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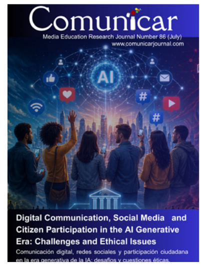

From Signs to Systems: A Semiotic–Pragmatic Framework for Digital Health

De los signos a los sistemas: Un marco semiótico-pragmático para la salud digital

Dra. Mónica Santillán Trujillo*, Universidad de las Fuerzas Armadas, ESPE, (Ecuador) (mlsantillan@espe.edu.ec) (https://orcid.org/0000-0003-2448-7530)
Dr. Carlos de Castro Lozano, Universidad de Córdoba, (Spain) (carlos@uco.es) (https://orcid.org/0000-0001-6603-843X)
Dr. C. José Miguel Ramírez Uceda, Universidad de Córdoba, (Spain) (miguel@interactvty.com) (https://orcid.org/0000-0002-5027-7521)
Dr. Marcelo Rea, Universidad de las Fuerzas Armadas, ESPE, (Ecuador) (amrea1@espe.edu.ec) (https://orcid.org/0009-0003-5532-4248)
Dr. Danilo Martínez, Universidad de las Fuerzas Armadas, ESPE, (Ecuador) (mdmartinez@espe.edu.ec) (https://orcid.org/0000-0001-6342-5928)

* Indicates the corresponding author

ABSTRACT

In contemporary digital health ecosystems, particularly in mental health, usability research has largely emphasized functional efficiency while under-theorizing communicative meaning-making. Despite advances in human–computer interaction, no empirically validated framework conceptualizes usability as a communicative semiotic phenomenon embedded in cultural and contextual conditions. This study addresses this gap by developing and empirically testing the Semiotic Framework for Usability (SFU), reconceptualizing usability as a communicative semiosphere grounded in Jakobson's language functions and Lotman's semiosphere theory. The framework was applied to eleven digital health applications and evaluated with 30 heterogeneous participants (aged 18–72) using a mixed-methods triangulated design combining semiotic coding, A/B testing, NASA-TLX cognitive load assessment, adaptive onboarding, surveys, and semi-structured interviews. Results indicate semiotic-informed redesign increased symbolic comprehension by 25%, reduced cognitive load by 39%, and improved task completion by 30%. Semantic ambiguity was the primary usability barrier, confirming the centrality of communicative clarity. Multimodal reinforcement strategies—including visual glossaries, interpretative metaphors, and redundant coding—enhanced emotional alignment and trust perception. These findings reposition usability as a communicative and educational practice rather than solely a technical attribute. The study contributes a replicable semiotic–pragmatic model for evaluating digital health interfaces, with implications for media education, inclusive design, and culturally sensitive systems aligned with ISO 9241-210 and WCAG standards.

RESUMEN

En los ecosistemas contemporáneos de salud digital, especialmente en salud mental, la investigación sobre usabilidad ha priorizado la eficiencia funcional, subteorizando la construcción de significado comunicativo. Pese a los avances en interacción humano–computadora, no existe un marco validado que conceptualice la usabilidad como fenómeno semiótico comunicativo inscrito en condiciones culturales y contextuales. Este estudio aborda esta brecha mediante el desarrollo y evaluación del Marco Semiótico para la Usabilidad (SFU), que reconceptualiza la usabilidad como semiósfera comunicativa basada en las funciones del lenguaje de Jakobson y la teoría de la semiósfera de Lotman. El marco se aplicó a once aplicaciones digitales y se evaluó con 30 participantes heterogéneos (18–72 años) mediante un diseño mixto triangulado que integró codificación semiótica, pruebas A/B, evaluación de carga cognitiva NASA-TLX, incorporación adaptativa, encuestas y entrevistas semiestructuradas. Los resultados muestran que el rediseño informado por semiótica aumentó la comprensión simbólica en 25 %, redujo la carga cognitiva en 39 % y mejoró la finalización de tareas en 30 %. La ambigüedad semántica fue la principal barrera de usabilidad. Estrategias multimodales

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—glosarios visuales, metáforas interpretativas y codificación redundante— fortalecieron la alineación emocional y confianza. Estos hallazgos reposicionan la usabilidad como práctica comunicativa y educativa. El estudio aporta un modelo semiótico–pragmático replicable para evaluar interfaces digitales, con implicaciones en educación mediática, diseño inclusivo y sistemas culturalmente sensibles alineados con ISO 9241-210 y WCAG.

