (HC). The four visualizations within the treatment and control groups were presented in random order. The participant randomization process is illustrated in Figure 3. Appendix C presents all visualizations used.

Figure 7.1 Condensed display for BP and medication adherence

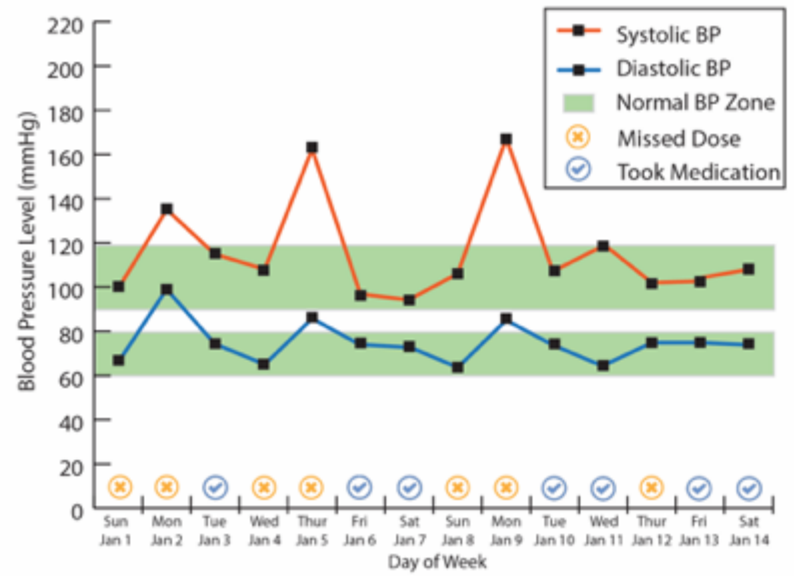
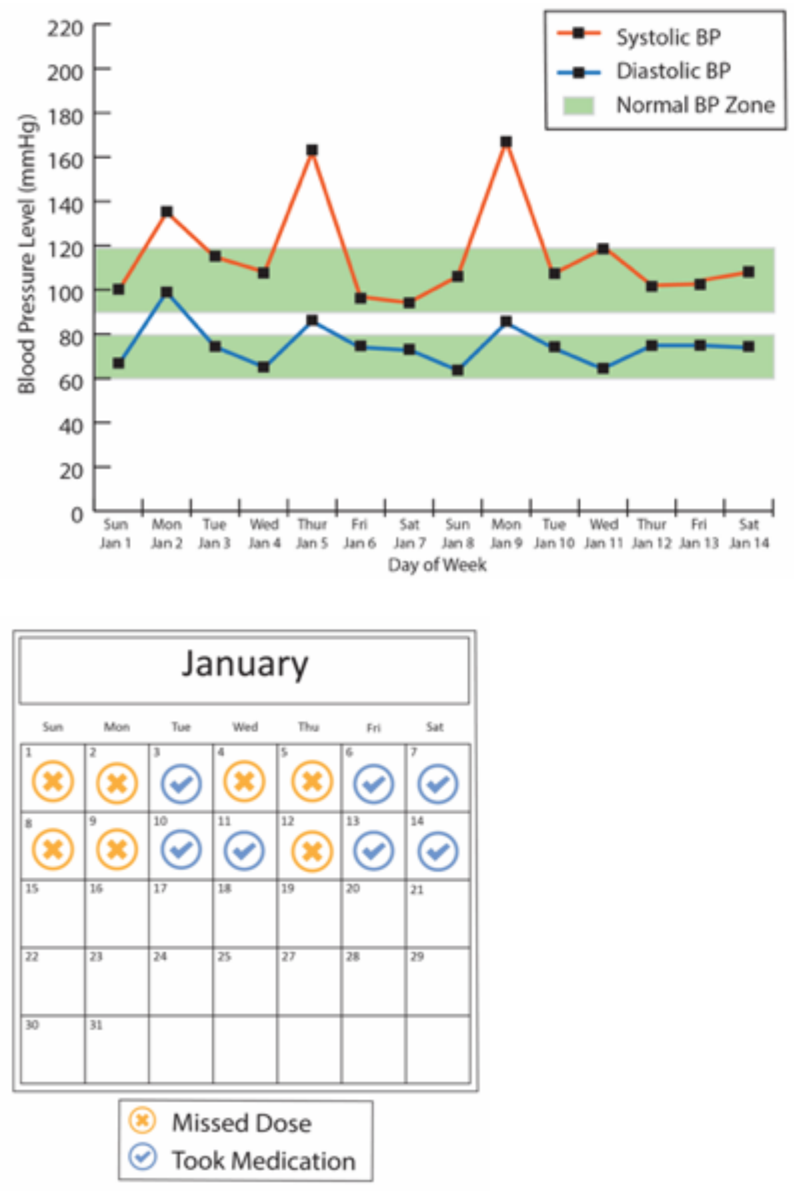


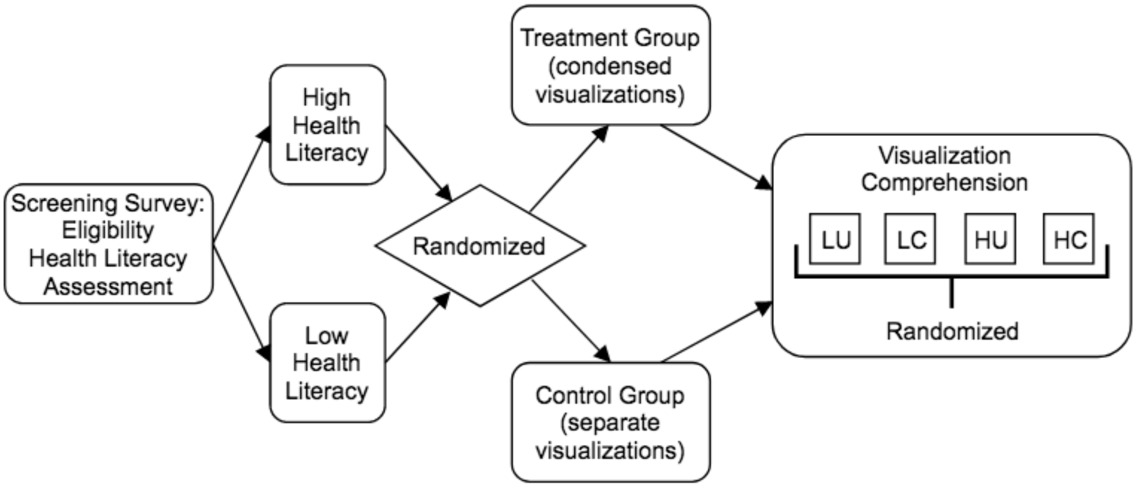
Figure 7.2 Separate display for BP and medication adherence



Sun	Mon	Tue	Wed	Thu	Fri	Sat
1 ✗	2 ✗	3 ✓	4 ✗	5 ✗	6 ✓	7 ✓
8 ✗	9 ✗	10 ✓	11 ✓	12 ✗	13 ✓	14 ✓
15	16	17	18	19	20	21
22	23	24	25	27	28	29
30	31					

✗ Missed Dose
✓ Took Medication

Figure 7.3 Participant randomization process



7.3.4 Measures

7.3.4.1 Comprehension

For each visualization, participants answered a 4-item visualization comprehension scale while viewing the visualization.[164] Questions (and response options) were as follows: 1) *Looking at the graph, would you say that this person's blood pressure levels: (are not related to how they take their medication/are related to how they take their medication)*, 2) *Looking at the graph, missing medication: (makes blood pressure worse/does not change blood pressure/I cannot tell from this graph)*, 3) *Looking at the graph, would you say that this person's blood pressure levels generally change when they do not take their medication? (yes/no/I cannot tell from this graph)*, 4) *On the days when blood pressure is high, did this person usually take their medication? (yes/no/there are no days with high blood pressure)*. Questions for the 4-item comprehension scale were coded as either correct (1) or incorrect (0), and scores for each individual comprehension assessment were summed with a total possible score ranging from 0 to 4.

7.3.4.2 Health literacy

To assess health literacy, participants completed the Health Literacy Skills Assessment Short Form (HLSI-SF).[76] The HLSI-SF is a validated 10-item questionnaire that can be self-administered on the web and assesses four domains of health literacy skills: 1) print literacy (reading and writing), 2) numeracy skills, 3) oral literacy skills (listening), and 4) information seeking skills (navigation of the Internet and a facilities map). Answers were coded as either correct (1) or incorrect (0) and summed with a total possible score ranging from 0 to 10. Scores were coded as high or low using previously established cut-off points: a score of 7 or higher was considered “adequate” or high health literacy, and scores below 7 were considered “inadequate” or low health literacy.[76]

7.3.4.3 Hypertension knowledge.

Hypertension knowledge was assessed using the Hypertension Knowledge-level Scale (HK-LS). The HK-LS is a validated and reliable (Cronbach’s alpha = .82) 22-item true/false assessment of six dimensions of HTN knowledge, including hypertension definition, treatment, drug compliance, lifestyle, diet, and complications.[13] Answers were coded as either correct (1) or incorrect (0), and summed with a total possible score ranging from 0 to 22.

7.3.4.4 Demographic characteristics

Participant characteristics assessed included number of currently prescribed medications, number of currently prescribed HTN medications, number of comorbid conditions using the Charlson Comorbidity Index,[146] frequency of medication and BP self-monitoring (never, rarely, sometimes, very often, always), wearable device ownership (yes/no), health app use (yes/no), and healthcare coverage (private, Medicaid, Medicare, employer-sponsored, private, none). Measures of participant demographic characteristics included age (years), race (White, Black or African American, Asian, Native American or Pacific Islander, Other-specify), ethnicity (Hispanic, non-Hispanic), gender (Male, Female), education (elementary, some high school, high school graduate, some college or technical school, college graduate, graduate degree, refused), and income (less than $10,000, $10,000 to $19,999, $20,000 to $29,999, $30,000 to $39,999, $40,000 to $49,999, $50,000 to $99,999, $100,000 or more, refused, don't know). Missing data was addressed using mean imputation, where missing values were replaced by a calculated value equal to the mean of available cases for each item.

7.3.5 Data Analysis

A sample size of 120 participants provided 80% power to detect a medium effect for the effect of visualization type (condensed vs. separate) on comprehension (.5) and a medium to large effect (.75) for the interaction between visualization type and health literacy with 80% power (two-tailed alpha = .025). [140] Differences in comprehension between the treatment and control groups was assessed using multiple regression. Because comprehension was assessed for four separate visualization types (LU, HU, LC, HC), within-subject correlations were accounted for by including within-subject covariance structure as part of the overall model residual using the Proc Mixed procedure in SAS Version 9.4 (SAS Institute, Inc. Cary, NC, USA). A treatment*visualization type interaction term was used to assess the magnitude of difference across the four visualization types, and a treatment*health literacy interaction term was used to assess the moderating effect of health literacy. To assess which control variables to include, backwards step-wise multiple regression was used. First, all control variables (visualization type, HTN knowledge, comorbidity, number of currently prescribed medications, number of currently prescribed HTN medications, number, frequency of medication and BP self-monitoring, wearable device ownership, health app usage, healthcare coverage, age, gender, race, ethnicity, education, and income) were included in a regression and evaluated individually to assess whether they met inclusion criteria ($p \leq .05$). Those variables meeting inclusion criteria were then included in a final regression model, which also included the independent variables (the experimental condition and health literacy) and interaction terms (treatment*visualization type and treatment*health literacy). The interaction terms were then evaluated to assess whether each met inclusion criteria ($p \leq .05$), and non-significant interaction terms were excluded from the final regression model. To assess multicollinearity, variance inflation factors (VIFs) were calculated. All analyses used an *a priori* significance level of alpha=.05.

Finally, to assess differences in comprehension scores across the four visualization types (LU, HU, LC, HC), analysis of variance was conducted and pairwise comparisons were made between all visualization types.

7.4 Results

7.4.1 Sample Demographics and Characteristics

A total of 431 individuals completed the screening survey. Of those that completed the screening survey, 54 were not invited to participate because the survey administration time suggested they did not spend a reasonable amount of time on the survey. Of the remaining 377 participants, 130 with high health literacy were not invited because the required sample size for participants with high health literacy was met before that of the required sample size for participants with low health literacy. A total of 247 participants were invited to complete the survey experiment (143 with low health literacy and 104 with high health literacy), of which 137 completed the survey and were included in the analysis (n=71 for the treatment group and n=66 for the control group). Thus, among eligible individuals who were invited to complete the survey, the survey participation rate was 55.5%. There were no differences in health literacy scores between those who completed the survey and those who did not.

Table 7.1 summarizes participant demographics. Participants had a mean age of 35.5 years (SD=11.8), and a majority of participants were male (57.7%), White (65.7%), had a college degree or higher (60.5%), and had an annual income below $50,000 (62.8%). The difference in age between the treatment and control groups was statistically significant; with participants in the treatment group being approximately four years older on average (p<.05).

Table 7.1 Participant demographics

	All	Treatment	Control
Age, *Mean (SD)*	35.55	37.62	33.32*
Gender, *n (%)*			
Male	79 (57.7)	39 (54.9)	40 (60.6)
Female	58 (42.3)	32 (45.1)	26 (39.4)
Race/Ethnicity, *n (%)*			
White	90 (65.7)	51 (71.8)	39 (59.1)
Black	10 (7.3)	4 (5.6)	6 (9.1)
American Indian or	3 (2.2)	1 (1.4)	2 (3.0)
Asian	31 (22.6)	13 (18.3)	18 (27.3)
Other	3 (2.2)	2 (2.8)	1 (1.5)
Hispanic, *n (%)*	18 (13.1)	7 (9.9)	11 (16.7)
Education, *n (%)*			
Graduate Degree	38 (27.7)	14 (19.7)	24 (36.4)
College Graduate	45 (32.8)	29 (40.8)	16 (24.2)
Some College or Technical School	41 (29.9)	20 (28.2)	21 (31.8)
High School or GED	12 (8.8	7 (9.9)	5 (7.6)
Some High School	1 (0.7)	1 (1.4)	0
Income, *n (%)*			
$100,000 or more	8 (5.8)	3 (4.2)	5 (7.6)
$50,000 to $99,999	43 (31.4)	20 (28.2)	23 (34.8)
$40,000 to $49,999	16 (11.7)	9 (28.2)	7 (10.6)
$30,000 to $39,999	19 (13.9	13 (18.3)	6 (9.1)
$20,000 to $29,999	25 (18.2)	12 (16.9)	13 (19.7)
$10,000 to $19,999	14 (10.2)	8 (11.3)	6 (9.1)
Less than $10,000	8 (5.8)	2 (2.8)	6 (9.1)
Missing	4 (2.9)	4 (5.6)	0

*p < .05

Table 7.2 summarizes participant characteristics. With regard to health literacy, 54.7% (n=75) participants had adequate health literacy and 45.3% (n=62) had inadequate health literacy. Participants had a mean HSLI-SF score of 6.82 (SD=2.17), which is nearly identical to estimates from the validation study (Mean=6.7, SD=2.3).[76] The mean HK-LS score was 17.49 (SD=3.46), which is nearly identical to estimates from the validation study (Mean=17.71, SD=3.77).[13] A majority of participants had either employee-sponsored or private health insurance (60.8%). Patients had an average of 1.2 (SD=1.93) health conditions. Participants reported being prescribed a total of 2.43 (SD=2.02) medications, and 1.44 (SD=0.91) antihypertensive medications, on average. A majority of participants reported using health management apps (56.2%), and half reported owning a wearable health tracking device (50.4%). On average, participants reported monitoring their BP (Mean=3.45, SD=0.92) and medication adherence (Mean=3.72, SD=1.22) sometimes to very often.

Table 7.2 Participant characteristics

	All	Treatment	Control
Health Care Coverage, *n (%)*			
Medicaid	19 (13.9)	11 (15.5)	8 (12.1)
Medicare	23 (16.8)	12 (16.9)	11 (16.7)
Employee-sponsored	56 (40.9)	27 (38.0)	29 (43.9)
Private	27 (19.7)	12 (16.9)	15 (22.7)
Other	5 (3.6)	4 (5.6)	1 (1.5)
None	7 (5.1)	5 (7.0)	2 (3.0)
Health Literacy (HLSI-SF), *Mean (SD)*			
Adequate Health Literacy *n (%)*	75 (54.7)	39 (54.9)	36 (54.5)
Below Adequate Health Literacy *n*	62 (45.3)	32 (45.1)	30 (45.5)
Hypertension Knowledge (HK-LS, 0-	17.49	17.52	17.45 (3.45)
Charlson Comorbidity Index, *Mean*	1.20 (1.93)	1.21 (2.03)	1.18 (1.84)
Total # of Medications, *Mean (SD)*	2.43 (2.02)	2.23 (1.64)	2.65 (2.36)
# of Antihypertensive Medications,	1.44 (0.91)	1.39 (0.96)	1.48 (0.86)
Use of Apps to Manage Health, *n (%)*	77 (56.2)	36 (50.7)	41 (62.1)
Ownership of Wearable Health	69 (50.4)	34 (47.9)	35 (53.0)
Frequency of Monitoring Blood	3.45 (0.92)	3.46 (0.88)	3.42 (0.98)
Frequency of Monitoring Medication	3.72 (1.22)	3.85 (1.21)	3.58 (1.23)

7.4.2 Regression Results

Based on results from the backwards stepwise regression, the following control variables were excluded from the final regression model because they were not significant: gender (male/female), race (coded categorically as 1=White, 2=Black or African American, 3=Asian, 4=Native American or Pacific Islander, 5=Other-specify), ethnicity (Hispanic/non-Hispanic), education (coded categorically as 1=elementary, 2=some high school, 3=high school graduate, 4=some college or technical school, 5=college graduate, 6=graduate degree, 99=refused), income (coded categorically as 1=less than $10,000, 2=$10,000 to $19,999, 3=$20,000 to $29,999, 4=$30,000 to $39,999, 5=$40,000 to $49,999, 6=$50,000 to $99,999, 7=$100,000 or more, 88=refused, 99=don't know), health care coverage (categorical), comorbidity (continuous), total number of medications (continuous), number of HTN medications (continuous), wearable health tracking device ownership (yes/no), health app usage (yes/no), and frequency of monitoring medication (continuous). Despite being not significant, age was kept in the final model due to significant differences in age between the treatment and control groups. Both the treatment*health literacy and treatment*visualization type interactions were not significant and were excluded from the final model.

The final model included the following variables: the experimental condition (i.e., treatment versus control), health literacy (adequate versus inadequate), HTN knowledge (continuous 0 to 22), visualization type (categorical), age (continuous), and frequency of BP monitoring (continuous). The final model explained approximately 35% of the total variance in comprehension (adjusted R^2=.345). All VIFs for variables in the final model were between 1.04 and 1.58, indicating low collinearity between variables.

The mean comprehension score for all participants across all four visualization types was 2.79 (SD=1.39). Table 7.3 presents the parameter estimates and p-values for independent and control variables explaining comprehension. With respect to the main hypothesis that comprehension of condensed visualizations will be higher than that of separate visualizations, there was no empirical support.

Overall, comprehension of condensed visualizations did not significantly differ from that of separate visualizations (B=.04, p=0.76). The second hypothesis of a treatment*health literacy interaction (excluded from the final model) was also not significant, *F*(1, 129) = 0.93, *p* = .33. The treatment*visualization type interaction was also not significant, *F*(1, 129) = .16, *p* = 0.92.

Table 7.3 Model effects and p-values

Variable (reference group/variable type)	Parameter Estimate	SE	df	F-value	p-value
Treatment (control)	0.04	0.14	1, 131	0.09	0.76
Health Literacy (less than adequate HL)	0.603	0.17	1, 131	13.17	<.001
Visualization Type (LU)	-	-	3, 131	32.18	<.0001
HU	-0.85	0.12	-	-	-
LC	-1.11	0.12	-	-	-
HC	-0.69	0.12	-	-	-
Hypertension Knowledge (continuous)	0.12	0.02	1, 131	25.39	<.0001
Age (continuous)	0.00	0.01	1, 131	0.02	0.88
Frequency of BP Monitoring (1 = Never, 5 = Always)	-0.13	0.08	1, 131	2.76	0.10

As expected, health literacy (B=0.61 p<.001) and HTN knowledge (B=0.12, p<0.0001) were both significant predictors of comprehension. Age (B=0.00, p=0.88) and frequency of BP monitoring (B=-0.13, p=0.10) were not significant. Table 7.4 presents the mean differences between the treatment and control groups for each visualization type, none of which are significant. Table 7.5 presents mean differences between high and low health literacy groups for each visualization type, all of which are significant at the p=.05 level.

Table 7.4 Mean differences in comprehension for visualization type by experimental group

	Treatment	Control	Difference	SE	df	t-value	p-value
LU	3.47	3.38	0.08	0.21	136	-0.4	0.69
HU	2.59	2.48	0.11	0.21	136	-0.54	0.58
LC	2.26	2.31	0.04	0.21	136	0.22	0.82
HC	2.72	2.68	0.04	0.21	136	-0.2	0.84

Table 7.5 Mean differences in comprehension for visualization type by health literacy

	High HL	Low HL	Difference	SE	df	t-value	p-value
LU	3.71	3.14	-0.56	0.21	136	-2.71	<.01
HU	3.22	1.85	-1.37	0.21	136	-6.63	<.0001
LC	2.89	1.68	-1.22	0.21	136	-5.87	<.0001
HC	3.37	2.03	-1.34	0.21	136	-6.48	<.0001

To further evaluate whether the final model included appropriate control variables, we conducted additional analyses. Specifically, the individual correlations of each control variable (gender, age, race, ethnicity, education, income, visualization type, HTN knowledge, comorbidity, frequency of BP tracking, frequency of medication monitoring, number of medications, number of HTN medications, health app usage, and wearable device ownership) with comprehension were assessed, and variables with significant correlations ($p < .05$) were included together in a regression model predicting comprehension. Control variables that were significantly correlated with comprehension included gender, age, race, ethnicity, education, visualization type, HTN knowledge, comorbidity, frequency of BP tracking, number of HTN medications, health app usage, and wearable device ownership. This is different from the final model described above where only visualization type, HTN knowledge, age, and frequency of BP monitoring were included as control variables. When variables that significantly correlated with comprehension were included in a regression model with health literacy and both interaction terms, results were nearly identical to the original model, with the exception of app usage (B=-0.323, p=0.047) being negatively associated with comprehension. Thus, the key findings of the effects of health literacy and HTN knowledge on visualization comprehension appear to be robust.

As Table 7.3 shows, visualization type was significant *F*(3, 408) = 32.18, *p* <.0001. Analysis of variance in comprehension scores between the four visualization types (LU, HU, LC, HC) revealed noteworthy results. On average, participants' comprehension scores were highest for the low adherence/uncontrolled blood pressure visualization type, and lowest for the low adherence/controlled BP visualization type. The mean comprehension score for each visualization type was as follows: LU (Mean=3.24), HU (Mean=2.39), LC (Mean=2.13), and HC (Mean=2.55). Specifically, all mean comparisons were significantly different, with the exception of HU and HC. Table 7.6 presents these mean differences.

Table 7.6 Mean differences in comprehension for LU, HU, LC, and HC

	LU	HU	LC	HC
LU	-			
HU	0.85*	-		
LC	1.11*	0.26*	-	
HC	0.69*	-0.16	-0.42*	-

*p<.05

7.5 Discussion

This study provides new insights into how variations in how BP and medication adherence information are presented in visualizations can influence patient comprehension of such information. The condensed visualization used in this study, which was based on both best practices and user preferences, used a single graph to display BP and adherence information, while the separate visualizations displayed BP and adherence information using a graph and a calendar, respectively. Contrary to our hypothesis, the condensed visualization did not improve patient comprehension of BP and adherence information. Also contrary to our hypothesis, health literacy did not significantly moderate the relationship between experimental condition and comprehension.

It is possible that the condensed display used in this study was not the most effective way to convey BP and adherence data simultaneously. In a prior study that assessed preferences for condensing the display of medication adherence and BP information into a single visualization, alternative visualization techniques, including using color-coded BP lines or shaded regions to show medication adherence, were not preferred by patients, and the location of the symbols on the x-axis was preferred over other locations (e.g., on or directly below the BP lines).[162] However, it is possible that the technique for condensing medication adherence and BP information preferred by patients is not the most effective technique for improving comprehension. In the condensed visualizations used, the distance between the symbols for medication adherence and the BP lines may have impeded comprehension. It is also possible that the technique used for condensing the display of BP and adherence information into a single visualization does not differ from the status quo (separate display) enough to affect comprehension, or that giving longer periods of time (e.g., via a web survey) to assess comprehension mitigates any negative effect visualization complexity may have on comprehension. Future research should further investigate whether different techniques for condensing medication adherence and BP information improve comprehension as well as other performance indicators, such as time to complete tasks such as extracting information from a visualization.