KEYWORDS | PALABRAS CLAVE

Semiotic Usability, Digital Health Interfaces, Human–Computer Interaction, Multimodal Communication, Accessibility in UX Design, Health App Design.
Semiotics, Digital health, Human–computer interaction, Multimodality, Cognitive load, Interface communication.

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1. Introduccion

1.1. Background and Context

The rapid expansion of digital health technologies, accelerated by the COVID-19 pandemic, has positioned mobile health (mHealth) as central infrastructures in contemporary healthcare delivery (WHO, 2021). Current estimates indicate that over 350,000 health-related are available across major platforms, with mental health representing one of the fastest-growing segments (Torous et al., 2021). However, this proliferation has not been accompanied by proportional improvements in usability, user comprehension, or sustained engagement—fundamental prerequisites for clinical effectiveness.

Traditional approaches to interface design in health have predominantly emphasized technical functionality, system efficiency, and regulatory compliance, often treating usability as a secondary consideration addressed through post-hoc heuristic evaluation (ISO, 2019; Norman, 2013). This paradigm assumes that well-functioning systems will naturally be comprehensible and usable. However, empirical evidence increasingly demonstrates that technical functionality does not guarantee communicative effectiveness—users may interact with fully functional systems while systematically misinterpreting their meaning, misjudging their trustworthiness, or failing to integrate them meaningfully into health behaviors (Islam et al., 2020).

This disconnect is particularly pronounced in mental health contexts, where applications must navigate complex emotional states, cultural variations in health conceptualization, diverse literacy levels, and accessibility constraints. Research shows that up to 45% of users abandon mental health within the first week, with comprehension difficulties and perceived irrelevance cited as primary factors (Nasr et al., 2023). These abandonment rates represent not usability failures but communicative breakdowns with potentially serious clinical implications.

Theoretical frameworks by Eco (1991), who views semiotics as a network of interconnected meanings, and Lotman (1990), with his concept of the semiosphere, highlight the importance of interfaces as spaces of interpretation—not mere tools of manipulation. Our study adopts this perspective, treating visual and verbal design as cultural texts embedded within the user's semiosphere.

In line with the conceptual orientation proposed in this study—From Signs to Systems: A Semiotic–Pragmatic Framework for Digital Health—usability is approached not merely as an ergonomic property but as a process of meaning-making occurring within a communicative ecosystem. In such ecosystems, interfaces operate as semiotic mediators that translate system logic into interpretable signs for users situated within specific cultural and experiential contexts.

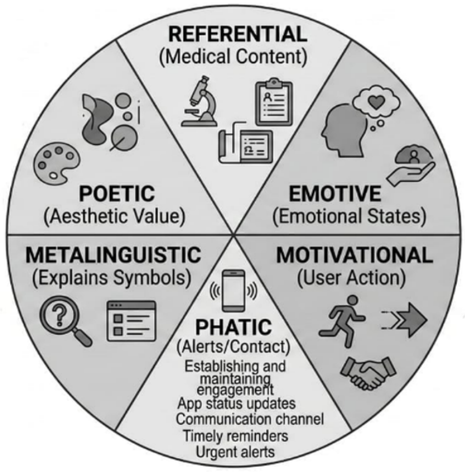
This perspective resonates with contemporary scholarship that revisits Roman Jakobson's functional model of communication as a productive analytical lens for digital and multimodal environments. Jakobson's framework has recently been reconsidered in design and communication theory as a way of explaining how informational, emotional, relational, and persuasive dimensions coexist within interactive systems (Krippendorff, 2023. Rather than functioning as isolated linguistic categories, these communicative functions can be interpreted as operational design dimensions that organize meaning across multimodal interfaces.

In digital environments—particularly in health applications where comprehension, trust, and behavioral engagement are critical—the interaction between referential, emotive, conative, phatic, metalinguistic, and poetic functions structures how users decode interface signals and construct situational meaning. Recent research in communication design and human–computer interaction suggests that Jakobson's model remains highly relevant for understanding how digital artifacts guide interpretation and coordinate user action across heterogeneous audiences and cultural contexts (de Souza, 2005; Krippendorff, 2023).

By integrating these communicative functions with Lotman's concept of the semiosphere, the present study conceptualizes digital health interfaces as dynamic semiotic systems in which signs interact to generate comprehension, emotional alignment, and behavioral engagement. In this sense, usability emerges not simply from interface efficiency but from the coherence of the communicative system that connects signs, users, and contexts of interpretation.

Figure 1 synthesizes these communicational functions within the context of health app development, illustrating how interface elements simultaneously perform informational, emotional, motivational, and relational roles in the user–system interaction. In doing so, the figure visually anticipates the semiotic–pragmatic framework later operationalized through the Semiotic Framework for Usability (SFU), directly aligning the theoretical foundations introduced in the abstract with the analytical structure of the study.

Figure 1: Communicational Functions in Health App Development.



1.2. Rationale and Research Gap

The problem addressed by this research is that conventional usability frameworks treat interfaces as neutral technical mediators rather than as communicative systems that actively construct meaning. While extensive work has examined usability from ergonomic, cognitive, and interaction design perspectives, there remains a critical gap in understanding and operationalizing interfaces as semiotic systems—structured environments where signs, symbols, and metaphors function as the primary medium through which system intentions are communicated and user understanding is negotiated.

This gap has both theoretical and practical dimensions. Theoretically, while semiotics has been extensively developed in linguistic, cultural, and media studies (Barthes, 1977; Eco, 1976; Lotman, 1990), and while human-computer interaction has acknowledged the role of signs in interface design (de Souza, 2005), systematic frameworks for applying semiotic principles to usability evaluation and design in health contexts remain underdeveloped. Practically, design teams lack operationalized methodologies for identifying, analyzing, and addressing semiotic barriers—the breakdowns in meaning-making that occur when interface signs fail to communicate designer intentions to users across diverse cultural, cognitive, and experiential contexts.

Recent advances in affective computing, accessibility standards, and user-centered design have begun to address some aspects of this challenge. However, these approaches typically focus on isolated dimensions—emotional response, accessibility compliance, or user preferences—without integrating them within a unified communicative framework that treats meaning-making as the central usability concern. This fragmentation limits both theoretical understanding and practical application, as designers lack conceptual tools for understanding how syntactic (structural), semantic (symbolic), and pragmatic (contextual) dimensions of interface communication interact to produce user experience outcomes.

To address this limitation, the present study proposes a semiotic–pragmatic reconceptualization of usability that integrates Jakobson's functional model of communication with Lotman's theory of the semiosphere. From this perspective, digital interfaces are not neutral technical artifacts but communicative environments where meaning emerges through the interaction of signs, users, and cultural contexts.

Building upon this theoretical integration, the research introduces the *Semiotic Framework for Usability (SFU)* as a structured analytical model capable of identifying semiotic barriers and guiding the design of communicatively coherent digital health systems. By linking syntactic organization, semantic clarity, and pragmatic contextualization within a single interpretative framework, SFU provides a methodological bridge between semiotic theory and empirical usability evaluation.

This approach directly supports the broader conceptual orientation articulated in the title of this study—*From Signs to Systems*—by demonstrating how individual interface signs operate collectively as communicative structures that shape user interpretation, trust formation, and behavioral engagement in digital health environments.

1.3. Research Objectives and Questions

This research responds to the identified gap by developing and validating the Semiotic Framework for Usability (SFU), which reconceptualizes digital health interface design as a communicative practice embedded within a semiosphere—a structured meaning-space where designers, applications, and users negotiate understanding through sign systems. The framework is grounded in Jakobson's (1960) model of communicative functions and Lotman's (1990) concept of the semiosphere as a prerequisite for meaning production.

The study addresses three primary research objectives:

To develop and operationalize SFU as a systematic framework for analyzing interface usability across syntactic, semantic, and pragmatic semiotic dimensions.

To empirically validate the framework through controlled comparison of standard versus semiotic-enhanced interfaces across diverse user profiles and real-world health applications.

To identify specific semiotic design strategies that demonstrably improve comprehension, reduce cognitive load, enhance satisfaction, and increase task completion in digital health contexts.

These objectives are operationalized through four research questions:

RQ1: What types of semiotic barriers (syntactic, semantic, pragmatic) most frequently impede user comprehension and task completion in current digital health applications?

RQ2: How do semiotic design interventions (visual glossaries, metaphorical alignment, redundant coding, adaptive feedback) affect measurable usability outcomes (cognitive load, satisfaction, task completion)?

RQ3: To what extent do improvements in semiotic clarity differentially benefit users with diverse accessibility needs, technological literacy levels, and cultural backgrounds?