Health literacy was significantly and positively associated with comprehension. In prior user assessments of visualizations, individuals with lower health literacy used different terminology in some instances (e.g., “normal blood pressure” versus “controlled blood pressure”), and commented more on how cluttered some visualizations were.[162] Future research should focus on different approaches for reducing clutter and increasing familiarity of certain features (e.g., terminology) that can facilitate comprehension among individuals with lower health literacy. Adding customizable features, such as toggling to turn on and off adherence indicators or BP indicators, may allow users to reduce clutter and understand information in its isolated and combined form.

New user experience (NUX) tutorials, that overlay mobile apps and provide a walk-through explanation of an app and its features may also improve comprehension and reduce initial perceived complexity by the patient. Message prompts (e.g., notifications of a poor and healthy status) may also facilitate understanding of visualizations by providing more context. For instance, cues to action in the form of warning messages when adherence is low, or BP reaches pre-specified elevated levels, may prompt people to review their data and lead to more accurate interpretation. Future work should explore whether integrating customization and NUX tutorials increase comprehension of visualizations. In addition, investigating alternative outcome measures (e.g., time to complete a task) may address the ethnicity effect found in this study by reducing or eliminating the need for participants to read and answer questions.

A surprising finding in the secondary model that included the control variables that significantly correlated with comprehension was the negative association between using mobile apps to manage one's health and comprehension of BP and adherence information. It would be expected that prior familiarity with health apps would facilitate one's understanding of the health-related visualizations used in this study.[162] It is possible that users of such apps are accustomed to interactive features, and the static images used in the current study negatively influenced their ability to understand the information in the visualization. It is also possible that users are more accustomed to viewing their own personal health data and find it difficult to evaluate unfamiliar scenarios.

It should be noted that overall comprehension of the different visualization types was significantly different between all but two visualizations (HU and HC). Interestingly, the two visualizations with arguably the most (LU) and least (HC) complex scenarios resulted in the highest comprehension. This suggests that perhaps there are more effective techniques for visualizing certain personal health scenarios than others, and lends support for tailoring the display of personal health data to the scenario rather than using the same technique regardless of the information communicated. For instance, it is possible a scenario with low adherence and uncontrolled BP shows less consistency in both adherence and BP than a scenario with high adherence and controlled BP. A more effective technique for scenarios with more consistent adherence and controlled BP may be to indicate an overall positive health status with a simple indicator, such as smiley face. Similarly, degrees of overall severity in BP status could be indicated by different emoticon expressions, prompting patients to further explore what is driving the status indicator to change.

Understanding the relationship of visualization design and patient characteristics that influence comprehension is of value and should continue to be investigated. Through further assessments of differences in comprehension associated with visualization design and the characteristics of those who use them, optimal techniques can be identified and incorporated in technologies built to facilitate the management of one’s condition (e.g., mobile apps for managing HTN). In doing so, certain health behavior theories such as self-regulation and the Health Belief Model may be used to better understand how technologies can improve health behaviors (via improved visualization comprehension).[15,19]

The importance of patient comprehension of medication adherence and BP information visualizations is supported by several heath behavior theories. According to the theory of self-regulation of chronic disease,[19] observations (i.e., changes one notices about their condition) of BP and adherence influence and are also influenced by the patient’s outcome expectations (i.e., whether taking medication will control BP), previous observations of BP and adherence, and judgments about the severity of their condition. Observations and judgments of BP and adherence information are also influenced by factors that can influence perception, including interpersonal factors, such as knowledge, attitudes, beliefs, and external factors, such as social support and material resources.[19] A patient's ability to make accurate observations and judgments of their BP and adherence requires that they understand the information they collect during HTN self-monitoring.

According to the Health Belief Model, perceptions of the benefits of taking medication are shaped by one's understanding that the behavior is associated with a positive outcome (e.g., BP control).[15] Visualizations of medication adherence and BP levels attempt to enhance this understanding by showing the association between adherence and BP control (i.e., high adherence leads to controlled BP). In addition, seeing a missed dose and subsequent elevation of BP may serve as a cue to action to adhere to anti-hypertensive medications. Thus, correct interpretation of visualizations may positively influence medication adherence. Future studies should examine this relationship.

This research has several limitations. First, recruiting a convenience sample of participants using Mturk resulted in a sample not representative of the overall population. Though control variables such as age, race, education, income, and healthcare did not significantly affect the outcome measure, participants were quite different in some respects. The average age of participants was 35.5 years while prevalence estimates of individuals with HTN who are 18 to 39 years is just 7.3%.[29] Participants were also more highly educated than the general population, with 60.5% of participants having a bachelor's degree or higher compared to just 30.3% of the general population.[165] In addition, eligibility was self-reported, so we cannot verify whether all participants truly had a diagnosis of HTN. While true representativeness considering study eligibility criteria may make it difficult to ascertain, these differences are noteworthy and limit generalizability.

Sample size may have also influenced results. This study was powered to detect a medium effect (.5) for the effect of visualization type (condensed vs. separate) on comprehension and a medium to large effect (.75) for the health literacy interaction. It is possible that the effect of condensed visualizations on comprehension are small and could not be detected in the current study.

Because of the context in which these visualizations would likely be used (i.e., mobile apps), these visualizations were optimized for mobile devices. However, this study was conducted with participants using a computer or laptop, which may have affected comprehension (e.g., a larger graph may have been easier to understand for some participants). In addition, the visualization in this study used a hypothetical situation and not the participants' personal health data, which may have affected how some participants perceived concepts such as high, normal, and controlled BP. Future research should assess comprehension of visualizations in a real-world context. Lastly, other factors, such as the two-week period displayed may have influenced the results, and visualizations showing longer periods of time (e.g., several months) may provide a broader perspective and be more conducive the comprehension of overall trends in the relationship of medication adherence with BP.

7.6 Conclusion

This study provides important insights into considerations for designing information visualizations for managing HTN. The results from this study suggest that certain techniques for condensing the display of medication adherence and BP information do not improve comprehension when compared to visualizations providing a separate display of the same information. However, health literacy and HTN knowledge were positively associated with overall visualization comprehension, while Hispanic ethnicity and the use of mobile apps were both negatively associated with comprehension. Future research should further investigate how different techniques for visualization of HTN-related information and user characteristics might influence visualization comprehension. Future research should also explore whether features can be added to apps (e.g., audio-assisted interpretation of data) to improve understanding of information for those with low health literacy.

CHAPTER 8: COMPREHENSION SCALE VALIDATION

8.1 Overview

Well-established procedures were used to assess the validity and reliability of a 6-item scale that was developed to measure patients' comprehension of the visualized relationship between medication adherence and BP control.[150] Development of scale items are described in Chapter 4, Section 4.4.5.3. First, face validity, readability, and relevance of the six scale items were examined by an expert panel that included four health behavior scientists, a physician, and a health informaticist. Patient understanding of the scale items was then assessed during cognitive interviews. Following analysis of the cognitive interviews, items were revised to reflect cognitive interview results and to accommodate their use for visualizations depicting four medication adherence and BP control scenarios: 1) high adherence (100%) and controlled BP (HC), 2) high adherence (100%) and uncontrolled BP (HU), 3) low adherence (50%) and controlled BP (LC), and 4) low adherence (50%) and uncontrolled BP (LU). Comprehension of each of the four visualization types was assessed for all (n=137) participants.

To assess the psychometric properties of the 6-item scale, we first performed exploratory factor analyses using principal component analysis (PCA) with promax rotations for the LU and HU visualization comprehension measures.[166] Parallel analysis was also used to identify the number of factors underlying the 6-item scale.[167] Then, confirmatory factor analysis (CFA) was performed for the LC and HC visualization comprehension measures to further validate the factor structure of the 6-item scale by comparing a hypothesized unidimensional model (Figure 8.1) to a possible 2-factor model (Figure 8.2). Finally, factor loadings and model fit statics were calculated to determine a best fit model. Kuder-Richardson Formula 20 (KR-20) was calculated to determine internal consistency reliability.[149]

Figure 8.1 Path diagrams for the hypothesized unidimensional solution for visualization comprehension

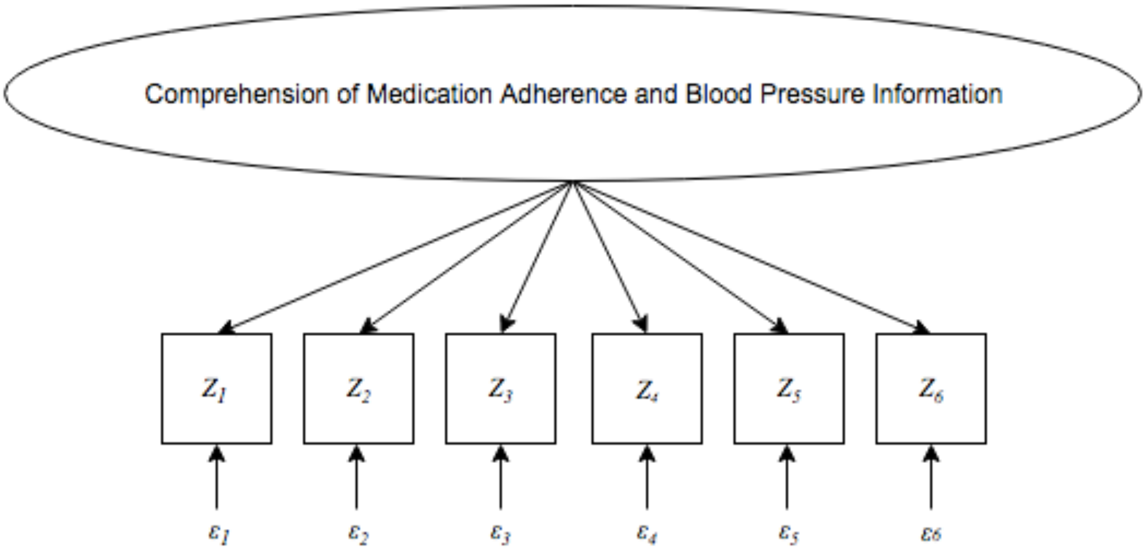
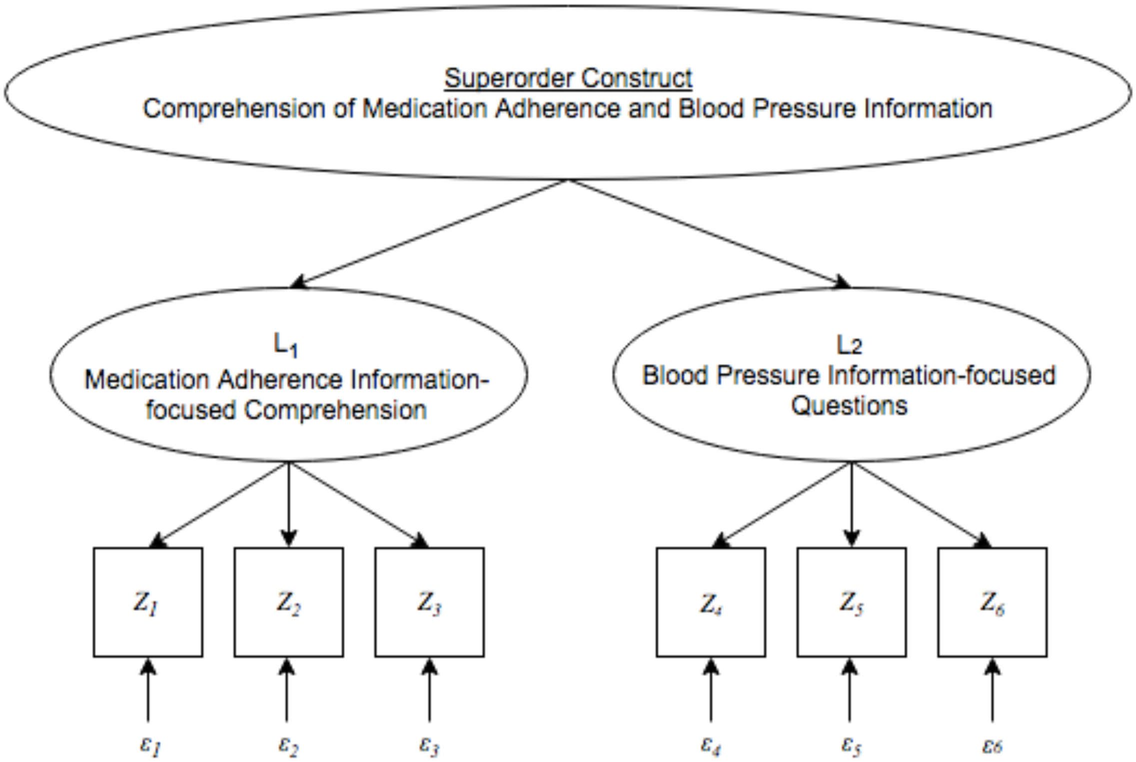


Figure 8.2 Path diagram for alternative 2-factor solution for visualization comprehension



8.2 Cognitive Interview Results

Table 8.1 summarizes characteristics of the study participants. The sample included 3 males and 3 females, with an average age of 57.2 years. Three participants were white, 1 was black, and 2 were Hispanic. Two participants had a college degree or more, 2 had some college, and 2 had a high school diploma or less. Two participants had less than adequate health literacy as measured via the REALM.[79]

Table 8.1 Sample characteristics

Characteristics (N=6)	**n (%)/Mean (SD)**
Age*, Mean (SD)*	55.7 (10.8)
Male	3 (50)
Race/ethnicity	
Non-Hispanic White	3 (50)
Non-Hispanic Black	2 (33)
Hispanic	1 (17)
Less than adequate health literacy (REALM)	2 (33)
Education	
College	2 (33)
Some College	2 (33)
High School or less	2 (33)

Audio-recorded cognitive interviews were conducted with six participants (n=6) to assess face validity and readability of the six questions. Participants were asked to read each question and its response options aloud. After reading each question, participants were asked if they understood the question and if there was anything about the question they would change. None of the participants indicated confusion or offered suggestions for changes. However, detailed analysis of the audio recordings revealed four instances when questions were read incorrectly or where participants misinterpreted the question. These specific instances are described below.

One participant *(White, Male, 65)* with low health literacy had difficulty reading questions verbatim, however the overall concept of the question was understood. This participant confused the phrase “this person” with the word “personal,” and when later asked to answer the questions about a graph, he referred to the graph and not himself, which suggests he understood the question despite reading one word incorrectly. Another participant with low health literacy *(Black, Female, 63)* read the word “with” as “when,” and re-read the question 3 times before understanding it. Despite instructions to consider whether they understood what the question was asking, two (n=2) participants with low health literacy *(White, Male, 65; Black, Female, 63)* initially answered questions based on personal experience even though there were no graphs to reference. In these cases, participants were provided additional instructions to read the question aloud, and only answer the follow-up questions asked by the interviewer.

No questions were eliminated based on the cognitive interview results. To address the issue of prematurely answering questions based on personal experience, some questions were edited to include a preface statement “looking at the graph [and calendar].” Upon further review by the expert panel, minor edits were made following the cognitive interviews to improve readability, and response options were edited so that they applied uniformly to each of the four visualization types (LU, HU, LC, HC). Specifically, the question “on days when blood pressure is high, did this person usually take their medication?” implies the graph includes days with high BP, so a response option of “there are no days with high blood pressure” was added to provide a correct response for graphs showing only controlled BP.

The final 6 items were as follows:

1. Looking at the graph, does it look like taking medication makes the person’s blood pressure levels normal?
    - ☐ yes
    - ☐ no

2. Looking at the graph, would you say that this person's blood pressure levels:

    ☐ are not related to how they take their medication

    ☐ are related to how they take their medication

3. Looking at the graph, missing medication:

    ☐ makes blood pressure worse

    ☐ does not change blood pressure

    ☐ I cannot tell from this graph

4. Looking at the graph, would you say that this person's blood pressure levels generally change when they <u>do not</u> take their medication?

    ☐ yes

    ☐ no

    ☐ I cannot tell from this graph

5. Looking at the graph, would you say this person's blood pressure levels are always normal when they <u>do take</u> their medication?

    ☐ yes

    ☐ no

6. On the days when blood pressure is high, did this person usually take their medication?

    ☐ yes

    ☐ no

    ☐ there are no days with high blood pressure

8.3 Principal Components Analysis Results

Repeated measures were used to assess four different scenarios of medication adherence and BP control, where each study participant answered the 6-item comprehension scale for each of the four scenarios (LU, HU, LC, HC). Exploratory factor analyses were conducted for two of the four scenarios (LU and HU) to examine the underlying factor structure of the six-item scale. Specifically, to explore the dimensionality of the 6-item comprehension scale, PCA with promax rotation, as well as parallel analysis were performed on the LU and HU measures.[166] A promax rotation is an oblique rotation, and was chosen because it allows factors to correlate, and it is assumed any factors contained within the 6-item comprehension scale would be correlated.

For the LU measure, PCA results suggested a two-factor solution, with questions 2, 3, 4, and 6 loading on the first factor, and questions 1 and 5 loading on the second. For the HU measure, all six items loaded on a single factor. Factor loadings from the PCA for the LU and HU measures are shown in Tables 8.1 and 8.2.

Table 8.2 PCA factor loadings for LU measure

Item	Factor1	Factor2
3	0.74039	-0.26011
4	0.68677	-0.08366
2	0.67094	-0.24341
6	0.55193	-0.15684
5	0.34427	0.72064
1	0.39818	0.63244

Table 8.3 PCA factor loadings for HU measure

Item	Factor1
2	0.84752
4	0.83028
3	0.77459
1	0.73428
5	0.71837
6	0.56157

In the parallel analysis, a random dataset was created with 6 variables and 137 observations, then simulated eigenvalues of the random dataset were calculated and compared to the actual eigenvalues.[167] When eigenvalues produced from the random dataset are greater than that of the actual dataset, this suggests the corresponding eigenvalues from the actual dataset are due to random noise. As shown in Table 8.4, the parallel analysis suggested a unidimensional solution for both the LU and HU measures; only one eigenvalue for both the LU and HU measures exceeded the predicted eigenvalue, while the remaining actual eigenvalues were smaller than the corresponding predicted eigenvalues. This suggests that the comprehension scale has one underlying factor.

Table 8.4 Actual and simulated eigenvalues for LU and HU measures

Predicted Eigenvalue	Actual Eigenvalue for LU	Actual Eigenvalue for HU
1.297	2.052	3.378
1.151	1.078	0.782
1.038	0.904	0.756
0.941	0.802	0.498
0.846	0.645	0.327
0.727	0.519	0.259

8.4 Confirmatory Factor Analysis Results

To confirm the exploratory factor analysis results that suggested a 1-factor solution, CFA with nested comparisons was performed. Separate CFAs were performed for both the LC and HC comprehension assessments. First, to assess dimensionality of the scale, nested model comparisons were made using Chi-square difference tests to assess the correlations between a 2-factor and 1-factor model. A chi-squared test statistic with a $p<.05$ threshold was used to determine dimensionality. By constraining the correlation of two latent variables to 1 in the first model (i.e., forcing a unidimensional factor), and comparing it to the model with an unconstrained correlation of two latent variables (i.e., allowing for a bidimensional structure), it can be determined if the correlations significantly differ. If the correlation between two latent variables significantly differed from 1, this would suggest a 2-factor solution. Following the chi-square difference tests, CFA was performed to determine which items to include for a best model fit. To evaluate goodness of fit, a Chi-square test statistic, Tucker-Lewis Index[151] (TLI), Incremental Fit Index[152] (IFI), Relative Non-centrality Index[153,154] (RNI), Root Mean Square Error of Approximation[155] (RMSEA), and Bayesian Information Criterion[156] (BIC) were calculated for each model. *A priori* criteria for determining a good fit were as follows: χ^2 $p > .05$, TLI $> .9$ and ≤ 1.0, IFI $> .9$ and ≤ 1.0, RNI $> .9$ and ≤ 1.0, RMSEA ≥ 0 and $< .1$, and BIC < 0.

The chi-square difference tests comparing L_1 versus L_2 for both the LC (χ^2 (1, N = 137) = .5412, p=.4619) and HC (χ^2 (1, N = 137) = .0057, p=.9399) models were not significant. For both models, these results further confirm the exploratory factor analysis results and suggest a unidimensional solution. Table 8.5 shows the CFA factor loadings and explained variance for each item of each for the LU, HU, LC, and HC measures.

Table 8.5 CFA factor loadings and variance explained for LU, HU, LC, and HC models

	Item Number	Factor Loading	Variance Explained (%)
LU	1	1.000	0.060
	2	1.702	0.272
	3	2.307	0.499
	4	1.353	0.356
	5	0.793	0.036
	6	1.547	0.146
HU	1	1.000	0.427
	2	1.337	0.639
	3	1.297	0.566
	4	1.408	0.667
	5	0.924	0.386
	6	0.586	0.219
LC	1	1.000	0.091
	2	-1.923	0.317
	3	-2.492	0.576
	4	-2.732	0.606
	5	-0.171	0.005
	6	-1.460	0.172
HC	1	1.000	0.025
	2	3.868	0.125
	3	13.763	0.846
	4	12.613	0.745
	5	1.068	0.019
	6	9.564	0.406

Next, to examine model fit, fit statistics were calculated, and models were adjusted until an overall good fit was found for all four measures. Table 8.6 shows model fit statistics for a 6-item, 5-item, and 4-item measure for both the LC and HC. First, model fit statistics for the LC and HC measures including all six items were calculated. Model fit for the 6-item LC was poor, as indicated by χ^2 = 23.064 (9, N=137, p<.01), TLI = 0.825, IFI = 0.899, RNI = 0.895, RMSEA = 0.107, and BIC = -21.216. Similarly, model fit for the 6-item HC was also poor, with fit statistics of χ^2 = 25.569 (9, N=137, p<.05), TLI = 0.88, IFI = 0.929, RNI = 0.928, RMSEA = 0.116, and BIC = -18.71.

Model fit was then assessed for a reduced model of the LC and HC measures, which excluded item 5 (*Looking at the graph, would you say this person's blood pressure levels are always normal when they do take their medication? yes/no*), which had the lowest factor loading and explained the least amount of variance. Model fit for the 5-item LC was somewhat better, but still poor overall. Similarly, model fit for the 5-item HC improved, but was also poor.

Given that the 5-item model still did not fit well, model fit was then assessed for a 4-item model. Item 1 (*Looking at the graph, does it look like taking medication makes the person’s blood pressure levels normal? yes/no*) was excluded in this model because this item had the second lowest factor loading and explained the lowest amount of variance in comprehension. Model fit for the 4-item LC was good as indicated by fit statistics of. Similarly, model fit for the 4-item HC was also good.

Table 8.6 Model fit statistics for 6, 5, and 4-item LC and HC models

Fit Statistic	LC (6-item)	LC (5-item)	LC (4-item)	HC (6-item)	HC (5-item)	HC (4-item)
χ^2	23.064	13.37	1.197	25.569	14.082	1.221
(df, N)	(9,N=137)	(5,N=137)	(2,N=137)	(9,N=137)	(5,N=137)	(2,N=137)
p-value	p<.01	p<.05	p=.549	p<.05	p<.05	p=.543
TLI	0.825	0.869	1.022	0.88	0.918	1.000
IFI	0.899	0.937	1.007	0.929	0.959	1.004
RNI	0.895	0.935	1.007	0.928	0.959	1.004
RMSEA	0.107	0.111	<.000	0.116	0.116	<.000
BIC	-21.216	-11.229	-8.643	-18.71	-10.517	-8.618

8.5 Internal Consistency Reliability Results

Kuder-Richardson 20 values were calculated for the LU, HU, LC, and HC measures for the reduced model, which includes items 2, 3, 4, and 6.[149] These scores ranged from questionable to good, with the LU (ρ_{KR20} = .61) measure having poor internal consistency, and the LC (ρ_{KR20} = .71), HC (ρ_{KR02} = .79), and HU (ρ_{KR02} = .81) measures showing acceptable internal consistency.[159]

CHAPTER 9: SUMMARY AND DISCUSSION

9.1 Summary of Findings

In summary, for Aim 1 I conducted user assessments to assess user preferences for visualizations for managing HTN and cognitive interviews to assess patient understanding of three visualizations that condensed the display of BP and medication adherence information into a single visualization. Results from both the user assessments and cognitive interviews informed the design of the visualizations that were used in the randomized experiment in Aim 2. Aim 3 focused on assessing the validity and reliability of a newly-developed visualization comprehension scale.

Results for the user assessments (Chapter 5) suggested that for condensed visualizations, the use of culturally recognizable symbols (e.g., ✓'s and X's) is preferred over other techniques of indicating adherence (e.g., color-coded BP lines or shaded regions below BP lines). In addition, labeling individual BP values, using reference lines, and indicating the region of normal BP were preferred features for facilitating the display of a BP value. However, combining all desired features users preferred would clutter the visualization; a problem for which participants with low health literacy specifically commented.

Each of the features users preferred was later assessed to determine which facilitates understanding of the visualization. Health literacy was also found to likely play a role in preference. While a majority of participants preferred a grid format for reference lines, two participants with low health literacy commented that it was "too much.” Alternative terminology was suggested for both systolic (upper, top, high) and diastolic (lower, bottom, low) BP, as well as controlled BP (normal). Lastly, when looking at preferences for tracking medication adherence alone, participants preferred a calendar view over a list view, which is contrary to how many current available mobile apps for tracking medication adherence visually present such information.