RQ4: What systematic guidelines can be derived from SFU analysis for designing culturally sensitive, symbolically coherent digital health interfaces?

1.4. Significance and Contribution

This research makes several significant contributions to digital health interface design, human-computer interaction theory, and software engineering practice. First, it provides the first systematic empirical validation of semiotic principles applied to health interface usability, demonstrating that meaning-centered design approaches yield measurable improvements across cognitive, affective, and behavioral dimensions. This extends theoretical understanding of usability from a primarily functional construct to a fundamentally communicative one.

Second, the study offers a transferable methodological framework (SFU) that can be integrated into existing quality standards (ISO/IEC, 2006) and accessibility guidelines (WCAG 2.2), providing design teams with concrete analytical tools for identifying and addressing semiotic barriers. The framework is intentionally designed for scalability across different health domains—telehealth, patient portals, clinical decision support, health education—and different cultural contexts.

Third, the research contributes to software engineering and UX/UI education by demonstrating that interface design competency requires not only technical implementation skills but also communicative literacy—the capacity to understand how signs function, how meaning is negotiated, and how cultural and contextual factors shape interpretation. This aligns with emerging calls for more humanistic, reflective, and socially situated approaches to computing education (Clear et al., 2020). By integrating these perspectives, the study contributes to educational discussions on how future software engineers are trained to design meaningful interactive systems (Nöth, 1995).

Finally, in the context of mental health applications specifically, the research addresses an ethical imperative. When users misunderstand interface communications in health contexts, the consequences extend beyond usability frustration to potential clinical harm—missed medications, misinterpreted symptoms, inappropriate self-treatment, or premature treatment abandonment. By establishing that semiotic clarity is not a luxury but a fundamental requirement for responsible health interface design, this research contributes to the broader goal of digital health equity and patient safety.

1.5. Paper Organization

The remainder of this paper is organized as follows. Section 2 presents the theoretical foundations and reviews relevant literature, introducing key semiotic perspectives and their relevance for digital interface design. Section 3 describes the research methodology, including participant recruitment, application selection criteria, data collection instruments, and analytical procedures. Section 4 presents the empirical findings, organized according to the research questions and the syntactic, semantic, and pragmatic dimensions of the Semiotic Framework for Usability (SFU). Section 5 discusses the theoretical and practical implications of the results, situates the findings within existing research, and addresses study limitations. Section 6 concludes by synthesizing the study's contributions and outlining recommendations for design practice, education, and future research.

2. Theoretical Framework

2.1. Foundational Semiotic Theory

Semiotics, as the systematic study of signs and signification processes, provides essential theoretical foundations for understanding how meaning is produced, transmitted, and interpreted in communicative systems (Eco, 1976; Peirce, 1931–1958). Cobley et al. (2002) emphasize that semiotics extends beyond linguistic analysis to encompass all systems of meaning-making, including visual, gestural, and multimodal communication—a scope particularly relevant for contemporary digital interfaces. In the Saussurean tradition, signs are understood as arbitrary relationships between signifiers (forms) and signifieds (concepts), whose meaning is determined not by inherent properties but by their position within structured systems of difference (de Saussure, 1983). Peirce's triadic model extends this by introducing the interpretant—the mental effect produced in the interpreter—emphasizing that signification is not a dyadic relation but a process involving sign, object, and interpretation.

Eco's (1976) theory of codes and the production of signs further develop this foundation by arguing that communication requires shared codes—culturally established systems of correlation between expressions and content—that enable decoding. Critically, Eco demonstrates that codes are never completely shared, and that interpretation always involves both coded competence and inferential processes. This theoretical position has direct implications for interface design: if interface elements function as signs, their effectiveness depends not on their inherent clarity but on the extent to which designers and users share interpretive codes.

In recent years, semiotic analysis has expanded beyond traditional linguistic domains to include digital environments and online behavior. Meta-analytic evidence demonstrates that semiotic variables—such as symbolic aesthetics, metaphorical coherence, and visual consistency—significantly influence decision-making, trust, and adherence in digital systems (Aguirre-Urreta & Marakas, 2025; Rönkkö et al., 2022). This expansion is particularly relevant for health applications, where user interpretation directly affects engagement and behavioral outcomes.

Lotman's (1990) concept of the semiosphere extends semiotic theory into cultural and spatial dimensions. The semiosphere is defined as the semiotic space outside of which semiosis cannot exist—it is simultaneously the result and the condition for the development of communication. Lotman argues that meaning emerges at boundaries where different semiotic systems encounter each other, requiring translation. Applied to interface design, this suggests that the interface itself constitutes a boundary zone where the semiotic system of software logic encounters the diverse semiotic systems of users' cultural, experiential, and cognitive contexts. Effective interfaces, from this perspective, are those that successfully translate across these boundaries.

Building on this foundation, Torkildsby et al. (2020) provides a framework for analyzing nonverbal interaction in interfaces, highlighting how iconography, gestures, and visual feedback operate as complete semiotic systems in contexts where textual language is minimal—a condition increasingly common in mobile health applications designed for diverse populations with varying literacy levels and linguistic backgrounds.

Leeds-Hurwitz (1993) argues that "communication is too often taken for granted when it should be torn to pieces. Semiotics is an appropriate tool to dismantle and unlock interactional meanings." This perspective is particularly relevant for health interface design: communication cannot be reduced to technical transmission but must be understood as a meaning-making process where signs, symbols, and interface elements mediate understanding between designers and users. When communication systems fail—when signs are ambiguous or contextually inappropriate—usability degrades even when technical functionality remains intact.

2.2. Semiotics in Human-Computer Interaction

The application of semiotic theory to human-computer interaction emerged prominently through de Souza's (2005) Semiotic Engineering, which conceptualizes HCI as a particular case of computer-mediated human communication. In this framework, interface designers send messages to users through the interface itself, which serves as their deputy in communicating their design vision, system logic, and intended interaction patterns. Users, in turn, interpret these messages to construct mental models of system functionality and appropriate use. Usability problems, from this perspective, are communication failures—instances where designers' intended messages are not successfully transmitted or are systematically misinterpreted.

Scolari (2009) extends semiotic engineering by conceptualizing interfaces as cultural texts embedded within users' semiospheres. His work emphasizes that interface design is not only a technical practice but also a cultural communication process, where visual and verbal elements function as symbolic translation systems mediating between software logic and user cognition. This perspective situates usability as dependent on the interface's capacity to successfully translate across semiotic boundaries separating designers' intended meanings from users' diverse interpretive frameworks.

Empirical applications of semiotic analysis to interface evaluation have demonstrated its capacity to reveal usability issues that traditional heuristic methods overlook. Derboven et al. (2012) conducted semiotic analysis of multi-touch interfaces, identifying how gestural signs carry cultural connotations that affect learnability and user preference. Their findings indicate that interaction patterns perceived as "natural" in one cultural context may be experienced as counterintuitive in another, suggesting that gesture design requires explicit consideration of embodied cultural codes.

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Riemer and Peter (2021) and Kautz (2021) applied the semiotic square—a structural model derived from Greimas' work—to analyze meaning structures on digital platforms, demonstrating how contradictions and tensions in sign systems shape user experience and platform affordances. Their analysis reveals that platforms often encode competing value systems (e.g., privacy vs. connectivity, autonomy vs. guidance) that create semiotic tensions users must navigate. In health specifically, such tensions might involve trade-offs between medical authority and personal agency, or between clinical precision and emotional reassurance.

Recent empirical work by Kohn et al. (2022) systematically reviewed learning analytics in biomedical education interfaces, finding that symbolic representation of complex medical data significantly affected comprehension and decision-making patterns among both students and practitioners. Their meta-analysis of 47 studies revealed that interfaces employing consistent metaphorical frameworks achieved 34% higher comprehension scores than those using abstract or inconsistent visualizations, with effects most pronounced among novice users. This provides direct empirical support for the hypothesis that semiotic coherence—the systematic alignment of signs within a unified conceptual framework—constitutes a measurable determinant of interface effectiveness.

Lim (2018) proposes a design framework that explicitly integrates semiotic principles with user-centered design methodologies, arguing that interaction models must account for meaning-making processes rather than assuming transparent communication. His framework emphasizes conceptualizing and materializing interactions through iterative semiotic evaluation, ensuring that designed artifacts successfully communicate intended affordances and interaction possibilities across diverse user populations.

2.3. Multimodality and Visual Grammar

Kress and van Leeuwen's (2006, 2021) theory of multimodality provides essential frameworks for analyzing how different semiotic modes—visual, linguistic, spatial, gestural, and auditory—combine to produce meaning in contemporary communicative practices. Their visual grammar analyzes how layout, color, typography, and compositional structure convey social meanings such as authority, intimacy, urgency,

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and credibility. In interface contexts, these visual-grammatical choices directly affect user interpretation of information hierarchy, system trustworthiness, and appropriate action.