In addition to the user assessments, the top 10 BP and top 10 medication tracking apps in both the Google Play and Apple app stores were reviewed to determine the most commonly used techniques for visualizing BP and medication adherence information. When the Google Play and Apple apps were compared with the user assessment results, visualization techniques both aligned and conflicted. Results of the user assessments showed that patients prefer numeric labels for blood pressure graphs, and all blood pressure monitoring apps reviewed (n=20) used numeric labels. For medication adherence, only 25% of apps reviewed (n=5) used symbols for showing medication adherence; whereas, all participants (n=6) in our study preferred the use of symbols. Similarly, all participants preferred to track medication using a calendar view versus a list view, but in the review of medication tracking apps, only 35% of apps (n=7) used a calendar view, and all of the apps (n=20) used a list view.

Results for the cognitive interviews (see Chapter 6) revealed two main insights that informed the final visualizations used in Aim 2. First, results suggested that visually dichotomizing controlled versus uncontrolled BP by using a shaded normal BP zone facilitates one’s ability to distinguish between controlled and uncontrolled BP. While labeled data points and horizontal reference lines may allow for more granular understanding of specific BP values, our results suggest it is not the most effective approach for communicating controlled versus uncontrolled BP values. Second, results suggested using symbols with perceptually distant colors may improve one's ability to distinguish between medication adherence and non-adherences compared to using just one symbol to show days of non-adherence. Section 9.2 discusses the implications of the results from Aim 1, and how results and limitations from Aim 1 may have influenced the results from Aim 2.

For Aim 2 (see Chapter 7) I conducted a survey experiment to test the two primary hypotheses of this dissertation: 1) that condensed visualizations will improve patient comprehension (i.e., main effect), and 2) that health literacy would moderate the relationship described in the first hypotheses (i.e., moderating effect). The primary hypothesis was not supported as there was no significant difference in comprehension between condensed or separate visualizations. Because the main effect was not significant, it was expected the moderating effect would also not be significant. This expectation was confirmed; health literacy did not moderate the relationship between visualization type and comprehension. Although the primary hypotheses were not supported, key control variables were significantly associated with comprehension: health literacy and HTN knowledge were both positively and significantly associated with comprehension. Section 9.2 expands the discussion on the implications of Aim 2 in regard to several topics, including HTN self-management, medication adherence, health literacy, HTN knowledge, and data visualization design for mobile apps for health management. Results and limitations of Aim 2 are also discussed, specifically methodological and sampling issues that may have influenced the overall results.

For Aim 3 (see Chapter 8), I analyzed the validity and reliability of a newly-developed 6-item comprehension scale. First, questions were developed and reviewed by an expert panel for face validity, content validity, readability, and relevance. Next, face validity was assessed during cognitive interviews. Items were revised and used in the survey experiment for Aim 2. Exploratory and confirmatory factor analysis determined the best model fit for a unidimensional solution necessitated the deletion of two items (items 1 and 5). The first hypothesis that HTN knowledge would be significantly and positively associated with comprehension was partially supported. While the factor analyses resulted in reducing the original 6-item scale to a 4-item scale, HTN knowledge was significantly and positively associated with comprehension. The second hypothesis that the comprehension scale would have acceptable internal consistency was also partially supported in that 3 of the 4 measures of comprehension (HU, LC, HC) for the 4-item scale demonstrated acceptable internal consistency ($\rho_{KR2} \geq .70$). The other scale (LU) demonstrated questionable internal consistency ($\rho_{KR2} = .61$). Section 9.2.8 discusses how the validity and reliability of the comprehension scale may have influenced the results of Aim 2.

9.2 Implications

The major implications of this study involve considerations for how HTN self-management information, specifically medication adherence and BP control, is visually communicated to patients, specifically in the context of mobile apps for monitoring medication adherence and BP control. This study focused on how to best design visualizations that optimize one's comprehension of one's state of health (i.e., BP control), a behavior that influences one's state of health (i.e., medication adherence), and the inferred correlation between the two. There are several topics related the potential utility of visualizations as health management tools that are worthy of discussion. Health literacy and HTN knowledge are personal characteristics directly related to one's ability to comprehend health data visualizations. Medication adherence and HTN self-management are behaviors that may be influenced by HTN-related data visualizations, suggesting that the effects of HTN-related data visualizations on comprehension, adherence, and self-management could be relevant to several health behavior theories. The tools and technologies used to connect a person to their personal health data, specifically mobile apps for HTN self-management and the data visualizations used in such apps, are also relevant to the development of mobile health apps. Finally, measurement of visualization comprehension may shed light on how features of visualizations impact comprehension as well as the impact that visualization comprehension can have on health behaviors.

9.2.1 Hypertension Management

Although self-management of HTN, including self-monitoring of BP and medication adherence, can lead to improved BP levels[22–25], self-monitoring is underutilized by patients with HTN.[35] In a 2008 survey of 530 patients with HTN, less than half (43%) reported using a home BP monitor.[35] In the current study, participants in Aim 2 reported monitoring their BP sometimes to very often. While not directly comparable, results would suggest that study participants may be more motivated to monitor their HTN than the overall patient population.[35]

The use of technology (e.g., mobile apps and patient web portals) in self-management of HTN has been shown to improve BP control,[38] and information visualizations are often a component of such technologies. Patient education has also been shown to be an effective intervention for improving HTN self-management.[25] Among participants in the survey experiment in Aim 2, approximately half (50.4%) reported using a wearable health tracking device, and a majority (56.2%) of participants reported using mobile apps for health management. As technologies for self-managing HTN become more widely available and adopted, the effectiveness of visually communicating the status of one's condition and how behaviors might affect such status will become increasingly important. While the approach for condensing visualizations for HTN tested in Aim 2 did not improve comprehension, it is possible that preferences, other untested techniques for condensing visualizations for HTN, or other methods for reducing the complexity of visualizations may improve comprehension. Future research should further investigate these possibilities.

Approaches to visualizing personal health data can range from simple line graphs to metaphoric animation or interactive customizable tools.[168] While this study considered user preference from the outset, then incorporated those preferences into future iterations of the visualization, future work should consider a fluid approach to determining user preference, whereby patients are given an interactive tool that allows users to choose which features to include and how the features look. In this way, a patient can customize features and characteristics of a personal health data visualization, such as a timeframe (e.g., daily, weekly, monthly), health indicators (e.g., BP levels, heartrate, blood glucose levels), and behaviors (e.g., taking medication, steps taken, tobacco use) displayed by the visualization. Tailored approaches for visualizing personal health data are likely to become increasingly necessary as wearable health tracking devices become more capable of monitoring multiple health indicators simultaneously and health monitoring of multiple physiologic and behavioral parameters becomes more centralized (e.g., the Apple Health app).

Physicians also play a key role in HTN self-management in that their involvement in self-management interventions (e.g., through physician-led patient education or recommendations to self-monitor HTN) has been shown to improve BP control.[25,37] Unfortunately, just 35% of patients with HTN recalled a doctor ever recommending the use of a home BP monitor.[35] When physicians recommend self-monitoring of BP, help set target BP goals with patients, and provide patients with medication use instructions, this knowledge could influence how a patient understands visual feedback while engaging in self-monitoring after the office visit. Including all stakeholders, such as physicians, patients, and caregivers, in the mobile app development process can help ensure that visualizations align with, or are capable of being customized to align with physician recommendations and instructions.

9.2.2 Medication Adherence Implications

Patient-related factors known to be associated with poor medication adherence among patients with hypertension include age (being younger),[5–7,48] gender (male),[48] race (non-White),[6,8,48] having comorbities,[7,48] lower health literacy,[8–10] less knowledge about their condition,[11,12] and less knowledge about the prescribed treatment (e.g., the duration of treatment, the reason for the medication).[11] As it relates to comprehension of visualizations for HTN self-management, we found that lower health literacy and less HTN knowledge were associated with less comprehension. For information visualizations to improve medication adherence among HTN patients, it is important to consider whether the patient population of interest is capable of comprehending the visualizations and the factors that may influence their ability to comprehend.

As it relates to a patient-centered design process, it is important to consider factors about one's condition as well, as it will likely inform who will benefit most from visual tracking of adherence. Research has shown a longer duration of HTN to be positively associated with adherence,[34] specifically having HTN for five or more years.[11] This suggests that a primary target population for the visualizations in this study are newly-diagnosed patients, as they are likely to be unfamiliar with tracking their adherence and BP, and may benefit most from seeing the connection between adhering to their medication and controlling their BP.

Evidence suggests that more complex pill regimens are associated with poorer medication adherence among patients with HTN.[4,5,8] Several other factors may explain poor adherence (e.g., side effects, cost, dosing frequency, and polytherapy). It is possible that visualizations for HTN self-management may facilitate a patient's ability to observe the effectiveness of particular medications, and ultimately improve adherence. By tracking medications, and understanding how BP is related to adherence, patients may be more likely to adhere to those particular medications. Visualization designs for HTN self-management should also be cognizant of complex antihypertensive pill regimens as the more information that is introduced is likely to increase the complexity of the visualization. This study only assessed complexity as a function of the presentation (condensed display versus separate display) of medication adherence and BP information. Furthermore, adherence information for only one medication was displayed. A possible explanation for why the condensed visualization did not result in improved comprehension is that visualization complexity was not distinguishable between the condensed and separate visualizations. In other words, the reduction in complexity of the treatment visualizations versus the control visualizations may have not been substantial enough to effect comprehension. It is possible that condensed data visualizations for more complex pill regimens might yield a greater improvement in comprehension than for when the pill regimen is relatively simple. Future research should assess how different approaches to visualizing adherence to complex HTN medication regimens and how they relate to BP levels influence abilities to comprehend the relationship between the two. Possible approaches include customizable views, where patients can view specific medications or groups of medications alongside BP levels, or summarizing and visually communicating overall adherence (e.g., as a percentage or by indicating any missed dose as non-adherent). These future studies should take into account that prior research suggests that less systematic change (e.g., random changes in adherence or BP levels) decreases one's ability to recognize an overall trend.[169]

9.2.3 Health Literacy

Several studies have shown an association between health literacy and antihypertensive medication adherence[8–10] and BP control[9,56–60] among patients with HTN. While the health literacy assessments used in Aim 1 (REALM[170]) and Aim 2 (HLSI-SF[76]) do not specifically measure numeracy and graph literacy, it is known that patients with high numeracy tend to better understand,[63] remember, and use quantitative information when making health-related decisions, whereas their lower-numerate counterparts tend to rely on non-quantitative information, such as narratives and emotions.[64–66] During the user assessments for Aim 1, participants with lower health literacy commented on the clutter of visualizations, which was considered in the design of visualizations used in Aim 2. Specifically, features used to reference BP levels (e.g., labeling BP data points, using references lines, and showing a shaded normal BP zone) increased clutter when they were combined into a single visualization. To address this, preferred features were tested independently to assess which of these features to display BP information best facilitated patients' abilities to correctly distinguish between controlled and uncontrolled BP.

Results from Aim 2 showed a positive association between health literacy and comprehension. It is difficult to know the extent to which perceptions of clutter on the graphs may have influenced the ability of individuals with low literacy to comprehend the information contained in the graph. Because comprehension questions required participants to evaluate quantitative information contained in the graph, it is possible that this may partially explain the association between health literacy and comprehension. It is worth noting that on average, Aim 1 participants were older and less educated than Aim 2 participants, and that results from Aim 1 did not accurately capture the preferences and understanding of visualizations of Aim 2 participants. When incorporating preference and understanding results from Aim 1 into the visualizations for Aim 2, it is possible that clutter and the quantitative burden of the visualization were not appropriately reduced. A failure to accurately capture these aspects of preference and understanding in Aim 1 could explain why the treatment effect among participants with low health literacy was not significantly greater than participants with high health literacy (i.e., the treatment*health literacy interaction was not significant). While the visualizations limited one's need to rely on quantitative information (e.g., using symbols, colors, and a shaded normal BP zone), there may be more effective ways to reduce quantitative tasks in the visualizations. For example, allowing patients to customize visualizations by adjusting the time period of the visualization, or summarizing consistent trends (e.g., consistent adherence with consistently controlled BP) with gist representations that summarize the overall effect of adherence on BP.[169,171,172]

It is also possible that the comprehension questions themselves were confusing to patients with low health literacy. During the cognitive interviews in which patients understanding of the comprehension scale was assessed, two participants with low health literacy initially answered comprehension questions based on their personal experiences with blood pressure medications even though there were no graphs to reference. Despite making corrections to the question wording to address this, it is possible that some participants during the survey experiment were confused and attempted to answer questions based on an incorrect interpretation of the question. Each visualization in the survey experiment was also accompanied by an explanation of high blood pressure and the values associated with it. It is possible that this explanation further confused participants with lower health literacy. Considering the graphs in this study using a visual reference (the shaded normal BP zone) to convey information about high BP values, it is possible that confusion could have been avoided if the explanation was excluded altogether. Future research should avoid including redundant information in visualizations and evaluate the best approaches for including ancillary information (e.g., via text or visual guides).

9.2.4 Hypertension Knowledge

Results from Aim 2 showed that HTN knowledge was positively and significantly associated with comprehension, which was expected based on previous work.[69] Health literacy was also significantly correlated with HTN knowledge (r=.57, p<.01), which has been shown in previous studies.[133,173] The relationship between HTN knowledge, health literacy, and comprehension of HTN-related visualizations suggests that familiarity with HTN is related to one's ability to process and understand information about their general health (including their HTN), and both of these factors influence one's ability to correctly interpret visual representations of behaviors and subsequent outcomes related to their HTN.

Having a diagnoses of HTN or a family member with HTN is known to be associated with higher HTN knowledge.[13] It is reasonable to assume that newly diagnosed patients have less knowledge about their condition than those having lived with HTN for a longer period of time, and that individuals with a longer diagnosis of HTN are better able to correctly understand the meaning and significance of a missed dose, BP level, and BP trends over time. This would further suggest that future designs of visualizations for HTN self-management pay particular attention to newly-diagnosed patients, as they may see the most benefit from understanding the information conveyed in BP and adherence visualizations.

9.2.5 Health Behavior Theory

Health behavior theories, such as the theory of self-regulation of chronic diseases and the Health Belief Model,[15,19] may be particularly relevant for understanding the effects of HTN self-management visualizations. Comprehension of medication adherence and BP information visualizations is salient to Clark and colleagues' model of self-regulation of chronic diseases in that making accurate observations of one's condition requires an understanding of the current condition (e.g., BP level) and the factors influencing the condition (e.g., medication adherence).[19] Results from Aim 2 found that key factors influence understanding of visualizations, including health literacy, HTN knowledge, and the use of health management mobile apps. These findings further emphasize the need to address the limitations of certain patients' abilities to accurately interpret and understand visually communicated information (e.g., ability to understand quantitative information, understand health information, or understand a graph legend) by presenting patient data in ways that either reduce the complexity of the task (e.g., providing reference guides that facilitate gist representations of quantitative information) or reduce the number of tasks occurring simultaneously (e.g., allowing patients to customize how many variables are included in a visualization).

While this study did not explicitly test whether improving observations about one's HTN through visualizations can improve self-regulation of their disease, future research should assess this component of interventions. By isolating the effect of improved observations on disease self-regulation, it can then be determined whether judgments and subsequent reactions are also improved, and whether these improvements as a whole improve HTN self-management.[19] Findings from this study also suggest that clinicians and researchers should not assume that simply introducing accurate visual information ensures it is understood or accurately perceived by patients. Many patients did not accurately interpret BP and adherence data contained in visualizations; thus, visualizations that are not well-understand could compromise patients' ability to self-observe their health conditions. This, in turn, could be associated with the decisions or judgments that one makes about their condition, which in turn adjusts future outcome expectations of future behaviors.

The Health Belief Model (HBM) posits that certain personal perceptions, particularly perceptions of the benefits of performing a behavior (e.g., taking medication), and cues to action can influence disease self-management behaviors.[15] As it related to HTN self-management, perceptions of the benefits of performing a behavior (e.g., taking medication) are shaped by one's understanding of HTN and the behaviors that can influence HTN outcomes. Visualizations of medication adherence and BP information can enhance understanding about the benefits of adherence by illustrating the correlation between adherence and BP control (i.e., high adherence leads to controlled BP). Data visualizations can also serve as cues to action by providing information about missed doses of medication. Future research should assess the extent to which the type visualizations tested in this study (e.g., communicating the correlation between medication adherence and BP control) influence the perceptions of the benefits of taking medication, and whether negative outcomes (e.g., elevated BP) effectively prompt the patient to take action (e.g., take medication or seek medical attention). For example, by incorporating such visualizations in a health monitoring intervention, perceptions of medication adherence benefits can be periodically assessed throughout an intervention. Different approaches to communicating negative outcomes (e.g., visualizations versus messaging prompts) can also be assessed by interventions where patients are randomized into text versus visualization-based communication.

9.2.6 Data Visualization Design

Data visualizations can take many forms while communicating the same information, and guidelines and best practices for designing visualizations serve to inform more effective communication of the underlying information.[20,120–122] Despite these guidelines and best practices, there remains subjective elements of aesthetic preference. Through user assessments of visualization preferences and cognitive interviews assessing understanding of condensed visualizations, this study sought to determine which visualization features were both preferred and understood by a diverse sample of individuals with HTN. These features, including the most preferred and understood approach to condensing medication adherence and BP information into a single visualization, were incorporated into the visualizations used in the survey experiment.

There are multiple possible explanations for the lack of support for the main hypothesis, that condensed visualizations would improve comprehension. First, it is possible that differences in Aim 1 and Aim 2 sample characteristics (i.e., age and education) resulted in an inaccurate assessment of preference for condensing BP and medication adherence information. It is also possible that the main hypothesis would not be supported regardless of the approach for condensing information. In

Aim 1, we assessed preferences for three approaches: 1) using color-coded BP lines to show medication adherence, 2) using a shaded region below the BP lines to show medication adherence, and 3) using symbols to show medication adherence. There may be additional approaches for which preferences were not assessed, and it is possible that despite achieving saturation, key questions were overlooked that may have changed the result (i.e., that using symbols was the most preferred approach). In the condensed visualizations used in Aim 2, the distance between the symbols for medication adherence and the BP lines may have impeded comprehension. Despite assessing preference for symbol location, this may also suggest that in some cases preference should not take priority over other considerations, such as best practices for visualization design. Other possible explanations for why the treatment visualizations did not improve comprehension are that demands on VSTM were not reduced, or that reducing demands on VSTM is inconsequential in the context of comprehending HTN-related visualizations. Improving comprehension in this context might require more than VSTM (i.e., a high order working memory), and addressing the burden visualizations place on working memory might be a more appropriate approach to improving visualization comprehension.

Fuzzy Trace Theory (FTT) could offer further insights into why the condensed visualization did not improve comprehension, and how to accurately and appropriately communicate the relationship between medication adherence and BP control using visualizations. FTT focuses on two representations of a meaningful stimulus (e.g., BP level): 1) a verbatim representation, or the actual numbers, words, or images used to communicate the risk, and 2) a gist representation, or the underlying meaning of information that is based in subjective experience. In terms of understanding risk and related decision making, FTT posits that verbatim representations of risk can become inaccessible as working memory is exhausted, and decisions using gist representations can still accurately reflect risk.[171] However, extracting the gist from visual information becomes more difficult as the display of inputs become less systematic and more scrambled.[169] This impediment to arriving at a gist understanding has been shown in both pictograph form, similar to how adherence was presented in this study, and in linear form (i.e., how BP was displayed in this study).[169,172] Results from the Aim 1 cognitive interviews would further support this as more granular levels of detail included in line graphs, specifically individually labeled BP data points, resulted in overall BP patterns being less understood than other approaches (e.g., horizontal reference lines or a shaded normal BP region). It is also possible that the lack of improvement in comprehension in Aim 2 was due to an impeded ability to extract gist because of scrambled inputs.

Future research should investigate how concepts of FTT can be applied to personal health data visualizations. For example, it should be assessed whether different visualization techniques facilitate or impede one’s ability to extract gist representations that align with verbatim information from HTN-related data visualizations. Future research should also assess how different scenarios of varying BP levels and medication adherence patterns impede one’s ability to make gist representations.

9.2.7 Mobile Apps and Wearable Health Tracking Devices

As was discussed in sections 9.2.3-5, the effectiveness of a self-regulation technique hinges on making accurate observations when self-monitoring one's condition, and health literacy and HTN knowledge influence one's ability to do so. While the use of technologies, such as mobile apps, has been shown to improve BP control,[38] and patient education has been shown to be an effective intervention technique for improving HTN self-management,[25] in-app tutorials (e.g., new user experience tutorials), may bridge the gap for individuals new to managing their HTN. In particular, patients with low health literacy and newly diagnosed patients who may have limited knowledge about their condition could benefit from a brief introductory explanation of visualizations and how to correctly interpret them. For example, new user experience (NUX) tutorials that overlay mobile apps and provide a walk-through explanation of an app and its features may improve comprehension and reduce initial perceived complexity by the patient.

9.2.8 Measurement and Other Possible Outcomes

To measure comprehension, we developed and examined the validity and reliability of a comprehension scale that measured patient understanding of visualizations for HTN self-management. While an acceptable solution for a unidimensional 4-item solution was found, exploratory and confirmatory factor analysis was not entirely consistent when applied to all four measures (LU, HU, LC, HC). Acceptable internal consistency ($\rho_{KR20} > .70$) was found for only 3 out of the four measures, with LU having poor internal consistency ($\rho_{KR20} = .61$). This may be an artifact of the extreme scenario where the comprehension scale was applied. For instance, the LU scenario, with low adherence and uncontrolled BP shows the most variation in both adherence and BP, and some questions in the scale may have been more difficult to answer. For instance, an overall trend (e.g., that missing medication results in uncontrolled BP) might be more difficult to ascertain given the amount of variation in both medication adherence and BP levels. The coherence of the LU and HC scenarios may have affected the results as well. Some questions may have been easier to answer given the LU and HC scenarios were logically consistent (i.e., that low adherence leads to uncontrolled BP and high adherence leads to controlled BP). This is supported by the average comprehension scores for the LU and HC scenarios (3.24 and 2.55, respectively), which were the highest among the four scenarios.

One possible explanation for the lack of improvement in comprehension of the condensed visualization is the conditions under which comprehension was assessed. It is possible that any effect a condensed visualization might have on comprehension was mitigated by allowing participants to have a long period of time to assess the visualizations (participants were given 2 hours to complete the survey before the Mturk task timed out). This survey experiment did not assess the amount of time each participant viewed each visualization. It is possible that amount of time spent studying the visualizations to answer each question (i.e., time-on-task) partially explains comprehension scores. In addition to time-on-task, other explanatory factors such as reaction and recall time are also measures of demands on VSTM.[94] In a real-life scenario, these factors likely contribute to app fatigue, where individuals tire in situations where personal health data is not easily comprehended or accessible and stop using an app rather than continue searching for an insight contained in a graph or chart. While amount of time spent viewing each visualization and answering questions could partially explain comprehension, this measure would also likely be confounded in a web survey as participants could be distracted during the survey. Assessing comprehension and interactions with visualizations in a lab environment would allow for more controlled observations of measures of VSTM. Future research should evaluate how different visualization techniques for health data affect other outcomes, such as time to complete task (e.g., finding information) and measures of burden (e.g., perceived difficulty).

9.3 Limitations

This research has several limitations. For the qualitative portion of the study (i.e., Aim 1 user assessments and cognitive interviews), a convenience sampling method was used to purposively sample individuals with HTN in order to ensure representation from males, females, racially and ethnically-diverse participants, participants with adequate and less than adequate health literacy, and individuals with a wide range of education. However, these participants may not be representative of either Aim 2 participants or the broader population of individuals with HTN that may rely on information visualizations to manage their HTN. For the purpose of this study and the stage in the visualization design process, the sampling method and interview process was sufficient for both the user assessments and cognitive interviews, and saturation was achieved for both the user assessments and cognitive interviews with 6 participants. A lack of representativeness of the sample in Aim 1 could have led to the selection of visualizations that were not necessarily optimal among the Aim 2 sample, which may account for the lack of support for the main Aim 2 hypothesis that condensed visualizations would improve comprehension.

It is clear that learning effects (e.g., patients became more adept at interpreting graphs over time) occurred during our cognitive interviews. Specifically, for questions about the meaning of symbols and tick marks on the vertical and horizontal axes, participants learned the meaning as they looked at more graphs. To avoid the influence of this in our results, we randomly ordered the sequence of graphs 1, 2, and 3 so that each graph appeared first, second, or third for two participants. However, it is still possible that learning effects occurred and could have influenced results.

For the survey experiment, a self-selected sample of Mturk users with self-reported HTN was recruited. Visualizations in the survey were optimized for viewing with mobile devices because of the context in which these visualizations would likely be used (i.e., mobile apps). However, this study allowed participants to using either a computer, laptop, tablet, or smartphone which may account for the differences in comprehension between those participants that use mobile apps for managing their health. It may be the case that users of mobile health tracking apps are more familiar with seeing health data visualizations on a mobile device and were less familiar with viewing visualizations of this nature on a larger computer screen, which could have affected the way in which the information contained in the visualization was understood.