Mayer's (2020) cognitive theory of multimedia learning provides empirical foundation for multimodal design principles. His research demonstrates that coordinating verbal and visual information reduces cognitive load and improves comprehension, particularly when redundant presentation across modes allows users to construct integrated mental models. In health interface contexts, these findings suggest that critical information should be encoded multimodally—combining visual representations with textual explanations—to support diverse learning styles and reduce interpretive uncertainty.

The concept of modal affordance is particularly relevant for health interfaces. Different semiotic modes offer different potentials for meaning making: visual modes excel at spatial relationships and emotional tone, linguistic modes at logical argumentation and qualification, gestural modes at direct action and embodied engagement. Effective multimodal design orchestrates these affordances to support both cognitive understanding and emotional alignment—requirements especially critical in mental health applications where users must simultaneously process medical information and manage affective states.

Edwards-Groves (2012) examined interactive creative technologies in educational contexts, documenting how multimodal literacies—the capacity to navigate meaning across visual, textual, and interactive modes—(The New London Group, 1996) constitute a prerequisite for effective technology use. Their longitudinal study of 156 students demonstrated that explicit instruction in multimodal interpretation improved both task performance (27% increase) and sustained engagement (41% increase) with educational technologies. Translated to health contexts, these findings suggest that interfaces incorporating explicit multimodal support—such as coordinated visual-textual redundancy or progressive disclosure mechanisms—may reduce interpretive burden and increase accessibility.

2.4. Affect, Emotion, and Health Communication

The relationship between emotional states and interface interaction has received increasing theoretical and empirical attention. Barrett's (2017) constructed theory of emotion provides a neuroscientific foundation for understanding how emotional experiences emerge from predictive processes that integrate interoceptive signals, contextual cues, and conceptual knowledge. Applied to interface interaction, this perspective suggests that emotional responses to health applications are not merely reactions to informational content, but predictive interpretations constructed from interface signs combined with users' prior experiences, bodily states, and health-related concerns.

Within human–computer interaction research, affect has been increasingly recognized as a fundamental mediator of technology use. Chamberlain et al. (2017) propose an affect-centered approach to information systems, arguing that affective responses shape how users interpret, trust, and engage with digital environments. Their work demonstrates that users' affective reactions to interface aesthetics, interaction rhythms, and feedback mechanisms influence long-term engagement patterns, often independently of purely functional evaluations of system utility. These findings challenge conventional assumptions that rational assessments of functionality alone drive technology adoption, suggesting instead that affective alignment between users and digital systems plays a co-determinant role in sustained interaction.

Research examining emotion in health communication further reinforces the importance of these dynamics. Barra Almagiá (2003) and Ramos Linares et al. (2009) show that persistent negative emotional states—such as fear, sadness, anger, or anxiety—can function as risk factors for both physical and mental illness, whereas positive emotional experiences are associated with improved coping mechanisms, treatment adherence, and recovery processes. In digital health environments, where users frequently interact with systems during moments of psychological vulnerability, the emotional tone of interface communication therefore becomes particularly significant.

Recent work on inclusive digital health design has extended this perspective by demonstrating that interfaces designed to accommodate diverse cognitive, sensory, and cultural profiles can significantly reduce user anxiety while strengthening perceptions of trust and reliability (Xie et al., 2025). Inclusive design strategies—such as clear language, predictable interaction patterns, and accessible visual hierarchies—help create communicative environments that users perceive as supportive rather than intimidating, thereby improving both comprehension and engagement.

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From a semiotic perspective, these findings suggest that emotional responses emerge through the interaction between interface signs and users' interpretive frameworks. Visual elements such as color palettes, typography, iconography, and animation rhythms function not only as aesthetic features but also as affective signals that shape perceptions of safety, urgency, credibility, and empathy within digital environments.

These affective dynamics reinforce the central premise of the Semiotic Framework for Usability (SFU) proposed in this study: usability emerges not only from functional efficiency but from the successful orchestration of cognitive, semiotic, and emotional communication within the digital health interface.