The use of Mturk to recruit participants presents additional limitations. Previous research has shown that Mturk users are just as representative of the U.S., population as other Internet-based sample pools (e.g., discussion forums), and are more representative than college undergraduate sample pools on key demographics including race, age, gender, and education.[139] However, it is clear that participants in Aim 2 are not representative of the population of interest (i.e., smartphone owners with HTN). It is difficult to know the extent to which a self-selected Mturk sample of patients with HTN who met the eligibility criteria for the survey experiment is representative of the entire U.S. population meeting the same criteria, but it is clear the Mturk sample in this study was younger and more educated. The average age of participants in Aim 2 was 35.5 years while HTN prevalence estimates of individuals 18 to 39 years is just 7.3%.[29] Participants were also more highly educated than the general population, with 60.5% of participants having a bachelor's degree or higher compared to just 30.3% of the general population.[165] While true representativeness considering study eligibility criteria may make it difficult to ascertain, these differences are noteworthy and limit generalizability. Because the sample was more educated, it possible that participants were more familiar with information visualizations, and thus more able to comprehend the data contained in the visualization regardless of whether information was presented in condensed or separate form.

Using Mturk to recruit study participants also presents the risk of recruiting people that do not truly meet eligibility criteria yet manage to pass all checks and validations. Eligibility was self-reported, so we cannot verify whether all participants truly had a diagnosis of HTN and were prescribed at least one antihypertensive. To limit this possibility, the first batch of completed screening surveys (n=257) was assessed to determine how long it took respondents to complete the survey, and participants with responses more than one standard deviation (5 minutes and 1 second) below the average time to complete (8 minutes and 53 seconds) (responses less that 3 minutes and 53 seconds) were not invited to participate in the full study. In doing so, a total of 54 individuals out of 431 were excluded throughout the screening process, with an average time 2 minutes and 23 seconds, and average health literacy score of 3.65 (compared to an average score of 6.82 among all Aim 2 participants).

For all aspects of this study, visualizations were hypothetical, and it is possible that real blood pressure and medication adherence data may be interpreted differently than hypothetical data. Future studies should use real data collected in apps to assess whether HTN patient preferences differ when viewing their own data. In regard to future research, it should be noted that preferences may differ when viewing BP and adherence information over longer periods of time. For instance, graphs depicting shorter or longer periods of time may benefit from labeling BP values, the use of color-coded lines to show adherence, or how the X-axis is labeled (e.g., day of week). In addition, visualizations showing longer periods of time (e.g., several months) may provide a broader perspective and be more conducive to the comprehension of overall trends in the relationship of medication adherence with BP. It should also be noted that for Aim 1, all visualizations were presented to participants on paper. Because the intended use of these visualizations is a mobile device, it is possible that the medium on which visualizations are seen affects interpretation, particularly as it relates to size and white space.

For the survey experiment, sample size may have also influenced results. This study was powered to detect a medium effect (.5) for the effect of visualization type (condensed vs. separate) on comprehension and a medium to large effect (.75) for the health literacy interaction. It is possible that the effect of condensed visualizations on comprehension are small and that this study was underpowered to detect a relationship of this size.

9.4 Directions for Future Research

An underlying assumption in hypothesizing that condensed visualizations would increase comprehension is that the condensed visualizations would reduce demands on VSTM. However, in this study, this reduction was not tested. In order to understand the true effects of VSTM on comprehension of visualization, future studies should occur in a lab setting, where measures of VSTM demands can be assessed, such as time to task.[94] It is possible that variations in key visualization features were overlooked in this study could reduce demands on VSTM, and thus significantly improve comprehension. In addition to overlooked features, future research should also assess alternative approaches to reducing the complexity of visualizations aside from variations in features. For example, different approaches for reducing clutter and increasing familiarity of certain features (e.g., terminology and icons) may facilitate comprehension among individuals with lower health literacy. Tooltips or pop-up labels that describe an app feature may further facilitate a user’s understanding of certain features. Adding customizable features, such as toggling to turn on and off adherence indicators or BP indicators, may also allow users to reduce clutter and understand information in its isolated or combined form.

Future interventions using visualizations for patient data should not assume that simply introducing accurate visual information ensures it is understood or accurately perceived. When visualizations for HTN self-management are developed that are shown to improve comprehension and other related outcomes, future research should assess their effectiveness in a broader context, such as health behavior theory-driven interventions using real patient data derived from devices patients use in their everyday lives. Health behavior theory-driven interventions should assess the extent to which the type of visualizations tested in this study (e.g., displaying the correlation between medication adherence and BP control) influence perception of the benefits of taking medication, and whether negative outcomes (e.g., elevated BP) effectively prompt the patient to take action (e.g., take medication or seek medical attention).

Clinicians and other health professionals should use caution when recommending that patients use apps or wearable devices to track their health. For some patients, particularly those with low health literacy, misunderstanding or an inability to comprehend the information and feedback provided by an app could lead to inaccurate interpretations about one’s health and negatively affect medication adherence or other health behaviors. When providing recommendations to track one’s health using a mobile app or wearable device, it is not only important for clinicians to answer questions patients may have, but to also ensure a fundamental understanding of key metrics and what to look for (e.g., noteworthy BP levels) in the app.

Finally, future development of mobile apps and wearables for HTN self-management, or any technologies that allow patients to interface with their own data in order to self-manage their HTN should adhere to patient-centered approaches for visually communicating patient data. As this study shows, visualizations used in current mobile apps do not always align with what the end-user wants, and their utility by some users (e.g., those with low health literacy) may be limited. As usability guidelines suggest, users should be involved throughout the entire mobile app develop process.[137] By incorporating user feedback early in the development process, potential barriers to the usefulness of an app can be corrected or avoided altogether. Furthermore, including a diverse team of expert consultants in the mobile app development process, such as clinicians, informaticists, and behavioral scientists, may help ensure the effectiveness of key functions of an app.

9.5 Conclusion

This study is an important step in developing useful and useable data visualizations for self-managing HTN. Using a mixed-methods approach, it was determined that condensed visualizations using a normal BP zone for reference along with color-coded symbols to indicate medication adherence and non-adherence best facilitated understanding of the meaning of the information contained in the visualization. The survey experiment showed that condensed visualizations based on user preferences did not improve comprehension of the visualized correlation between medication adherence and BP control. However, health literacy and HTN knowledge were shown to be positively associated with overall visualization comprehension.

This research demonstrates the importance of using a patient-centered approach for visualizing patient data, as there can be limitations to the utility of such visualizations for some patient populations (e.g., those with low health literacy). Furthermore, it is important to investigate alternative techniques for condensing the display of HTN-related information into a single visualization, or otherwise reducing the complexity of visualizations to make them more accessible to all patients. Finally, the effectiveness of HTN-related visualizations optimized for understanding in a real-world context is unknown and should be considered in future studies.

APPENDIX A: USER ASSESSEMNT PROTOCOL

Consent Form

University of North Carolina at Chapel Hill
Consent to Participate in a Research Study
Adult Participants

Consent Form Version Date: 5/1/2017
IRB Study # 17-0466
Title of Study: Optimizing patient comprehension of information visualizations for medication adherence and blood pressure
Principal Investigator: Adam Sage
Principal Investigator Department: UNC Eshelman School of Pharmacy-Division of Pharmaceutical Outcomes and Policy
Principal Investigator Phone number: 330-388-3025
Principal Investigator Email Address: asage@email.unc.edu
Faculty Advisor: Delesha Carpenter
Faculty Advisor Contact Information: (828) 250-3916

Funding Source and/or Sponsor: Pharmaceutical Research and Manufacturers of America Foundation (PhRMA)

What are some general things you should know about research studies?
You are being asked to take part in a research study. To join the study is voluntary. You may choose not to participate, or you may withdraw your consent to be in the study, for any reason, without penalty.

Research studies are designed to obtain new knowledge. This new information may help people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study.

You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

What is the purpose of this study?
The purpose of this research study is understand preferences related to information visualizations (e.g., charts and graphs) for medication adherence and blood pressure, and to understand how patients with hypertension understand these visualizations.

You are being asked to be in the study because you take medication to control your hypertension.

Are there any reasons you should not be in this study?
You should not be in this study if you have vision or cognitive impairments.

How many people will take part in this study?
There will be approximately 10 people in this research study.

How long will your part in this study last?
Your participation will last 1 hour.

What will happen if you take part in the study?
We will ask you to either come to the Eshelman School of Pharmacy for a one-time visit, or meet with a researcher in a private location. During this visit, you will:
Be interviewed by the researcher.
As part of this interview, you will be presented with several difference information visualizations that show information about medication adherence and blood pressure.
As part of this interview, you will be asked several questions about your preferences and understanding of the information displayed in these visualizations.
Your responses and interaction during the interview will be audio-recorded, but your name or any other identifying information will not be associated with your responses.
You be given a $25 cash incentive for your participation.

What are the possible benefits from being in this study?
Research is designed to benefit society by gaining new knowledge. You will not benefit personally from being in this research study.

What are the possible risks or discomforts involved from being in this study?
You may feel uncomfortable sharing responses to answers with the interviewer. We have trained professionals conducting these interviews to minimize the chance of this happening. You should report any problems to the researcher.

What if we learn about new findings or information during the study?
You will be given any new information gained during the course of the study that might affect your willingness to continue your participation.

How will information about you be protected?
You will be assigned an identification number when you agree to participate in the study. All data collected in this study, including your personal information and responses during the interview will be recorded under your identification number, not your name.

Participants will not be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies (for example, the FDA) for purposes such as quality control or safety. Audio recordings of this interview will be stored on a secure UNC server. After the audio recordings are analyzed, the file will be destroyed/permanently deleted. Check the line that best matches your choice:

_____ OK to record me during the study

_____ Not OK to record me during the study

You will not be asked to reveal your name during the interview.

What if you want to stop before your part in the study is complete?
You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

Will you receive anything for being in this study?
You will be receiving $25 cash for taking part in this study. If you decide to withdraw, you will receive the entire $25.

Will it cost you anything to be in this study?
It will not cost you anything to be in this study.

What if you are a UNC student?
You may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration if you take part in this research.

What if you are a UNC employee?
Taking part in this research is not a part of your University duties, and refusing will not affect your job. You will not be offered or receive any special job-related consideration if you take part in this research.

Who is sponsoring this study?
This research is funded by the Pharmaceutical Research and Manufacturers of America Foundation (PhRMA). This means that the research team is being paid by the sponsor for doing the study. The researchers do not, however, have a direct financial interest with the sponsor or in the final results of the study.

What if you have questions about this study?
You have the right to ask, and have answered, any questions you may have about this research. If you have questions about the study (including payments), complaints, concerns, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

What if you have questions about your rights as a research participant?
All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject, or if you would like to obtain information or offer input, you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

Participant's Agreement:

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

____ ____________________
Signature of Research Participant Date

____
Printed Name of Research Participant

____ ____________________
Signature of Research Team Member Obtaining Consent Date

____
Printed Name of Research Team Member Obtaining Consent

Introduction:

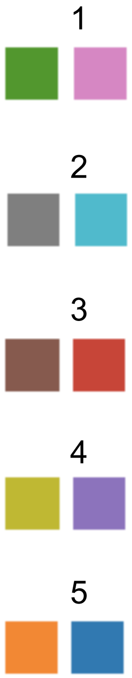
The purpose of this interview is to understand your preferences and understanding of difference charts and graphs that are intended to show a patient information about whether they took their medication, as well as information about their blood pressure. There are several ways this information can be shown in a chart or graph, so it’s important for us to understand which ways are the best for someone that might rely of these types of visualizations for managing their hypertension.

I will give you two pieces of paper with several visualizations or certain parts of visualizations. As you will see, items will have a number, which I will refer to throughout the interview. In some cases, I will ask you to write directly on the paper. These will be collected by me at the end of the interview. I will also display the visualization on an overhead projector.

Please keep in mind that our discussion will be audio recorded, which will allow me to go back and review your responses, so please try to communicate your thoughts clearly.

To begin, take a look at this first piece of paper.

Colors-pallet for coding medication adherence:



For each pair, which color best represents something positive (like taking your medication as instructed) and which color represents something negative (like missing a dose of your medication)?

Looking at this color pallet, which pair would you prefer to show when you do or don’t take your medication? Use the numbers above each color to refer to your preference.

Why did you choose this color pair?

Are there any other colors you would use for something positive and negative?

Looking at this chart, which color pair would you use for the blood pressure lines to differentiate between the two?

Symbols for coding medication adherence:

1

○ +

2

▷ □

3

✱ ×

4

◇ ▽

5

◁ △

6

✓ 🛇

7

✔⃝ ✖⃝

For each pair, which symbol best represents something positive (like taking your medication as instructed) and which symbol represents something negative (like missing a dose of your medication)?

Looking at these symbol pairs, which pair would you prefer to show when you do or don’t take your medication? Use the numbers above each color to refer to your preference.

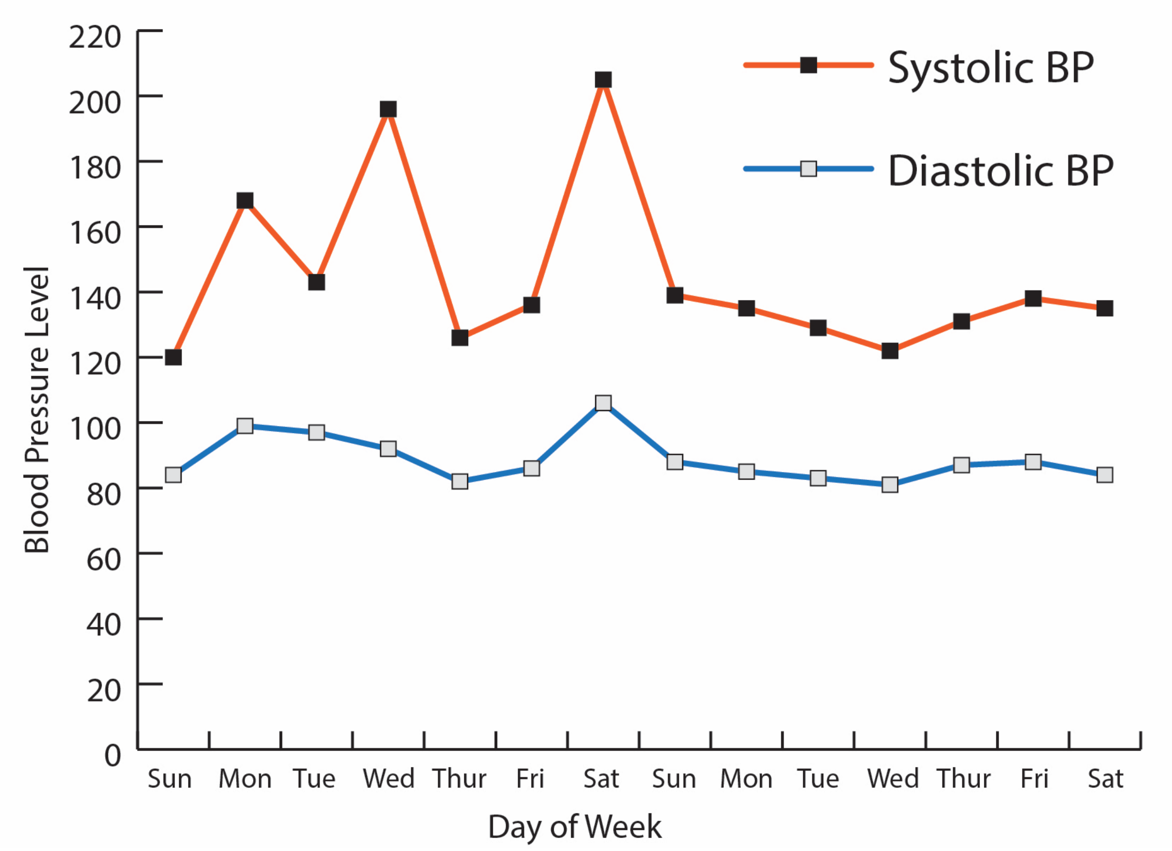
Why did you choose this symbol pair?

Are there any other symbols you would use for something positive and negative?

Labels:

Take a look at GRAPH 1 and the location of the labels that say Day of Week and Blood Pressure Level. Is there anything confusing here, or something you would do differently?

GRAPH 1



Labels:

For the graphs with the symbols (10, 11, and 12), what do you think of the location of the symbols? Is there anything confusing here, or something you would do differently?

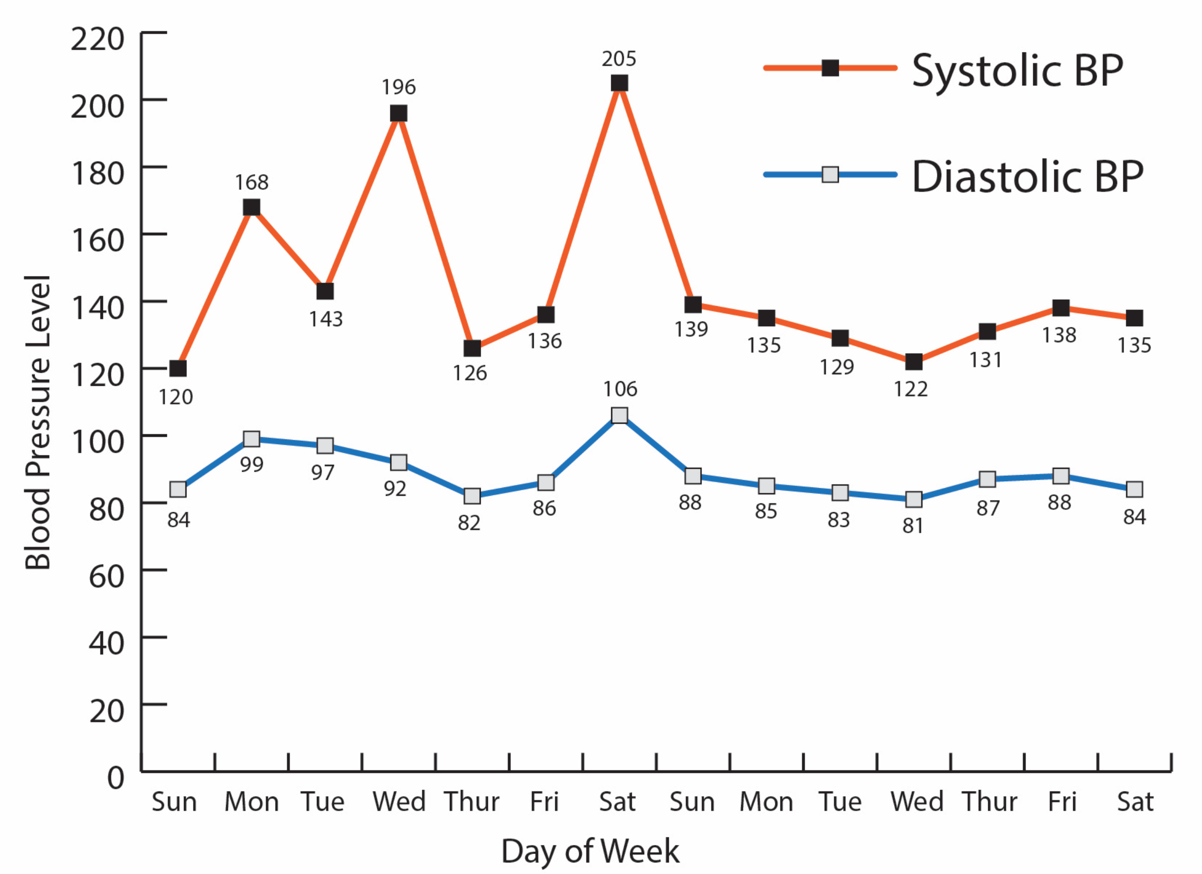
Take a look at the legend that shows the colors indicating whether medication was taken or missed. Is the location good here, or would you place it somewhere else?

Do you think it’s necessary?

Is there some other way you would prefer this color-coding be shown?

Would you prefer each value to be labeled like in GRAPH 2?

GRAPH 2

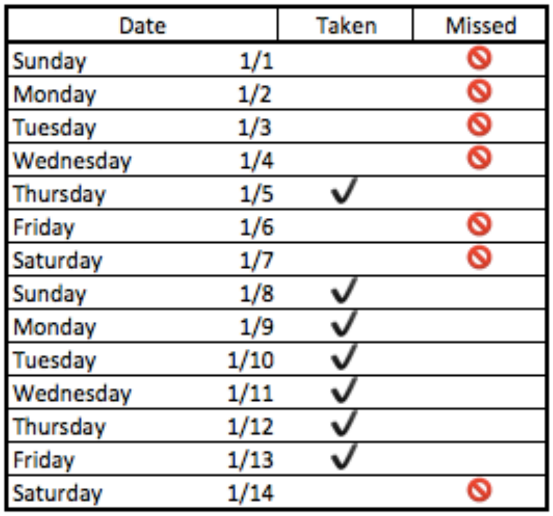


<u>Label Terminology</u>:

How about the words used on the graph? Are there any other words or date format you would use instead for:

Blood Pressure Level
Systolic BP
Diastolic BP
Day of Week
Taken Medication
Missed Dose
Medication
Controlled BP Zone
Normal BP Zone

Chart type for medication adherence:



Date		Taken	Missed
Sunday	1/1		⊘
Monday	1/2		⊘
Tuesday	1/3		⊘
Wednesday	1/4		⊘
Thursday	1/5	✓	
Friday	1/6		⊘
Saturday	1/7		⊘
Sunday	1/8	✓	
Monday	1/9	✓	
Tuesday	1/10	✓	
Wednesday	1/11	✓	
Thursday	1/12	✓	
Friday	1/13	✓	
Saturday	1/14		⊘

January

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1 ⊘	2 ⊘	3 ⊘	4 ⊘	5 ✓	6 ⊘	7 ⊘
8 ✓	9 ✓	10 ✓	11 ✓	12 ✓	13 ✓	14 ⊘
15	16	17	18	19	20	21
22	23	24	25	27	28	29
30	31					

Looking at these two chart types, between the calendar and list, which would you prefer to track your medication?

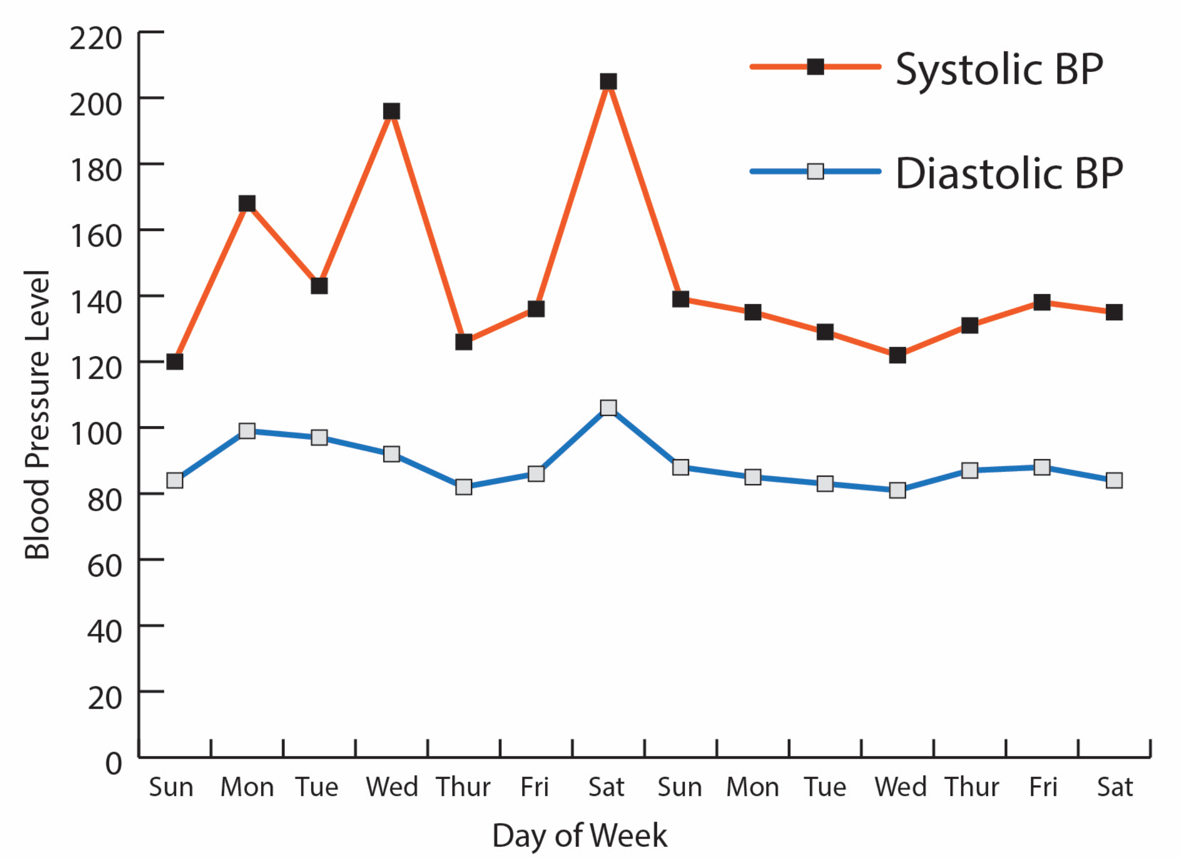
Why did you choose this?

Is there anything confusing about any of these options?

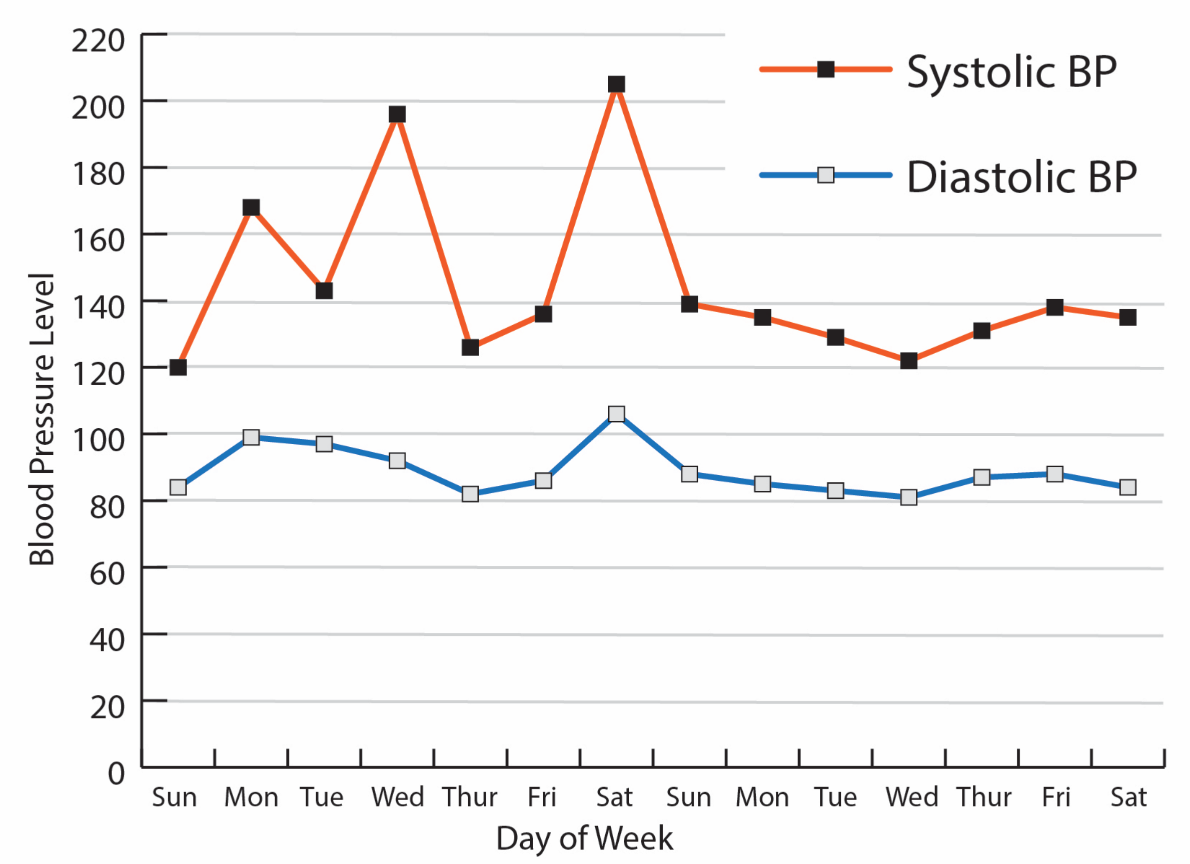
Is there anything about either one of these that you would change to improve the chart?

Reference markers:

GRAPH 3

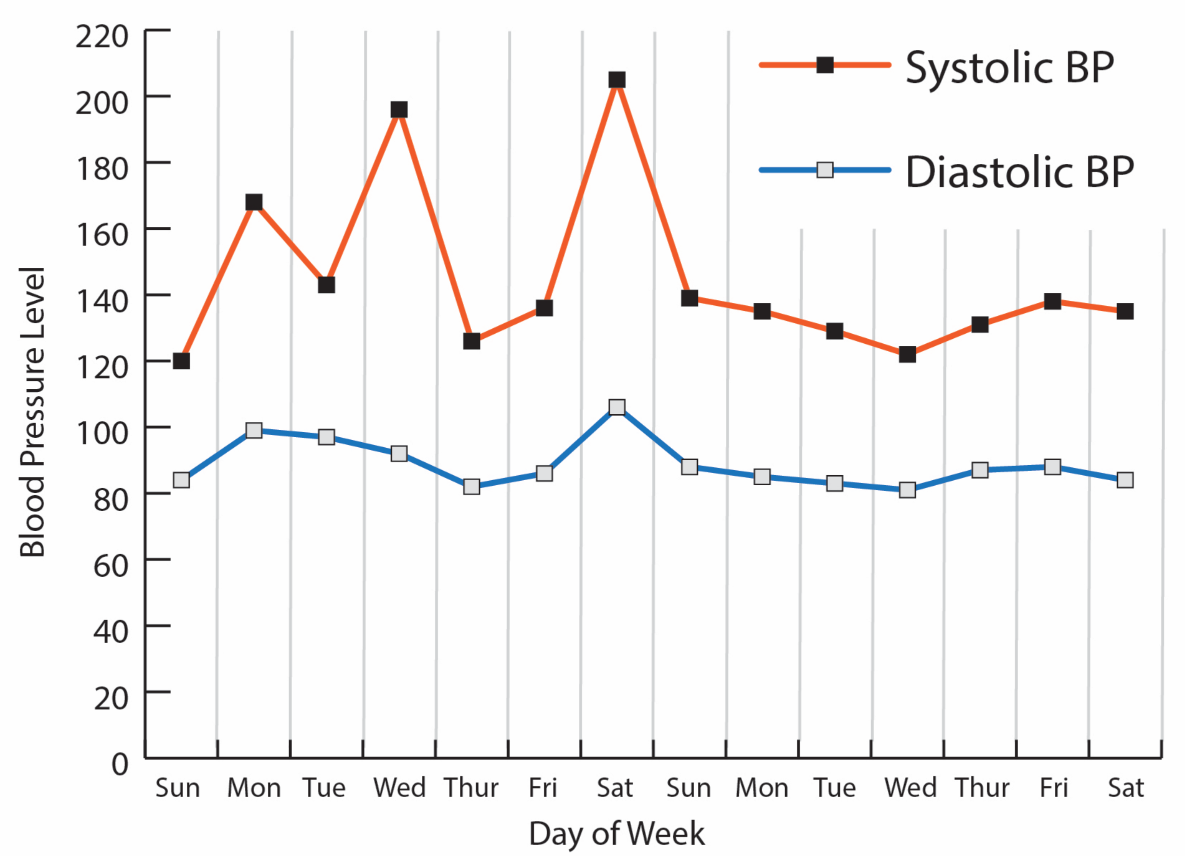


GRAPH 4



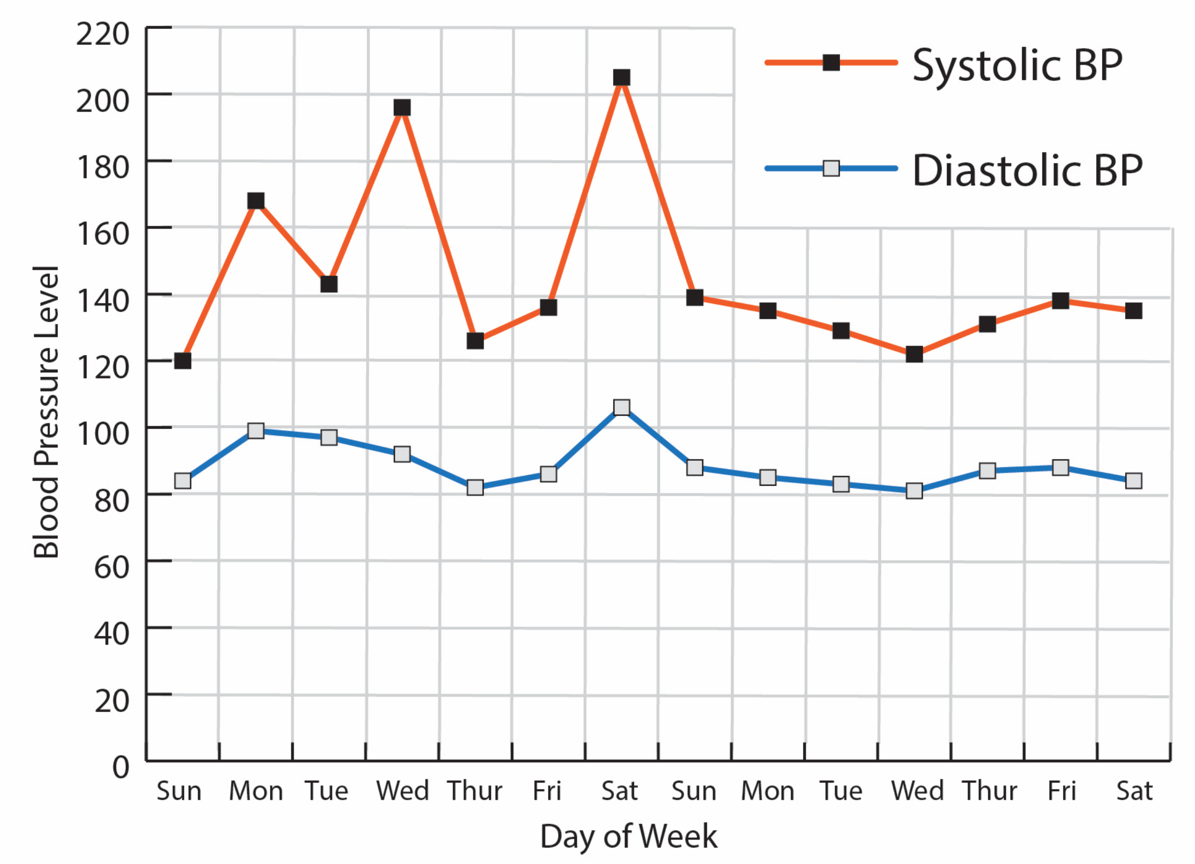
Systolic BP
Diastolic BP
Blood Pressure Level
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

GRAPH 5

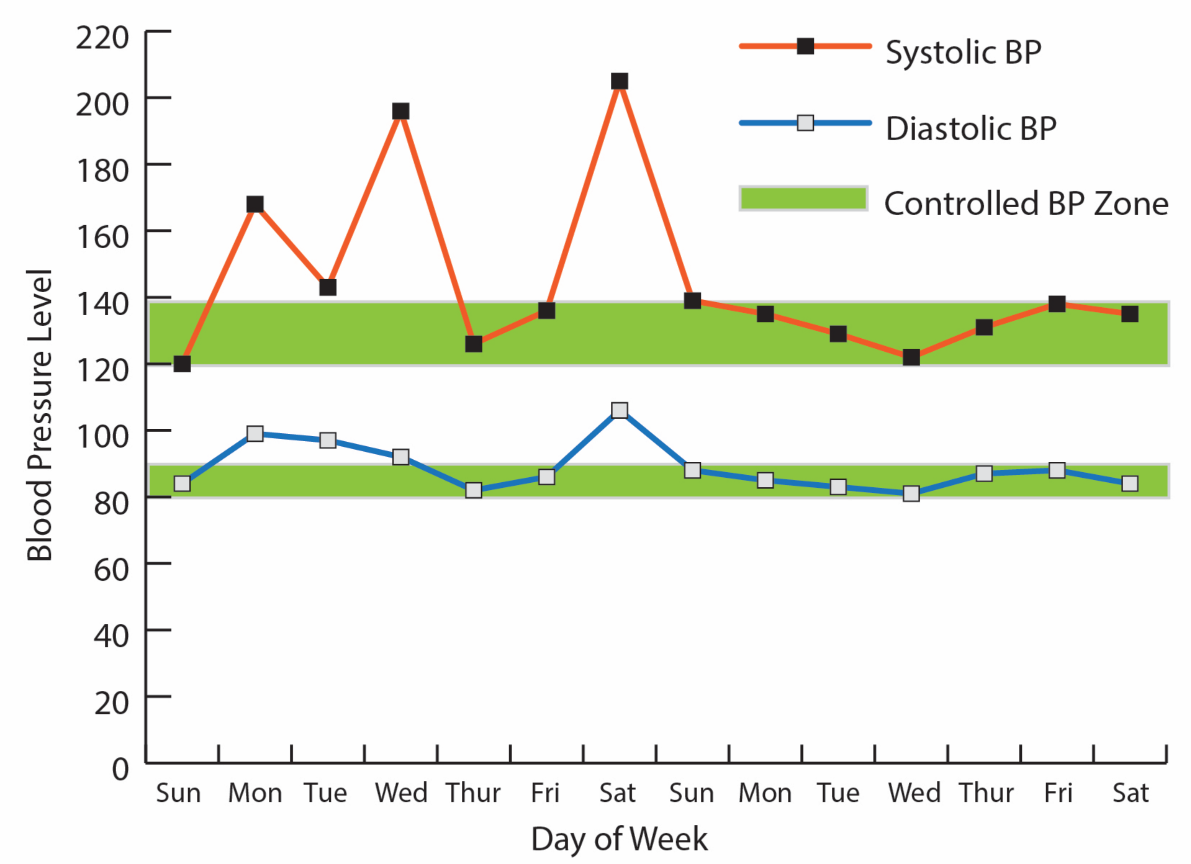


Systolic BP
Diastolic BP
Blood Pressure Level
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

GRAPH 6


Systolic BP
Diastolic BP
Blood Pressure Level
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

GRAPH 7



Looking at the GRAPH 3 for blood pressure, how often would you place a tick mark on the Y-axis for blood pressure level? For instance, would you prefer increments of 10, 20 etc?

How often would you put a tick mark for day of the week? One for every day, every week?

Why did you choose this?

Is there anything confusing about how the blood pressure values or days of week are separated?

Do you like the gridlines for GRAPHS 3, 4, 5, and 6? Do you prefer horizontal only, vertical, or horizontal and vertical?

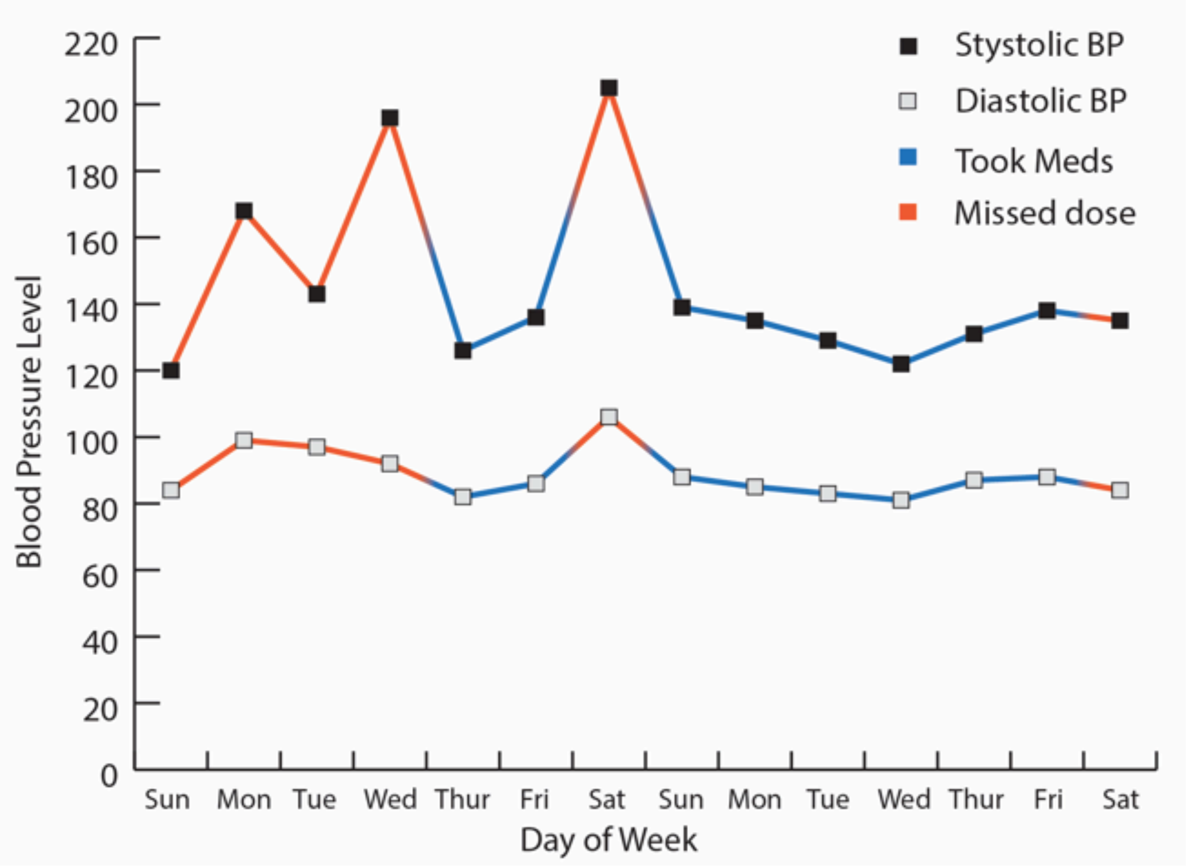
How about a zone, such as the green zone for controlled BP in GRAPH 7? Would you find any of these useful?

Condensed Visualizations:

Here are three types of graphs that shows daily blood pressure changes over a month period, and whether medication was taken for each day.

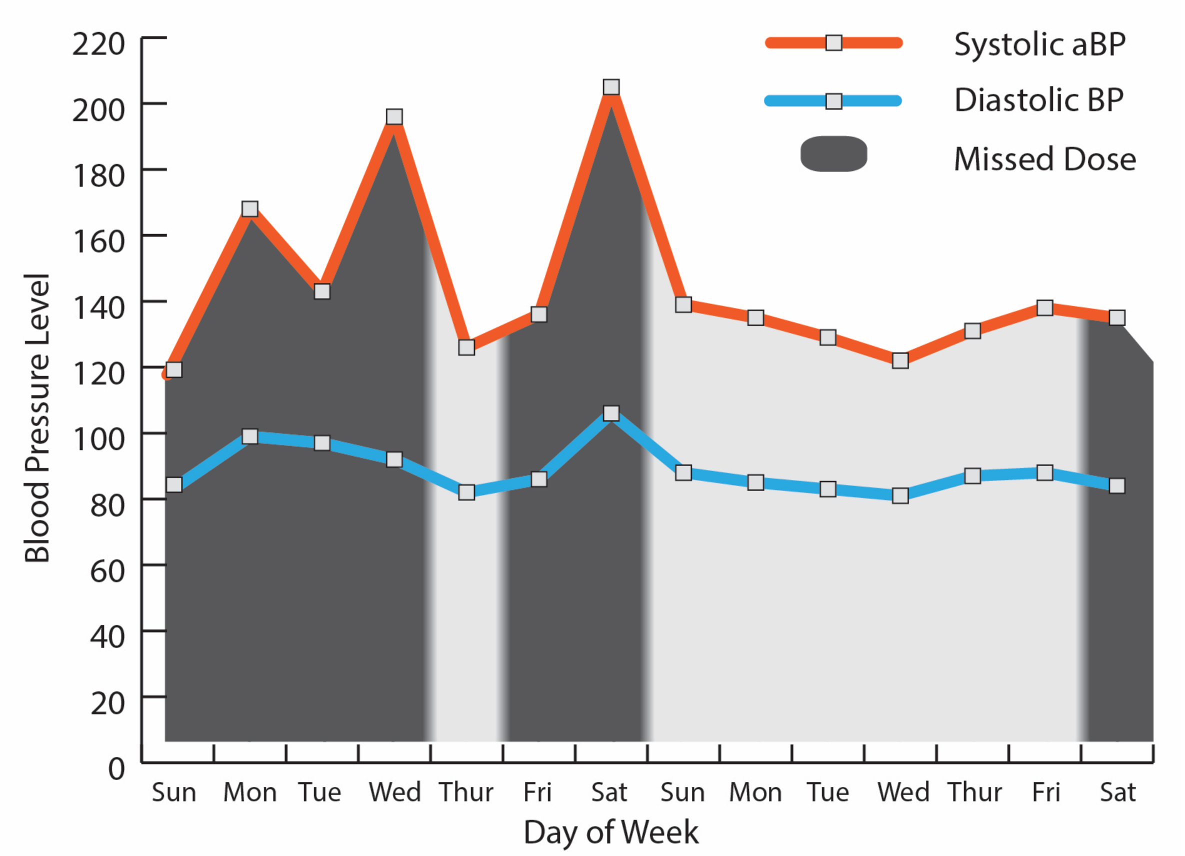
GRAPH 8 shows a color-coded line:

GRAPH 8



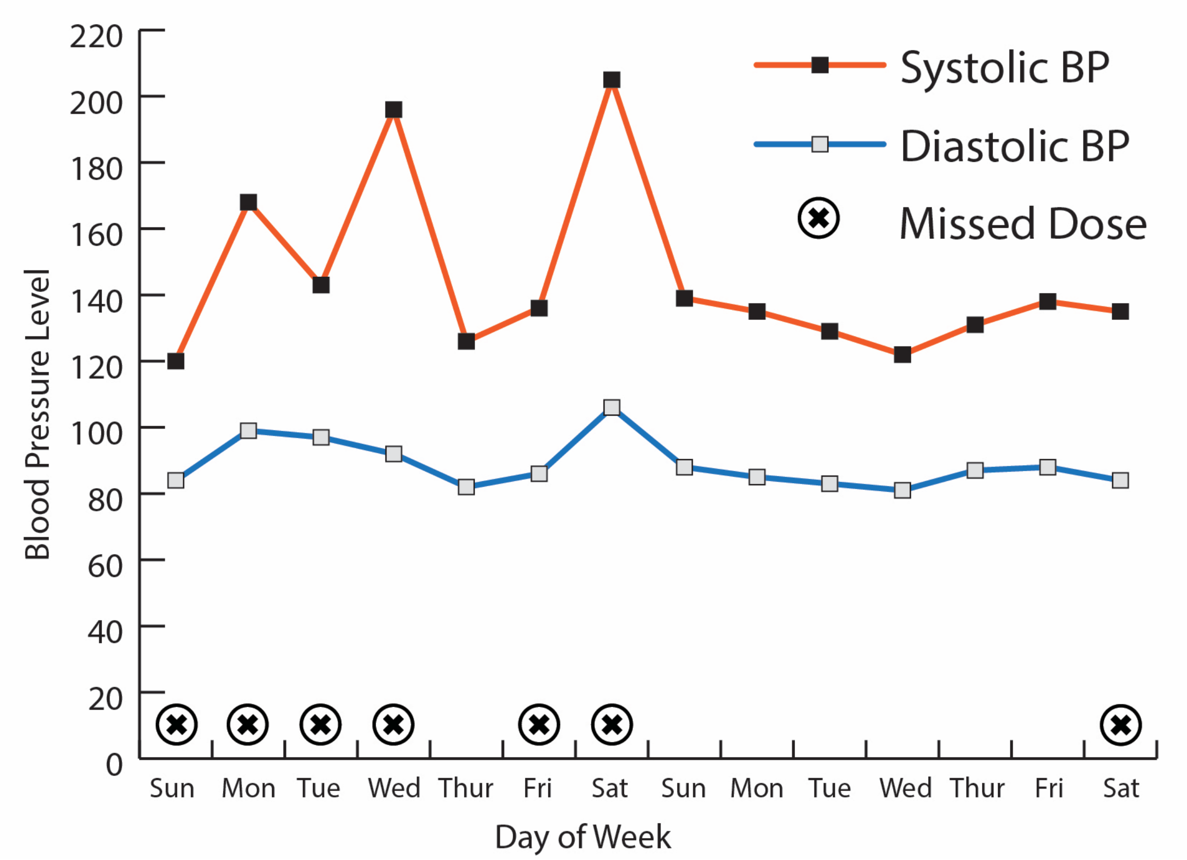
GRAPH 9 is similar, but shaded the area under the line:

GRAPH 9

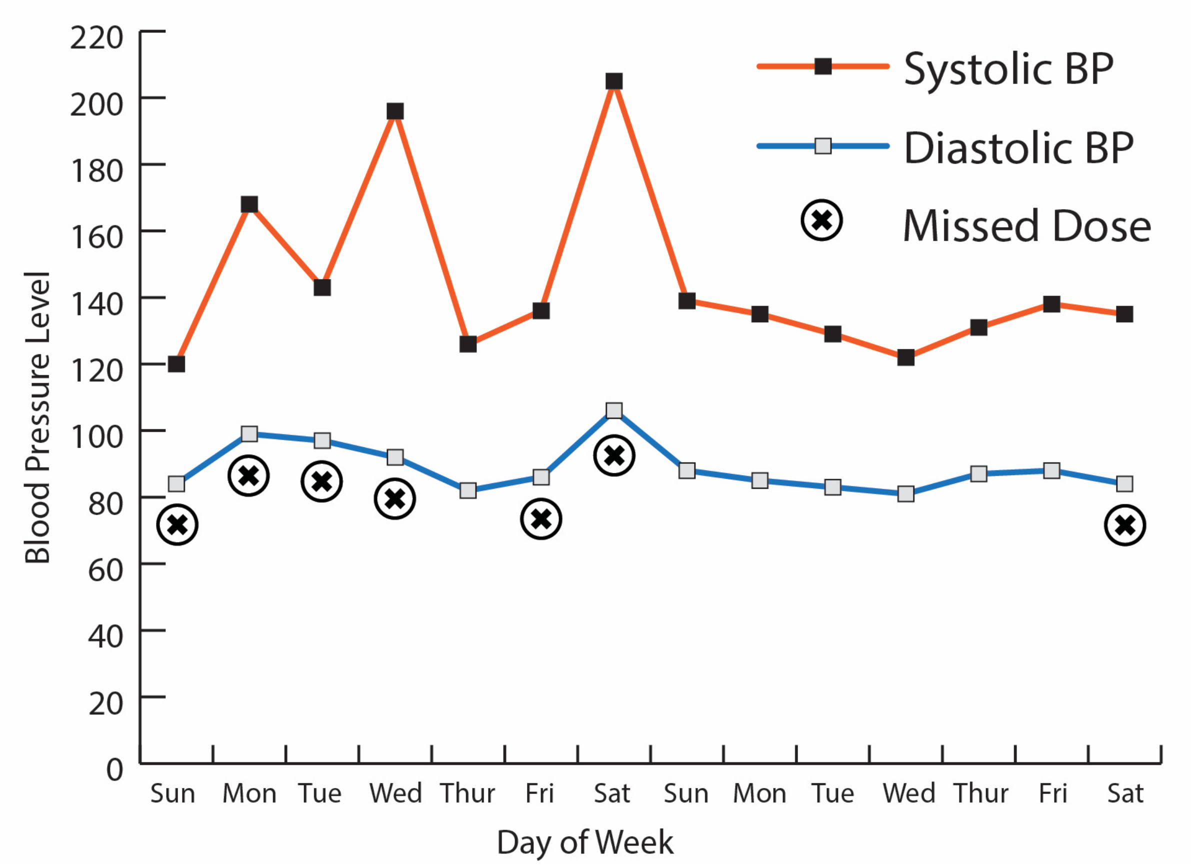


GRAPHS 10, 11, and 12 use symbols at each day instead of colors:

GRAPH 10

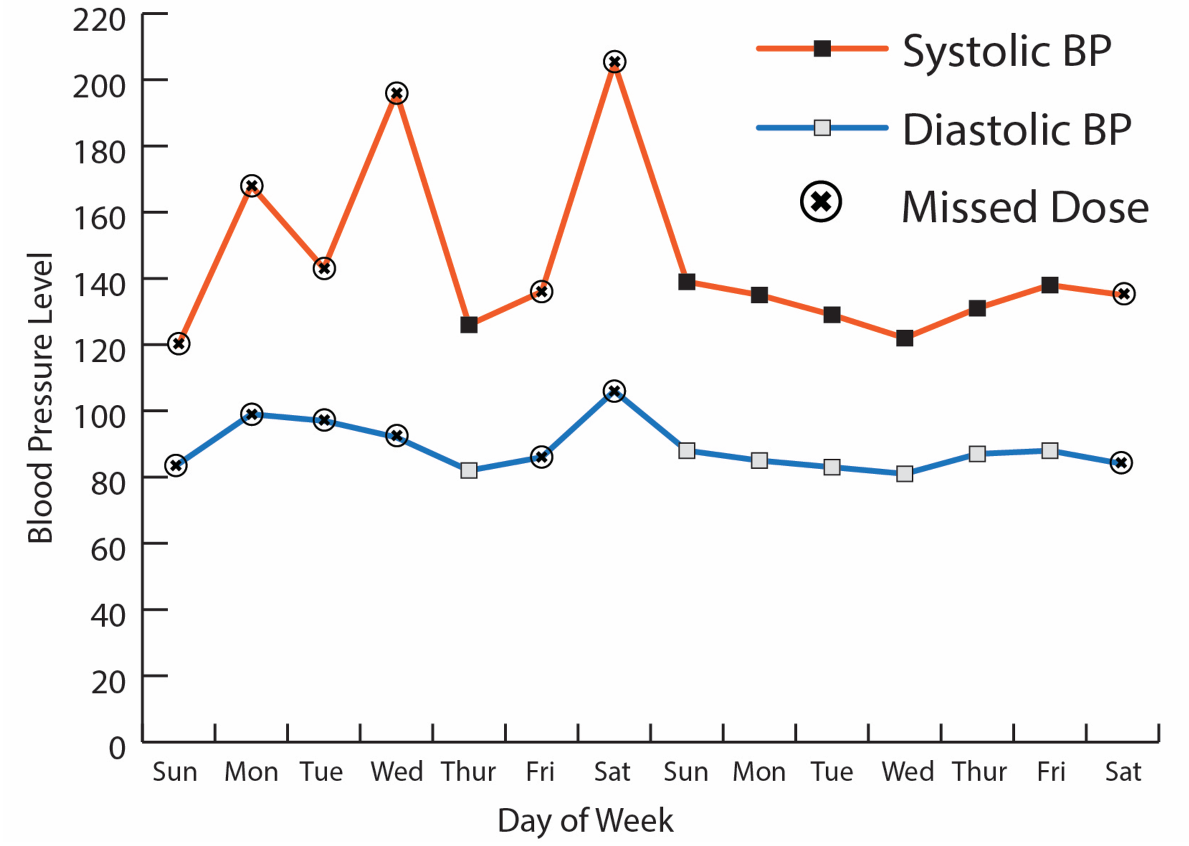


GRAPH 11



Blood Pressure Level
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week
Systolic BP
Diastolic BP
Missed Dose

GRAPH 12



Keep in mind these colors and symbols can change (that's why I asked you about colors and symbols earlier).

Which of these charts would you prefer if you had to view both pieces of information in one graph? Which would be your 2nd and 3rd choice?

Recap:

Is there something confusing or that you didn't like about the graphs you did not choose as your first choice?

What, if anything would you change about these graphs?

Did you have a favorite graph or chart? Why was this your favorite?

If you could combine any of these graphs, what colors, symbols, and features would you choose?

Thank you for your time!

APPENDIX B: COGNITIVE INTERVIEW PROTOCOL

Consent Form

University of North Carolina at Chapel Hill
Consent to Participate in a Research Study
Adult Participants

Consent Form Version Date: 10/25/2017
IRB Study # 17-0466
Title of Study: Optimizing patient comprehension of information visualizations for medication adherence and blood pressure
Principal Investigator: Adam Sage
Principal Investigator Department: UNC Eshelman School of Pharmacy-Division of Pharmaceutical Outcomes and Policy
Principal Investigator Phone number: 330-388-3025
Principal Investigator Email Address: asage@email.unc.edu
Faculty Advisor: Delesha Carpenter
Faculty Advisor Contact Information: (828) 250-3916

Funding Source and/or Sponsor: Pharmaceutical Research and Manufacturers of America Foundation (PhRMA)

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Research studies are designed to obtain new knowledge. This new information may help people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

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You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

What is the purpose of this study?

The purpose of this research study is understand how well people understand information visualizations (e.g., charts and graphs) for medication adherence and blood pressure, and to understand how well people understand questions that assess comprehension of such data visualizations.

You are being asked to be in the study because you take medication to control your hypertension.

Are there any reasons you should not be in this study?
You should not be in this study if you have vision or cognitive impairments.

How many people will take part in this study?
There will be approximately 6 people in this research study.

How long will your part in this study last?
Your participation will last 1 hour.

What will happen if you take part in the study?
We will ask you to either come to the Eshelman School of Pharmacy for a one-time visit, or meet with a researcher in a private location. During this visit, you will:
Be interviewed by the researcher.
As part of this interview, you will be presented with three difference information visualizations that show information about medication adherence and blood pressure.
As part of this interview, you will be asked several questions about your understanding of the visualizations, as well as different questions assessing the comprehension of the visualizations.
Your responses and interaction during the interview will be audio-recorded, but your name or any other identifying information will not be associated with your responses.
You be given a $25 cash incentive for your participation.

What are the possible benefits from being in this study?
Research is designed to benefit society by gaining new knowledge. You will not benefit personally from being in this research study.

What are the possible risks or discomforts involved from being in this study?
You may feel uncomfortable sharing responses to answers with the interviewer. We have trained professionals conducting these interviews to minimize the chance of this happening. You should report any problems to the researcher.

What if we learn about new findings or information during the study?
You will be given any new information gained during the course of the study that might affect your willingness to continue your participation.

How will information about you be protected?
You will be assigned an identification number when you agree to participate in the study. All data collected in this study, including your personal information and responses during the interview will be recorded under your identification number, not your name.
Participants will not be identified in any report or publication about this study.
Although every effort will be made to keep research records private, there may be

times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies (for example, the FDA) for purposes such as quality control or safety. Audio recordings of this interview will be stored on a secure UNC server. After the audio recordings are analyzed, the file will be destroyed/permanently deleted. Check the line that best matches your choice:

_____ OK to record me during the study

_____ Not OK to record me during the study

You will not be asked to reveal your name during the interview.

What if you want to stop before your part in the study is complete?
You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

Will you receive anything for being in this study?
You will be receiving $25 cash for taking part in this study. If you decide to withdraw, you will receive the entire $25.

Will it cost you anything to be in this study?
It will not cost you anything to be in this study.

What if you are a UNC student?
You may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration if you take part in this research.

What if you are a UNC employee?
Taking part in this research is not a part of your University duties, and refusing will not affect your job. You will not be offered or receive any special job-related consideration if you take part in this research.

Who is sponsoring this study?

This research is funded by the Pharmaceutical Research and Manufacturers of America Foundation (PhRMA). This means that the research team is being paid by the sponsor for doing the study. The researchers do not, however, have a direct financial interest with the sponsor or in the final results of the study.

What if you have questions about this study?

You have the right to ask, and have answered, any questions you may have about this research. If you have questions about the study (including payments), complaints, concerns, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

What if you have questions about your rights as a research participant?

All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject, or if you would like to obtain information or offer input, you may contact the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

Participant’s Agreement:

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

____ __________
Signature of Research Participant Date

____
Printed Name of Research Participant

____ __________
Signature of Research Team Member Obtaining Consent Date

____
Printed Name of Research Team Member Obtaining Consent

Introduction:

The purpose of this interview is to see how easy it is to understand charts and graphs that are intended to show a patient information about whether they took their medication, as well as information about their blood pressure. In addition, I will have you read questions that ask about the charts and graphs to learn how we might improve the questions.

First, I will show you a few different charts and graphs, and ask you questions about those charts and graphs. Then I will show you a list of six questions, ask you to read them, then ask you questions about your understanding of these questions.

Please keep in mind that our discussion will be audio recorded, which will allow me to go back and review your responses. I may ask for clarification at times just so I can capture your thoughts on audio.

There are no right or wrong answers.

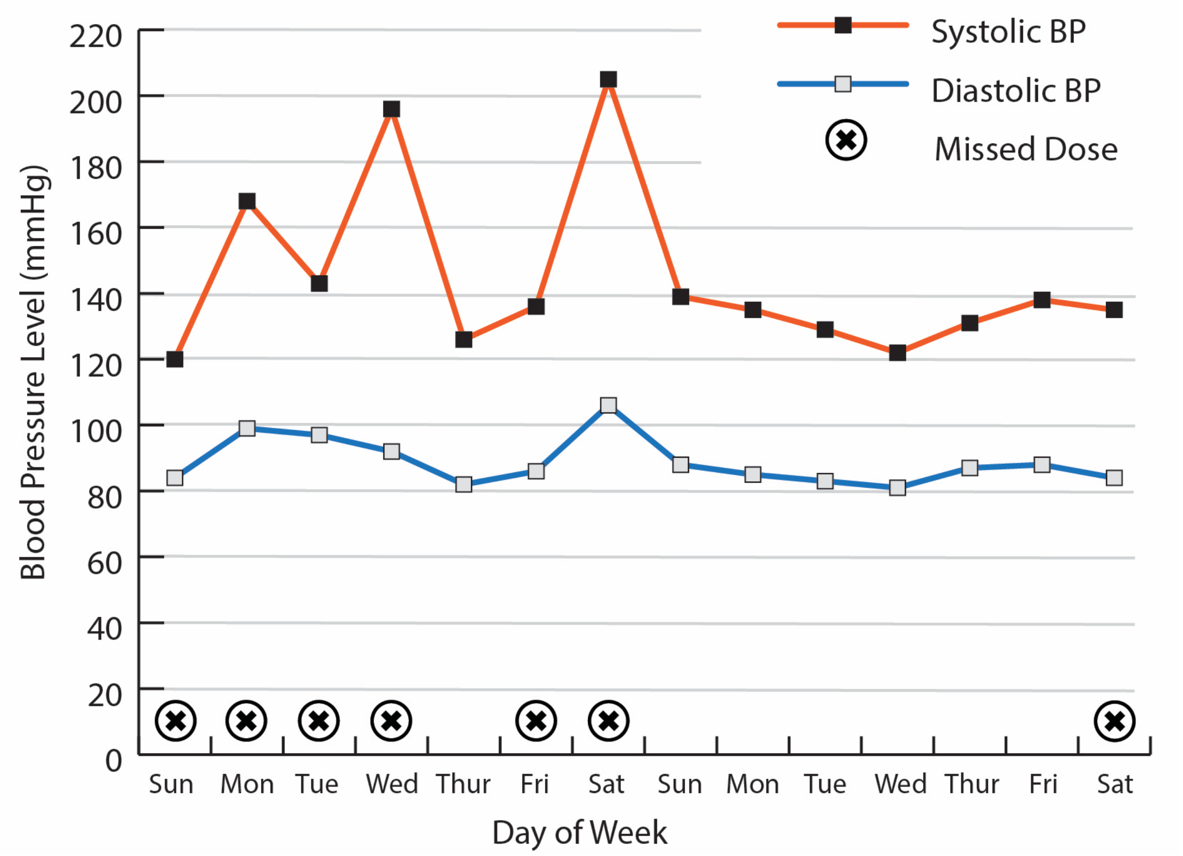
Do you have any questions before we start recording?

To begin, take a look at these graphs.

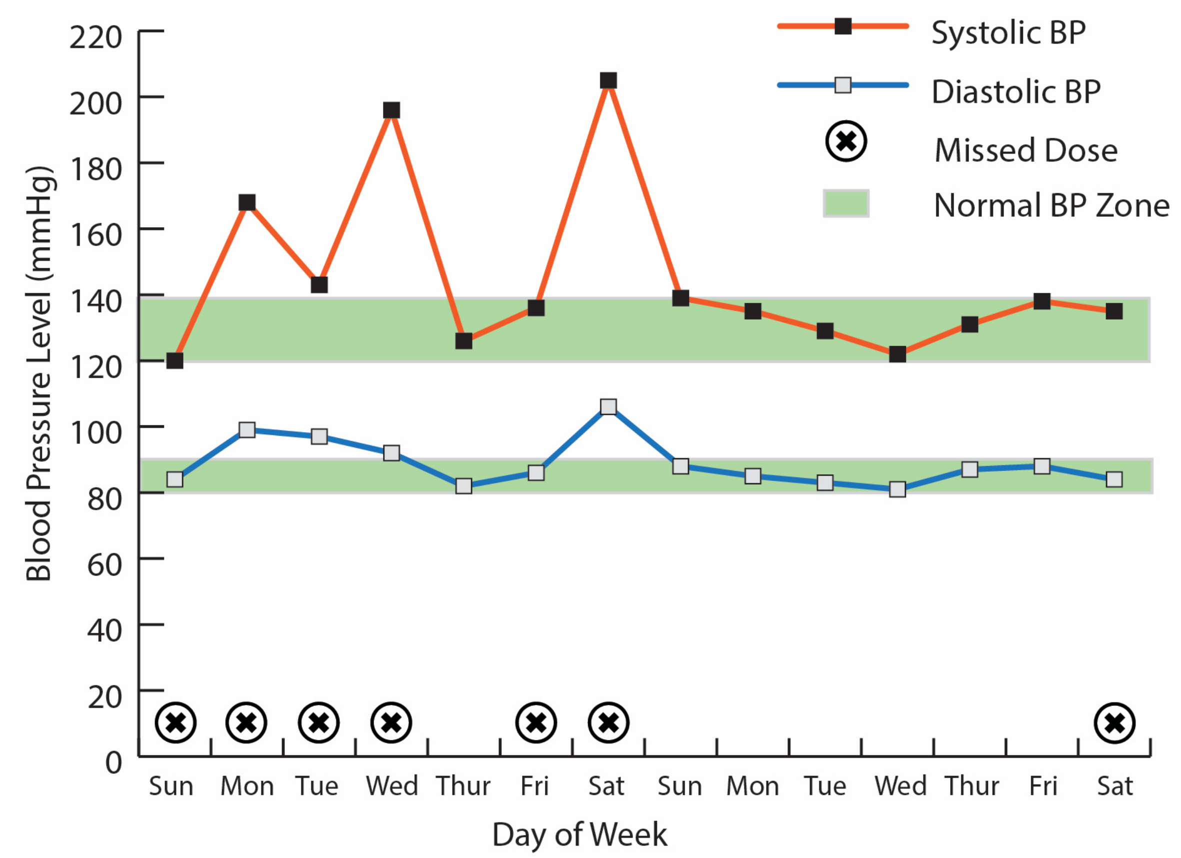
[FOR EACH GRAPH, ASK QUESITONS AND PROBE WHERE NECESSARY]

[RANDOMIZE ORDER OF WHICH GRAPHS ARE PRESENTED}

GRAPH 1

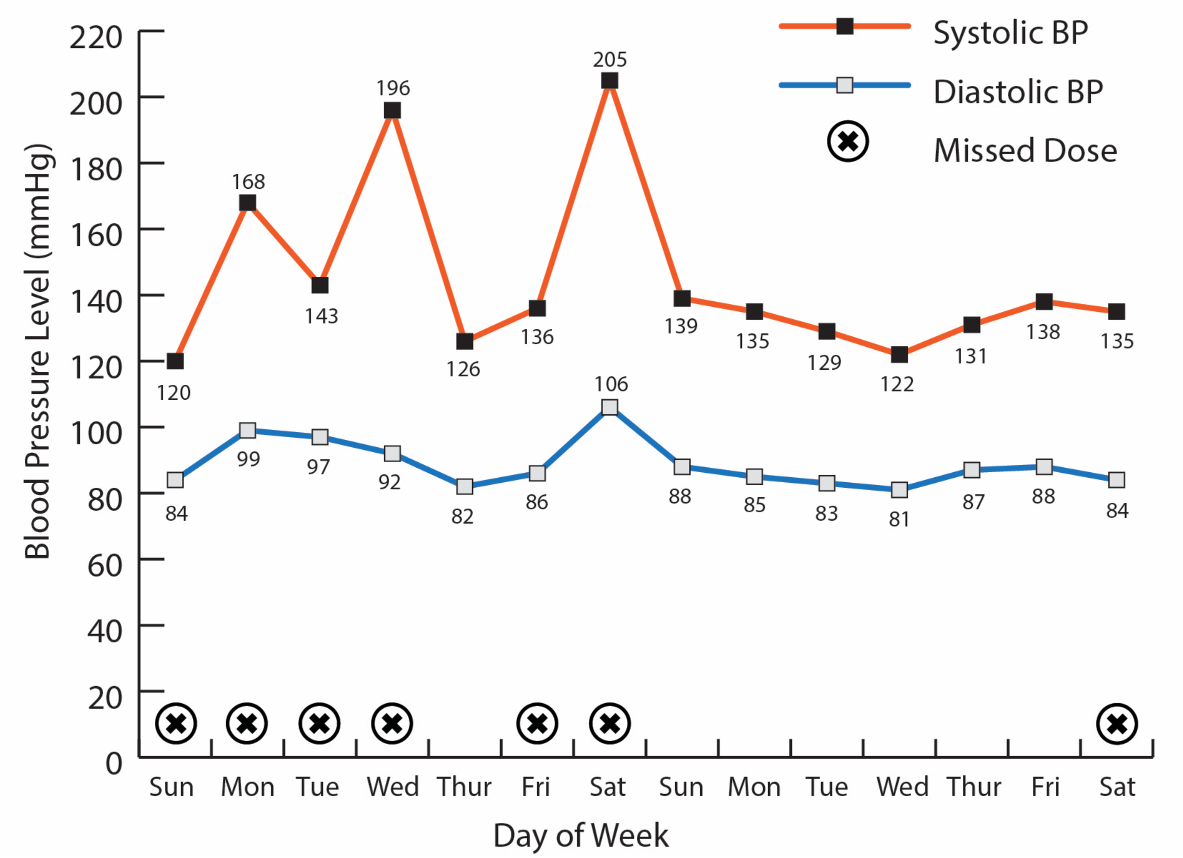

Systolic BP
Diastolic BP
Missed Dose
Blood Pressure Level (mmHg)
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

GRAPH 2



Systolic BP
Diastolic BP
Missed Dose
Normal BP Zone
Blood Pressure Level (mmHg)
220
200
180
160
140
120
100
80
60
40
20
0
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

GRAPH 3


Systolic BP
Diastolic BP
Missed Dose
Blood Pressure Level (mmHg)
220
200
180
160
140
120
100
80
60
40
20
0
168
196
205
120
143
126
136
139
135
129
122
131
138
135
106
99
97
92
84
82
86
88
85
83
81
87
88
84
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Sun
Mon
Tue
Wed
Thur
Fri
Sat
Day of Week

[ASK THE FOLLOWING QUESTIONS FOR EACH GRAPH]

1. Can you tell me what the top and bottom lines represent? What about this chart tells you that?

2. Can you tell me what the different colors on the chart mean?

3. What does this symbol represent/numbers?

4. Next, I'm going to read a list of words that are used as labels. Can you briefly tell me what they mean? [ONLY ASK FOR FIRST GRAPH]

Blood Pressure Level
Systolic BP
Diastolic BP
Day of Week
Missed Dose
Normal BP Zone

[FOR WORDS THEY UNDERSTAND] Do you have another word for this that you use instead?

5. For this graph/chart, can you tell me which days the medication was taken?

6. Which days did this person miss a dose?

7. What about this chart tells you that?

8. Can you tell me which axis (the bottom line of the graph or the line on the left side of the graph) is for blood pressure, and which is for day of week?

9. What do the tick marks on the blood pressure axis mean?

10. How about the tick marks above the days of the week?

For the next questions, I want you to keep in mind that controlled or normal blood pressure is considered between 120 and 140 for systolic (or the top line) and 80 and 90 for diastolic (or the bottom line).

11. What days have uncontrolled, or high blood pressure levels?

6-item scale validation:

For this next part, I want to see if I can improve the wording of these questions. There are no right or wrong answers here. The purpose of this is to make sure we create questions that everyone can understand, and that people understand the questions the way we intended.

For each question, I want you to read the question aloud, and tell me in your own words what the question is asking. If there is something you don't understand, such as a specific word or phrase, or a word that seems unfamiliar, let me know – it's important to know if anything is confusing.

1. According to this graph, would you say that taking medication affects blood pressure levels?
   - ☐ Yes
   - ☐ No

[PROBE] Was this question easy to understand? Would you change the wording of this question?

2. According to this graph, would you say this person's blood pressure levels are (select one):
   - ☐ The same whether or not they take their medication
   - ☐ Higher when they take their medication
   - ☐ Lower when they take their medication

[PROBE] Was this question easy to understand? Would you change the wording of this question?

3. Does taking medication appear to make this person's blood pressure better or worse?
   - ☐ Yes
   - ☐ No

[PROBE] Was this question easy to understand? Would you change the wording of this question?

4. According to this graph, would you generally say that this person's blood pressure levels change <u>when medication is not taken</u>?
   - ☐ Yes
   - ☐ No

[PROBE] Was this question easy to understand? Would you change the wording of this question?

5. According to this graph, how would you say this person's blood pressure levels change <u>when they do take their medication</u>?
   - ☐ It stays the same
   - ☐ It is higher
   - ☐ It is lower

[PROBE] Was this question easy to understand? Would you change the wording of this question?

6. On the days with higher blood pressure levels, does this person usually take their medication?
   - ☐ Yes
   - ☐ No

[PROBE] Was this question easy to understand? Would you change the wording of this question?

APPENDIX C: SCREENING AND SURVEY INSTRUMENTS

Study Invite Text

We are conducting an academic research survey about high blood pressure. We need to understand how people with high blood pressure understand charts and graphs about their blood pressure and medication.

We are looking for participants for a larger survey, which if you qualify, will pay $4.00. This short survey will pay $0.50 and will take about 7 minutes, and will determine if you qualify.

To be eligible for this study, you must:

- Be 18 years of age or older
- Speak English
- Have high blood pressure
- Take at least 1 medication for high blood pressure
- Own a smartphone
- Not have any sever vision or hearing impairments

If you meet these criteria, select the link below to complete the survey. At the end of the survey, you will receive a code to paste into the box below to receive credit for taking our survey.

If you qualify for the full study, you will receive a qualification and invite to participate. The full study will pay $4.00, and will take about 25 minutes.

Make sure to leave this window open as you complete the survey. When you are finished, you will return to this page to paste the code into the box.

Screening Consent Text

Thank you for your interest in participating in this research. This study is being conducted by Adam Sage at the Eshelman School of Pharmacy at the University of North Carolina at Chapel Hill. If you have any questions about the study, you may contact Mr. Sage by telephone at 330-388-3025 or by email at asage@email.unc.edu. If you have questions about your rights as a research participant, you can contact the Institutional Review Board at 919-966-3113 or by email IRB_subjects@unc.edu.

This survey will take approximately 7 minutes to complete. If you complete the survey, you will receive a code that you can use to redeem a $0.50 payment.

To be eligible for this survey, you must:

- Be 18 years of age or older
- Own a smartphone
- Have high blood pressure
- Take at least 1 medication for high blood pressure
- Not have any sever vision or cognitive impairment

The study is designed to determine if you are eligible for a larger study to learn how people understand visual information about blood pressure and medication tracking. You are being asked to be in this study because you take medication to control your hypertension. This research is designed to benefit society by gaining new knowledge, and you will not personally benefit from your participation. You may feel uncomfortable sharing information, but your answers will not be connected to your identity. Your participation in the study is voluntary. Refusal to participate will involve no penalty or loss of benefits, and you may discontinue participation at any time without penalty or loss of benefits. Your Mturk ID will only be used for payment, and will not be connected to your answers in any way. The unique code given to you for payment will be connected to your answers, which will be stored in a password protected file on a secure server.

If you would like to participate in the study, click the YES option below. Otherwise, simply close this window to exit out of the survey.

(IRB #17-0466, version date 1/12/2018)

YES
EXIT

[IF EXIT, SKIP TO INELIGIBLE MESSAGE]

Q1. Do you own a smartphone?

- ☐ Yes
- ☐ No [SKIP TO INELIGIBLE MESSAGE]

Q2. What is your age in years?

ENTER NUMBER

Q3. Do you have high blood pressure, also known as hypertension?

- ☐ Yes
- ☐ No [SKIP TO INELIGIBLE MESSAGE]

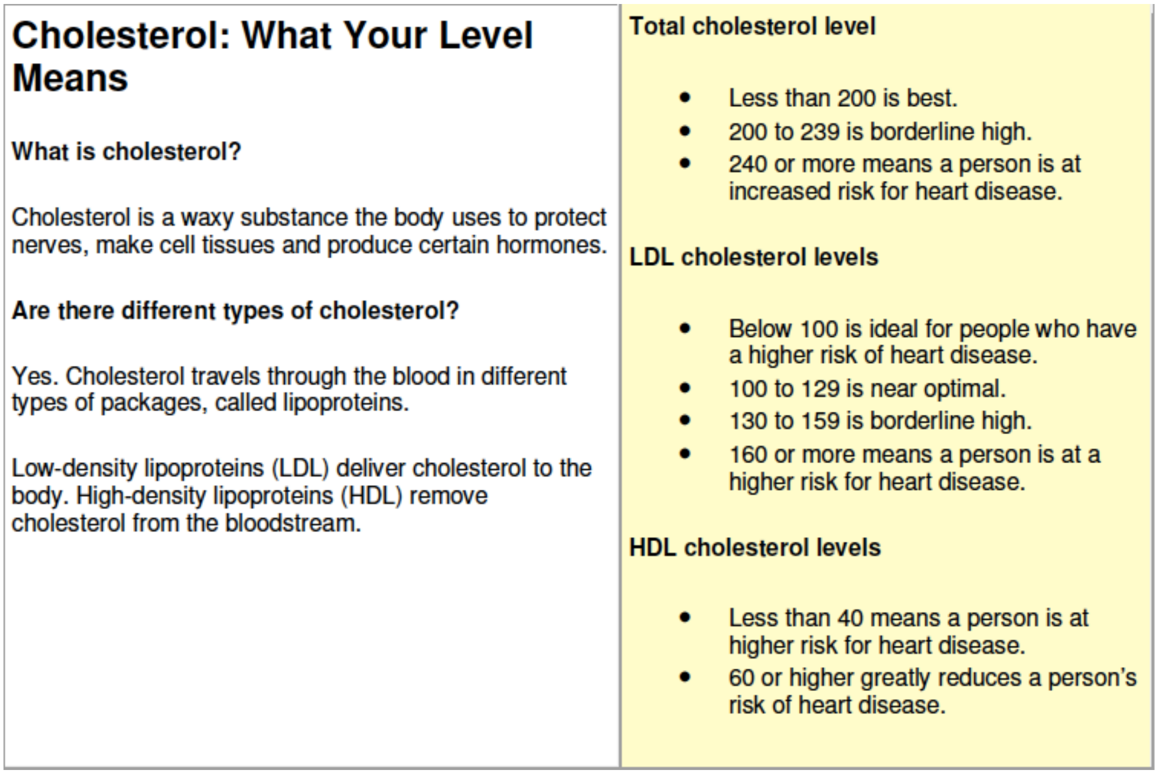
Q4. Do you take medication for your high blood pressure?

- ☐ Yes
- ☐ No [SKIP TO INELIGIBLE MESSAGE]

Q5. Do you have any hearing or cognitive impairments?

- ☐ Yes [SKIP TO INELIGIBLE MESSAGE]
- ☐ No

Q1



Cholesterol: What Your Level Means

What is cholesterol?

Cholesterol is a waxy substance the body uses to protect nerves, make cell tissues and produce certain hormones.

Are there different types of cholesterol?

Yes. Cholesterol travels through the blood in different types of packages, called lipoproteins.

Low-density lipoproteins (LDL) deliver cholesterol to the body. High-density lipoproteins (HDL) remove cholesterol from the bloodstream.

Total cholesterol level

- Less than 200 is best.
- 200 to 239 is borderline high.
- 240 or more means a person is at increased risk for heart disease.

LDL cholesterol levels

- Below 100 is ideal for people who have a higher risk of heart disease.
- 100 to 129 is near optimal.
- 130 to 159 is borderline high.
- 160 or more means a person is at a higher risk for heart disease.

HDL cholesterol levels

- Less than 40 means a person is at higher risk for heart disease.
- 60 or higher greatly reduces a person's risk of heart disease.

Please answer the following question based on the information in the text above.

Which set of low density lipoprotein (LDL) and high density lipoprotein (HDL) levels is the best?

☐ LDL of 134 and HDL of 61
☐ LDL of 98 and HDL of 82
☐ LDL of 140 and HDL of 50
☐ LDL of 165 and HDL of 80

Q2

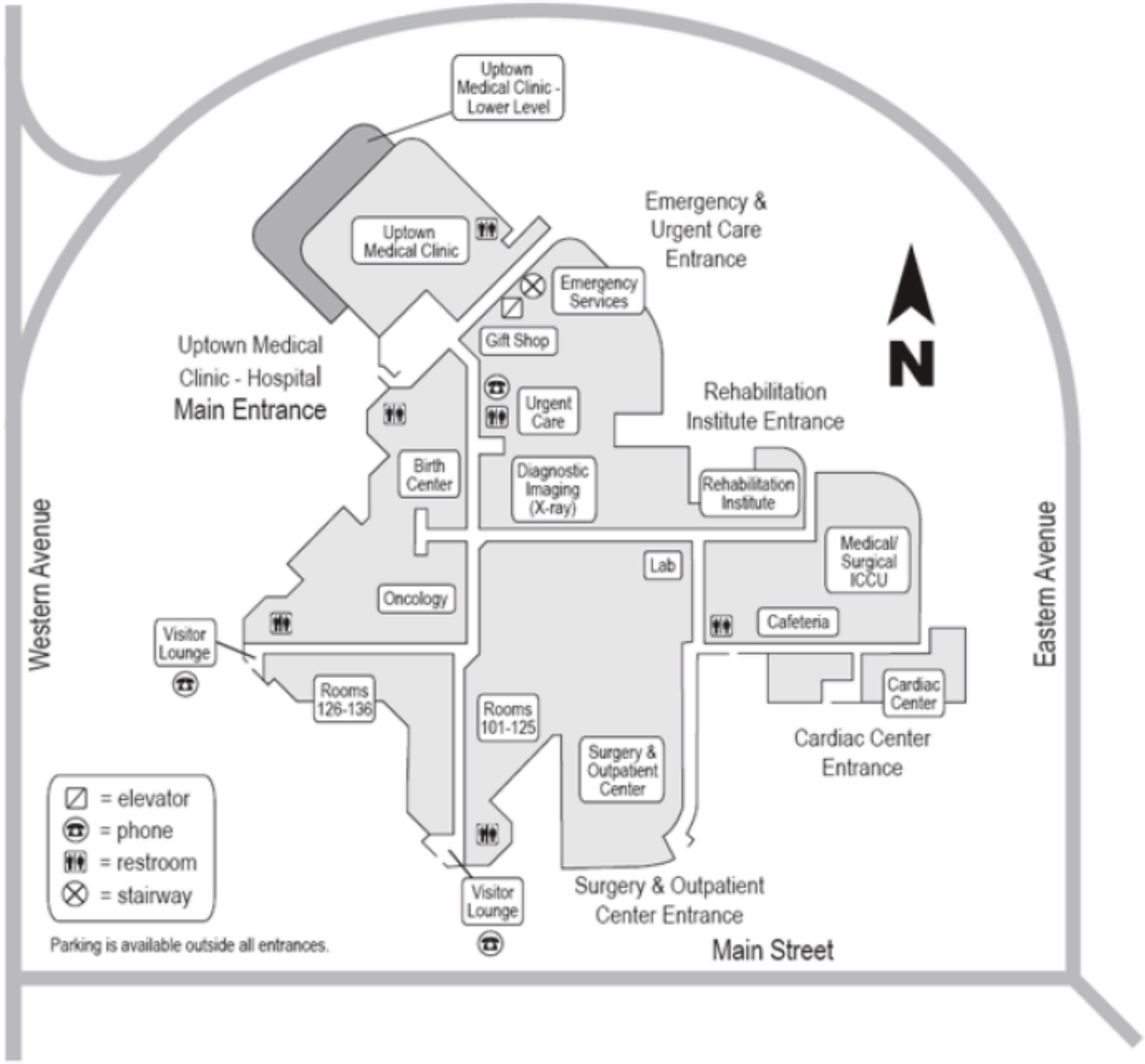
[AUDIO CLIP]

Please answer the following question based on the information in the audio clip.

If a person was worried about his cough, what number should he press?

- ☐ 1
- ☐ 2
- ☐ 4
- ☐ Call 911
- ☐ Not Sure

Q3

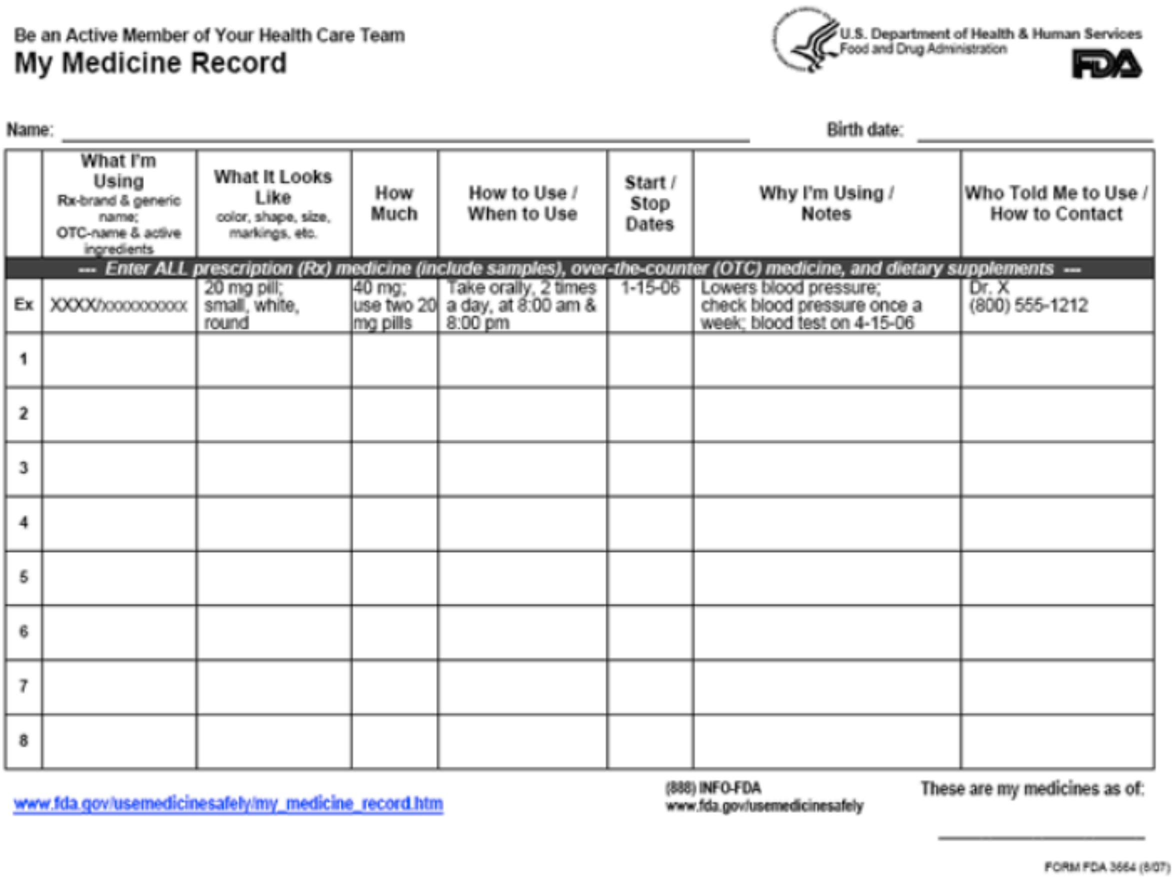


Please answer the following question based on the information in the map.

Which of the following entrance is closest to the elevator?

- ☐ There is no elevator
- ☐ Surgery & Outpatient Center Entrance
- ☐ Rehabilitation Institute Entrance
- ☐ Main Entrance
- ☐ Don't Know

Q4



Be an Active Member of Your Health Care Team

My Medicine Record

U.S. Department of Health & Human Services
Food and Drug Administration
FDA

Name: ____________________ Birth date: ____________________

	What I'm Using Rx-brand & generic name; OTC-name & active ingredients	What It Looks Like color, shape, size, markings, etc.	How Much	How to Use / When to Use	Start / Stop Dates	Why I'm Using / Notes	Who Told Me to Use / How to Contact
	--- Enter ALL prescription (Rx) medicine (include samples), over-the-counter (OTC) medicine, and dietary supplements ---						
Ex	XXXX/xxxxxxxxxx	20 mg pill; small, white, round	40 mg; use two 20 mg pills	Take orally, 2 times a day, at 8:00 am & 8:00 pm	1-15-06	Lowers blood pressure; check blood pressure once a week; blood test on 4-15-06	Dr. X (800) 555-1212
1							
2							
3							
4							
5							
6							
7							
8							

www.fda.gov/usemedicinesafely/my_medicine_record.htm

(888) INFO-FDA
www.fda.gov/usemedicinesafely

These are my medicines as of: ____________________

FORM FDA 3664 (8/07)

Please answer the following question based on the information in the chart.

In the example listed in the first row of the table, when should the medicine be taken?

- ☐ Two time a day anytime between 8 a.m. and 8 p.m.
- ☐ At 8 a.m. or 8 p.m. each day
- ☐ At 8 a.m. and 8 p.m. each day
- ☐ Don’t Know

Q5

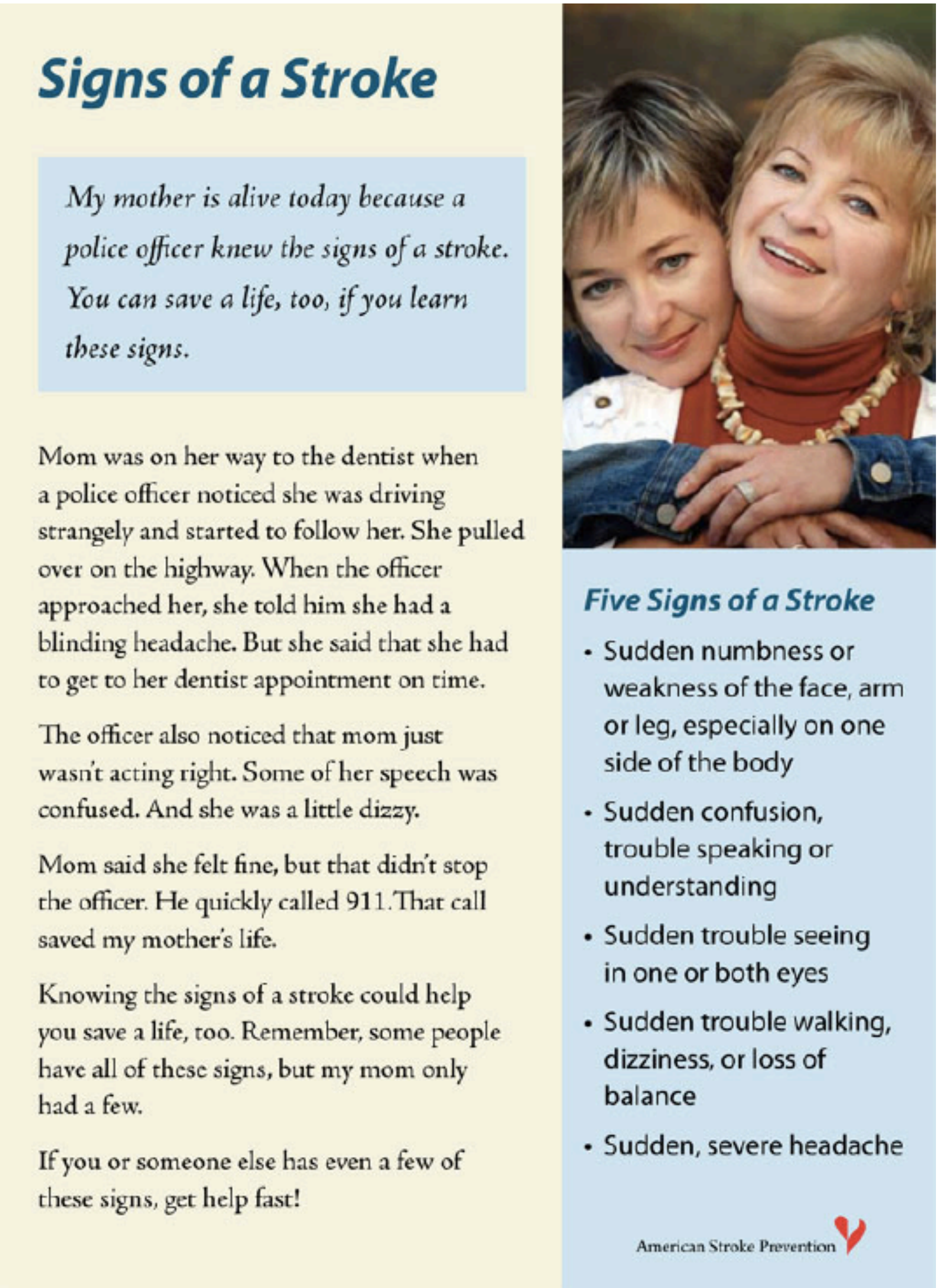
Please read the question below, then visit the following website to answer the question. Answer the question based on the information in the website.

https://www.healthwise.net/rti/Content/StdDocument.aspx?DOCHWID=tx4394

Kate weighs 150 pounds. Which activity would burn the most calories?

- ☐ Walking at a medium pace for 30 minutes
- ☐ Raking the lawn for 30 minutes
- ☐ Bowling for 30 minutes
- ☐ Don’t Know

Q6



Signs of a Stroke

> *My mother is alive today because a police officer knew the signs of a stroke. You can save a life, too, if you learn these signs.*

Mom was on her way to the dentist when a police officer noticed she was driving strangely and started to follow her. She pulled over on the highway. When the officer approached her, she told him she had a blinding headache. But she said that she had to get to her dentist appointment on time.

The officer also noticed that mom just wasn't acting right. Some of her speech was confused. And she was a little dizzy.

Mom said she felt fine, but that didn't stop the officer. He quickly called 911. That call saved my mother's life.

Knowing the signs of a stroke could help you save a life, too. Remember, some people have all of these signs, but my mom only had a few.

If you or someone else has even a few of these signs, get help fast!

Five Signs of a Stroke

- Sudden numbness or weakness of the face, arm or leg, especially on one side of the body
- Sudden confusion, trouble speaking or understanding
- Sudden trouble seeing in one or both eyes
- Sudden trouble walking, dizziness, or loss of balance
- Sudden, severe headache

American Stroke Prevention

Please answer the following question based on the information in the flyer.

Which of the following is NOT a sign of a stroke?

- ☐ Shaking chills
- ☐ Blurred vision
- ☐ Bad headache
- ☐ Numbness on one side
- ☐ Don’t Know

Q7

Are you eating a variety of healthy foods, exercising and still struggling with your weight? Some people may need to pay closer attention to portion control — managing the amount of food that they eat — as their total calorie intake determines their weight.

A serving isn't what they happen to put on their plate. It's a specific amount of food defined by common measurements, such as cups, ounces or pieces. The serving sizes represented here are part of the Mayo Clinic Healthy Weight Pyramid — a food pyramid designed to promote weight loss and long-term health. Use these serving sizes in conjunction with a diet based on a variety of healthy foods. Add the right amount of regular physical activity, and a person will be well on their way to enjoying good nutrition and controlling their weight.

Vegetables

Until they're comfortable judging serving sizes, you may need to use measuring cups and spoons. A half a cup of cooked carrots, for example, equals one serving. Here are the recommended serving sizes for other vegetables:

Food		Serving size
Raw leafy vegetables	=	2 cups
Raw vegetables, chopped	=	1 cup
Chopped, cooked or canned vegetables	=	1/2 cup

Meat and beans

Familiar objects can help a person picture proper portions for meat, poultry, fish and beans. For example, a 3-ounce serving of fish is about the size of a deck of cards. Here are the serving sizes for meat and meat substitutes:

Food		Serving size
Cooked skinless poultry or fish	=	3 ounces
Cooked lean meat	=	1 1/2 ounces
Cooked legumes or dried beans	=	1/2 cup or about the size of an ice cream scoop
Egg	=	1 medium

Please answer the following based on the information in the text and charts.

A person is cooking dinner for himself and he wants to include one serving from the meats and beans group. What should he choose?

- ☐ 1 ½ ounces of cooked lean beef
- ☐ 1 ½ ounces of cooked fish
- ☐ 3 boiled eggs
- ☐ 1 cup of cooked kidney beans
- ☐ Don’t Know

Q8

Please read the question below, then visit the following website to answer the question. Answer the question based on the video in the website.

https://www.mayoclinic.org/healthy-lifestyle/fitness/multimedia/lunge/vid-20084662

What parts of the body do lunge exercises work?

- ☐ Arms and shoulders
- ☐ Back and abdomen
- ☐ Legs and buttock
- ☐ Don’t Know

Q9

Nutrition Facts

Serving Size 140 grams (140g)
Servings Per Container 1

Amount Per Serving

Calories 140 Calories from Fat 70

	% Daily Value*
Total Fat 7g	**11%**
Saturated Fat 2.5g	**13%**
Trans Fat 0g	
Cholesterol 25mg	**8%**
Sodium 300mg	**13%**
Total Carbohydrate 9g	**3%**
Dietary Fiber 2g	**8%**
Sugars 3g	
Protein 8g	

Vitamin A 10% • Vitamin C 20%
Calcium 4% • Iron 10%

* Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories:	2,000	2,500
Total Fat	Less than	65g	80g
Saturated Fat	Less than	20g	25g
Cholesterol	Less than	300mg	300mg
Sodium	Less than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

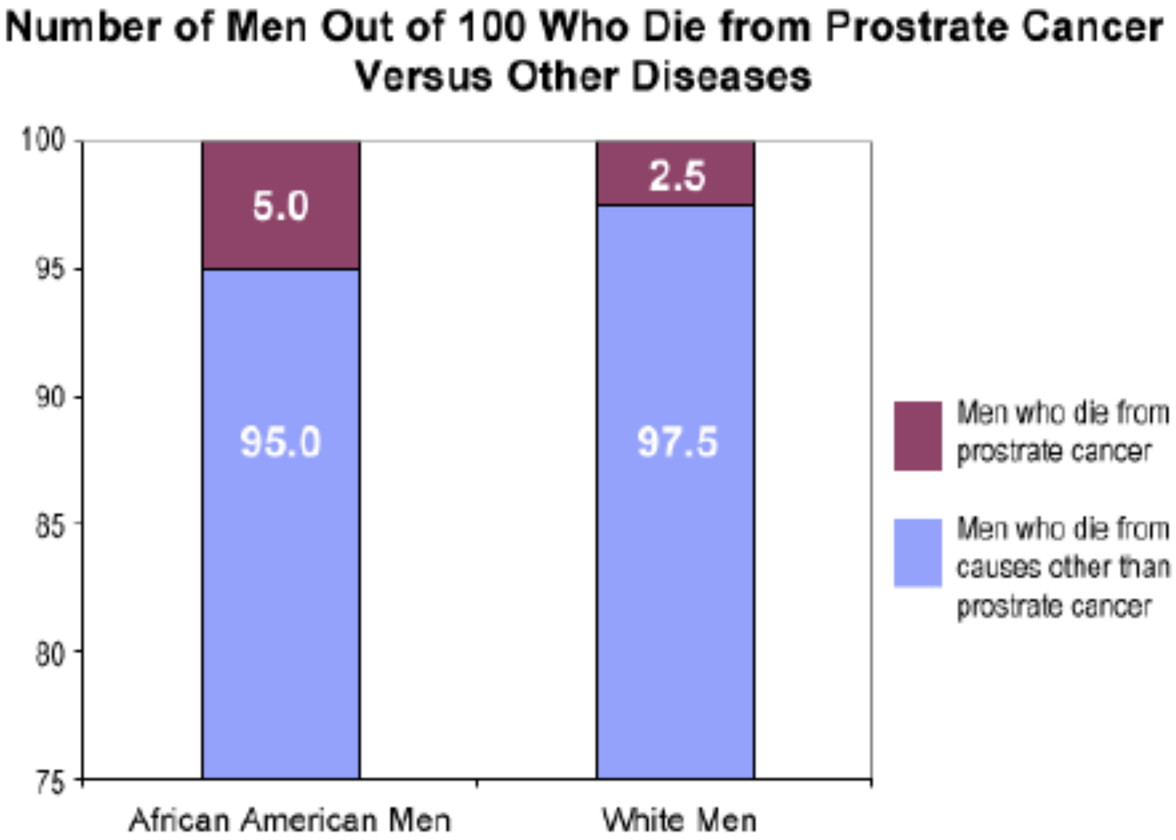
Ingredients: Tomatoes; Chicken; Mushrooms; White Wine; Celery; Onions; Green Bell Pepper; Flour; Butter; Olive Oil; Salt; Black Pepper.

Please answer the following question based on the information in the label.

If a person is on a 2,500 calorie diet, what percent of the daily value of saturated fat would he get from one serving?

☐ 10 percent
☐ 11 percent
☐ 12 percent
☐ 13 percent
☐ Don’t Know

Q10



Please answer the following question based on the information in the chart.

More men die from prostate cancer than from other causes. Based on the chart above, would you say this is true, false, or are you not sure?

- ☐ True
- ☐ False
- ☐ Not Sure

[END SURVEY MESSAGE]

Thank you for your time! Use the below survey code to confirm completion for payment.

If you qualify for the full study, you will be given a qualification that will grant you access to participate. Participants for the full study will be paid $4.00.

[RANDOM NUMBER]

[INELIGIBLE MESSAGE]

Thank you for taking our survey. As stated in the Consent Form, there are certain requirements that must be met in order to participate and receive compensation. You are seeing this message because you are not eligible to complete the study and receive compensation. This may be due to any of the following reasons:

You do not agree to participate.

- You are under 18 years old.
- You failed to answer a question that checked to see if you read and understood the instructions.
- You do not own a smartphone.
- You do not have high blood pressure.
- You do not take medication for high blood pressure.
- You reported having a severe vision or cognitive impairment.

This follows Amazon Mechanical Turk policy, which states that "a Requester may reject your work if the HIT was not completed correctly or the instructions were not followed."

You may close this window or use your explorer bar to navigate back to the Amazon Mechanical Turk site.

The Consent Form from the beginning of the study is below if you would like to review it:

Thank you for your interest in participating in this research. This study is being conducted by Adam Sage at the Eshelman School of Pharmacy at the University of North Carolina at Chapel Hill. If you have any questions about the study, you may contact Mr. Sage by telephone at 330-388-3025 or by email at asage@email.unc.edu. If you have questions about your rights as a research participant, you can contact the Institutional Review Board at 919-966-3113 or by email IRB_subjects@unc.edu.

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- Own a smartphone
- Have high blood pressure
- Take at least 1 medication for high blood pressure
- Not have any sever vision or cognitive impairments

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If you would like to participate in the study, click the YES option below. Otherwise, simply close this window to exit out of the survey.

(IRB #17-0466, version date 1/12/2018)

Survey Consent Text

Thank you for your interest in participating in this research. This study is being conducted by Adam Sage at the Eshelman School of Pharmacy at the University of North Carolina at Chapel Hill. If you have any questions about the study, you may contact Mr. Sage by telephone at 330-388-3025 or by email at asage@email.unc.edu. If you have questions about your rights as a research participant, you can contact the Institutional Review Board at 919-966-3113 or by email IRB_subjects@unc.edu.

This survey will take approximately 25 minutes to complete. If you complete the survey, you will receive a code that you can use to redeem a $4.00 payment.

The study is designed to learn how people understand visual information about blood pressure and medication tracking. You are being asked to be in this study because you take medication to control your hypertension. This research is designed to benefit society by gaining new knowledge, and you will not personally benefit from your participation. You may feel uncomfortable sharing information, but your answers will not be connected to your identity. Your participation in the study is voluntary. Refusal to participate will involve no penalty or loss of benefits, and you may discontinue participation at any time without penalty or loss of benefits. Your Mturk ID will only be used for payment, and will not be connected to your answers in any way. The unique code given to you for payment will be connected to your answers, which will be stored in a password protected file on a secure server.

If you would like to participate in the study, click the YES option below. Otherwise, simply close this window to exit out of the survey.

(IRB #17-0466, version date 1/12/2018)

YES
EXIT

Charlson Comorbidity Index

Q1. As far as you know, do you have any of the following health conditions at the present time?

Check all that apply:

- ☐ Myocardial Infarction
- ☐ Congestive Heart Failure
- ☐ Peripheral Vascular Disease
- ☐ Cerebrovascular Disease
- ☐ Dementia
- ☐ Chronic Pulmonary Disease
- ☐ Connective Tissue Disease (CTD)/Rheumatoid Arthritis (RA)
- ☐ Ulcer Disease
- ☐ Liver Disease
- ☐ Diabetes
- ☐ Hemiplegia
- ☐ Moderate or Severe Renal Disease
- ☐ Diabetes with end-organ damage
- ☐ Any Tumor
- ☐ Leukemia
- ☐ Lymphoma
- ☐ Metastatic Solid Tumor
- ☐ AIDS

HTN Knowledge

Q2. Below are statements about high blood pressure. Some are true, and some are false. To the best of your knowledge, indicate which statements are true and which statements are false:

Increased diastolic blood pressure also indicates increased blood pressure.

High diastolic or systolic blood pressure indicates increased blood pressure.

Drugs for increased blood pressure must be taken everyday.

Individuals with increased blood pressure must take their medication only when they feel ill.

Individuals with increased blood pressure must take their medication throughout their life.

Individuals with increased blood pressure must take their medication in a manner that makes them feel good.

If the medication for increased blood pressure can control blood pressure, there is no need to change lifestyles.

Increased blood pressure is the result of aging, so treatment is unnecessary.

If individuals with increased blood pressure change their lifestyles, there is no need for treatment.

Individuals with increased blood pressure can eat salty foods as long as they take their drugs regularly.

Individuals with increased blood pressure can drink alcoholic beverages.

Individuals with increased blood pressure must not smoke.

Individuals with increased blood pressure must eat fruits and vegetables frequently.

For individuals with increased blood pressure, the best cooking method is frying.

For individuals with increased blood pressure, the best cooking method is boiling or grilling.

The best type of meat for individuals with increased blood pressure is white meat.

The best type of meat for individuals with increased blood pressure is red meat.

Increased blood pressure can cause premature death if left untreated.

Increased blood pressure can cause heart diseases, such as heart attack, if left untreated.

Increased blood pressure can cause strokes, if left untreated.

Increased blood pressure can cause kidney failure, if left untreated.

Increased blood pressure can cause visual disturbances, if left untreated.

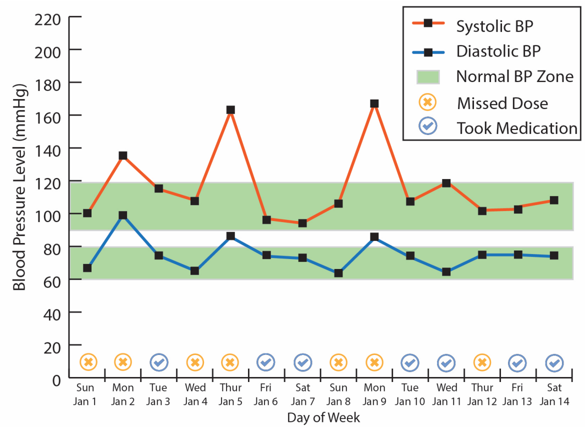
Data Visualization Comprehension

[RANDOMIZE INTO CONDENSED VS STANDARD VISUALIZATIONS]

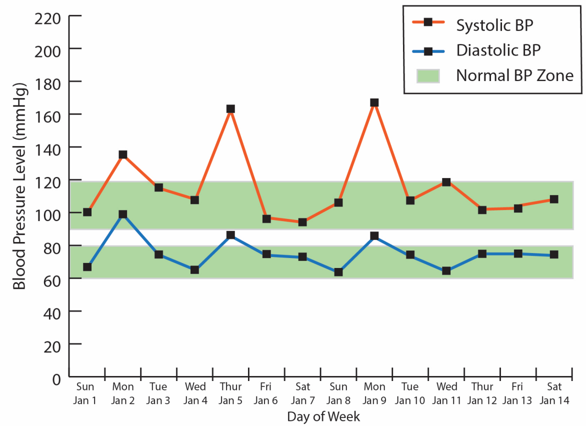
[RANDOM ORDER for Q]

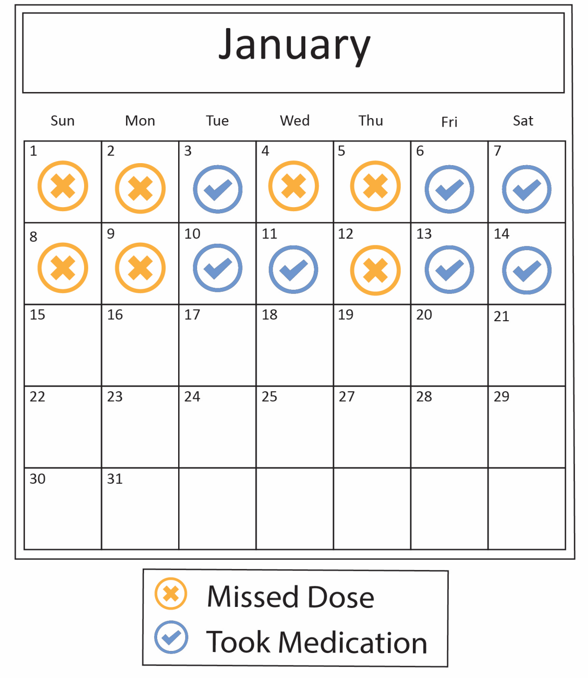
You will be shown a series of 4 graphs [and calendars] that show the days that someone took their medication, and their blood pressure levels for those days.

There are 6 questions about each graph [and calendars]. Please refer to the graph [and calendar] to answer each question.



[PARTICIPANT TO RECEIVE CONDENSED OR GRAPH WITH CALENDAR]





High blood pressure is considered 130 mm Hg and above for systolic blood pressure (the top number) and 80 mm Hg and above for diastolic blood pressure (the bottom number).

Q3.1 Looking at the graph [and calendar], does it look like taking medication makes the person's blood pressure normal:

- ☐ Yes
- ☐ No

Q3.2 Looking at the graph [and calendar], would you say this person's blood pressure levels:

- ☐ Are related to how they take their medication
- ☐ Are not related to how they take their medication

Q3.3 Looking at the graph [and calendar], missing medication usually:

- ☐ Makes blood pressure worse
- ☐ Does not change blood pressure
- ☐ I cannot tell from this graph [and calendar]

Q3.4 Looking at the graph [and calendar], would you say that this person's blood pressure levels generally change when they <u>do not</u> take their medication?

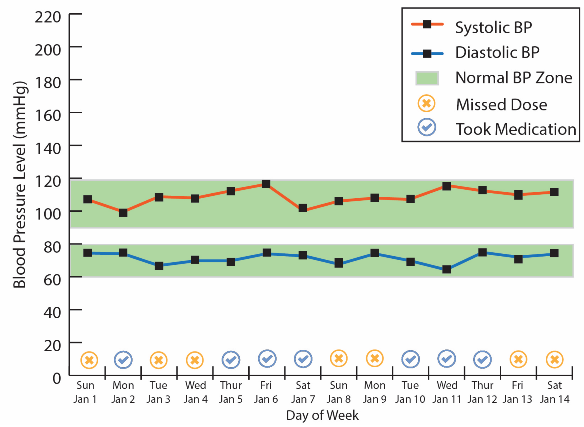
- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q3.5 Looking at the graph [and calendar], would you say this person's blood pressure levels are always normal when they <u>do take</u> their medication?

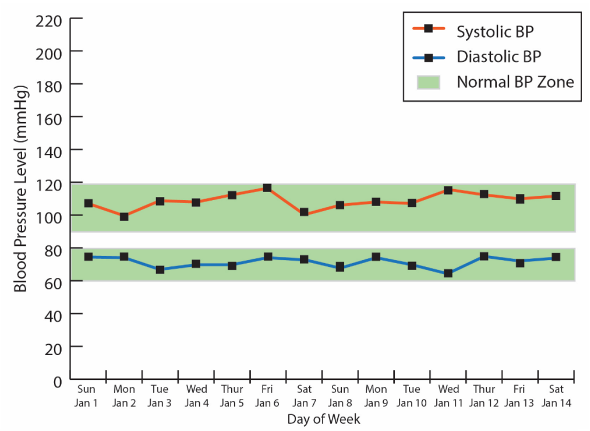
- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

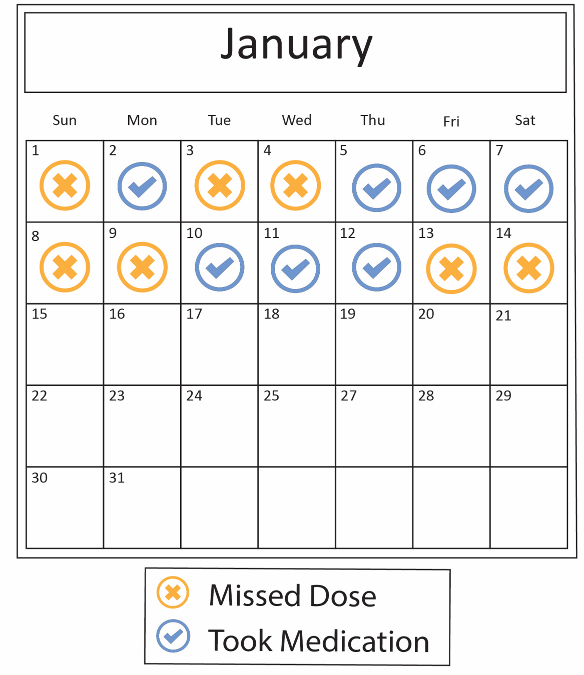
Q3.6 On the days when blood pressure is high, did this person usually take their medication?

- ☐ Yes
- ☐ No
- ☐ There are no days with high blood pressure



[PARTICIPANT TO RECEIVE CONDENSED OR GRAPH WITH CALENDAR]





High blood pressure is considered 130 mm Hg and above for systolic blood pressure (the top number) and 80 mm Hg and above for diastolic blood pressure (the bottom number).

Q4.1 Looking at the graph [and calendar], does it look like taking medication makes the person’s blood pressure normal:

- ☐ Yes
- ☐ No

Q4.2 Looking at the graph [and calendar], would you say this person's blood pressure levels:

- ☐ Are related to how they take their medication
- ☐ Are not related to how they take their medication

Q4.3 Looking at the graph [and calendar], missing medication usually:

- ☐ Makes blood pressure worse
- ☐ Does not change blood pressure
- ☐ I cannot tell from this graph [and calendar]

Q4.4 Looking at the graph [and calendar], would you say that this person's blood pressure levels generally change when they <u>do not</u> take their medication?

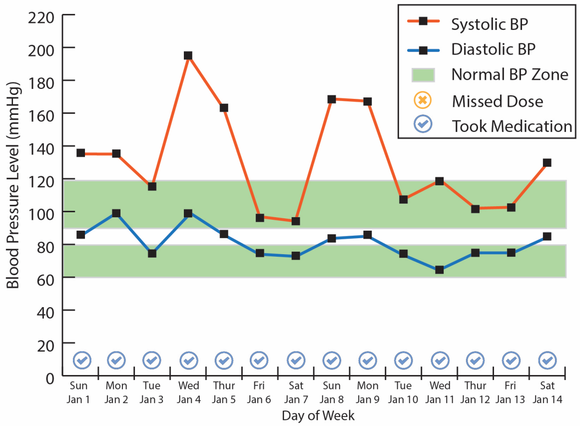
- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q4.5 Looking at the graph [and calendar], would you say this person's blood pressure levels are always normal when they <u>do take</u> their medication?

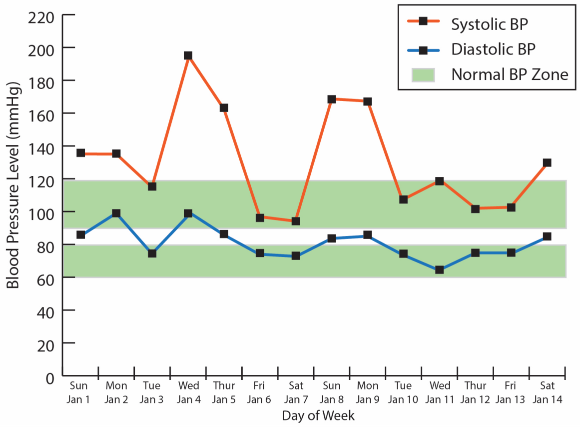
- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q4.6 On the days when blood pressure is high, did this person usually take their medication?

- ☐ Yes
- ☐ No
- ☐ There are no days with high blood pressure



[PARTICIPANT TO RECEIVE CONDENSED OR GRAPH WITH CALENDAR]



January

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1 ✓	2 ✓	3 ✓	4 ✓	5 ✓	6 ✓	7 ✓
8 ✓	9 ✓	10 ✓	11 ✓	12 ✓	13 ✓	14 ✓
15	16	17	18	19	20	21
22	23	24	25	27	28	29
30	31					

☒ Missed Dose
✓ Took Medication

High blood pressure is considered 130 mm Hg and above for systolic blood pressure (the top number) and 80 mm Hg and above for diastolic blood pressure (the bottom number).

Q5.1 Looking at the graph [and calendar], does it look like taking medication makes the person’s blood pressure normal:

- ☐ Yes
- ☐ No

Q5.2 Looking at the graph [and calendar], would you say this person’s blood pressure levels:

- ☐ Are related to how they take their medication
- ☐ Are not related to how they take their medication

Q5.3 Looking at the graph [and calendar], missing medication usually:

- ☐ Makes blood pressure worse
- ☐ Does not change blood pressure
- ☐ I cannot tell from this graph [and calendar]

Q5.4 Looking at the graph [and calendar], would you say that this person’s blood pressure levels generally change when they <u>do not</u> take their medication?

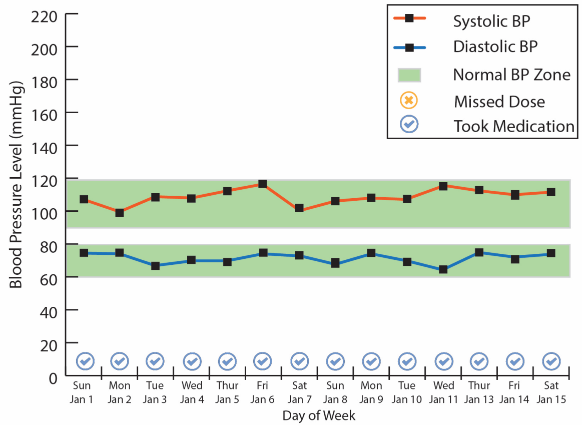
- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q5.5 Looking at the graph [and calendar], would you say this person’s blood pressure levels are always normal when they <u>do take</u> their medication?

- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q5.6 On the days when blood pressure is high, did this person usually take their medication?

- ☐ Yes
- ☐ No
- ☐ There are no days with high blood pressure



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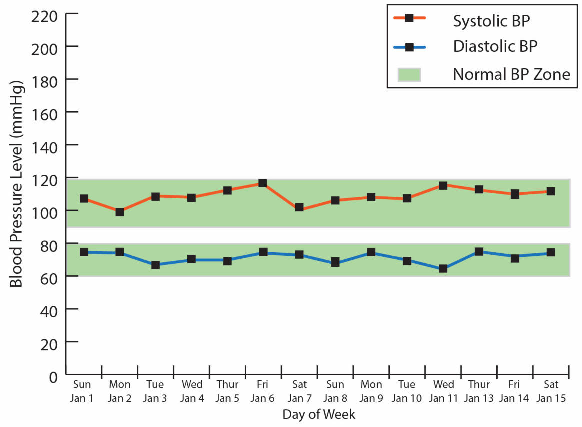

January

Sun	Mon	Tue	Wed	Thu	Fri	Sat
1 ✓	2 ✓	3 ✓	4 ✓	5 ✓	6 ✓	7 ✓
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30	31					

☒ Missed Dose
✓ Took Medication

High blood pressure is considered 130 mm Hg and above for systolic blood pressure (the top number) and 80 mm Hg and above for diastolic blood pressure (the bottom number).

Q6.1 Looking at the graph [and calendar], does it look like taking medication makes the person's blood pressure normal:

- ☐ Yes
- ☐ No

Q6.2 Looking at the graph [and calendar], would you say this person's blood pressure levels:

- ☐ Are related to how they take their medication
- ☐ Are not related to how they take their medication

Q6.3 Looking at the graph [and calendar], missing medication usually:

- ☐ Makes blood pressure worse
- ☐ Does not change blood pressure
- ☐ I cannot tell from this graph [and calendar]

Q6.4 Looking at the graph [and calendar], would you say that this person's blood pressure levels generally change when they <u>do not</u> take their medication?

- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q6.5 Looking at the graph [and calendar], would you say this person's blood pressure levels are always normal when they <u>do take</u> their medication?

- ☐ Yes
- ☐ No
- ☐ I cannot tell from this graph [and calendar]

Q6.6 On the days when blood pressure is high, did this person usually take their medication?

- ☐ Yes
- ☐ No
- ☐ There are no days with high blood pressure

Attention Check

This question is an attention check. Select "Somewhat agree" below to continue:

- ☐ Strongly agree
- ☐ Agree
- ☐ Somewhat agree
- ☐ Neither agree or disagree
- ☐ Somewhat disagree
- ☐ Disagree
- ☐ Strongly Disagree

Characteristics

Q7. Do you own a smartphone?

- ☐ Yes
- ☐ No

Q8. Do you use apps to manage your health in any way?

- ☐ Yes
- ☐ No

Q9. Do you own a wearable health tracking device? (For instance, an app to track your blood pressure, diabetes, or medication)

- ☐ Yes
- ☐ No

Q10. What type of healthcare coverage do you have?

- ☐ Medicaid
- ☐ Medicare
- ☐ Employee-sponsored
- ☐ Private
- ☐ Other (specify)
- ☐ None

Q11. How often do you monitor your blood pressure?

- ☐ Never
- ☐ Rarely
- ☐ Sometimes
- ☐ Often
- ☐ Always

Q12. How often do you track when you take your medication?

- ☐ Never
- ☐ Rarely
- ☐ Sometimes
- ☐ Often
- ☐ Always

Demographics

Q13. What is your age in years?

Q14. What is your race?

- ☐ White
- ☐ Black or African American
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Native Hawaiian or Other Pacific Islander
- ☐ Other (specify)

Q5. What is your ethnicity?

- ☐ Hispanic
- ☐ Non-Hispanic

Q15. What is the highest level of education you have completed?

- ☐ Elementary
- ☐ Some High School
- ☐ High School Graduate,
- ☐ Some College or Technical School
- ☐ College Graduate
- ☐ Graduate Degree
- ☐ Prefer not to answer

Q17. What is your annual income?

- ☐ less than $10,000,
- ☐ $10,000 to $19,999
- ☐ $20,000 to $29,999
- ☐ $30,000 to $39,999
- ☐ $40,000 to $49,999
- ☐ $50,000 to $99,999
- ☐ $100,000 or more
- ☐ I don’t know
- ☐ Prefer not to answer

[END SURVEY MESSAGE]

Thank you for your time! Use the below survey code to confirm completion for your $4.00 payment.

[RANDOM NUMBER]

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