2.5. Usability Frameworks and Standards

Contemporary usability standards—particularly ISO 9241-210:2019 (Ergonomics of human-system interaction) and ISO 25010 (Systems and software quality)—provide widely adopted definitions and evaluation criteria for assessing interactive systems. ISO 9241-210 defines usability as "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use." These frameworks acknowledge the importance of context of use and user diversity, and they provide measurable indicators such as task completion time, error rates, and user satisfaction for evaluating system performance.

While these metrics are essential for benchmarking interaction efficiency and guiding iterative design processes, they often treat meaning-making as an implicit process. In practice, usability evaluation frequently focuses on performance outcomes without systematically examining how users interpret the symbolic and communicative structures through which digital interfaces convey information and instructions.

Despite these advances, existing usability standards rarely provide analytical tools for examining how meaning and emotion are constructed within interface communication. In many usability assessments, communicative interpretation remains a "black box": designers observe whether users succeed or fail in tasks but lack structured methods for analyzing how interface signs contribute to misunderstanding, ambiguity, or misinterpretation.

The Web Content Accessibility Guidelines (WCAG 2.2) extend usability considerations by emphasizing perceivability, operability, understandability, and robustness for users with disabilities. Among these principles, understandability comes closest to acknowledging the interpretive dimension of interaction, requiring that information and user interface operations be clear and predictable. However, WCAG primarily specifies functional accessibility requirements rather than providing methodological guidance for ensuring symbolic clarity, metaphorical transparency, or culturally interpretable visual communication.

The Semiotic Framework for Usability (SFU) proposed in this study is designed to complement and extend these standards by introducing analytical tools that explicitly address the communicative dimension of interface interaction. Rather than replacing established usability metrics, the framework adds a semiotic layer of analysis that examines how interface elements encode, transmit, and transform meaning within specific cultural and contextual environments.

Formal analytical approaches can further strengthen qualitative semiotic evaluation. Ganter and Wille's (1999) Formal Concept Analysis (FCA) provides a mathematical method for modeling conceptual relationships and hierarchical structures within complex information systems. When applied to interface content, iconographic systems, and natural language components, FCA enables systematic mapping of semantic relationships between interface elements and user interpretations. This formalization helps identify structural ambiguities, conceptual gaps, and inconsistencies that may otherwise remain difficult to detect through purely qualitative analyses.

Such analytical integration is particularly relevant in digital health contexts, where clarity of meaning, interpretability of symbols, and consistency of communicative signals directly affect users' ability to understand medical information and perform health-related actions accurately.

These limitations become especially significant in the context of digital health technologies, where misunderstandings in interface communication may directly affect users' health decisions, emotional states, and treatment adherence. Consequently, examining the communicative and semiotic dimensions of digital health applications becomes essential for understanding persistent usability challenges in this domain.

2.6. Digital Health Applications: Specific Challenges

Literature examining digital health applications has identified several persistent challenges that conventional usability approaches struggle to address. Although the technical reliability and availability of mobile health (mHealth) systems have increased significantly in recent years, problems related to user comprehension, engagement, and sustained interaction remain widespread.

Torous et al. (2021) conducted a systematic review of mental health applications and found that, despite improvements in functionality and platform stability, user engagement remains limited. Their analysis of more than 500 applications revealed that 68% employed specialized medical terminology without adequate explanation, 72% relied on abstract visualizations lacking interpretive support, and only 14% offered culturally adapted content for diverse user populations. These findings suggest that many usability issues in health applications stem not from technical limitations but from communicative mismatches between interface design and users' interpretive frameworks.

Molina-Recio et al. (2020) proposed a user-centered design methodology for health applications emphasizing multi-stakeholder participation and iterative development processes. Their four-session design model demonstrates improvements in user satisfaction and acceptability; however, it remains primarily focused on functional requirements and user preferences rather than on the systematic analysis of how health concepts are semiotically encoded and interpreted within interfaces. Integrating explicit semiotic evaluation into each iteration stage could strengthen the communicative clarity of such methodologies.

Recent global research by Moungui et al. (2024) further highlights the importance of cultural and contextual interpretation in mHealth adoption. Their cross-national study across twelve countries found that applications adapted to local cultural contexts achieved sustained usage rates 2.3 times higher than non-adapted counterparts, even when their functional capabilities were identical. This suggests that cultural relevance—an implicitly semiotic phenomenon involving shared meanings, symbols, and communicative conventions—plays a decisive role in determining whether health technologies become integrated into everyday health practices.

Selwyn (2016) offers an additional perspective by emphasizing that digital technologies in educational and health contexts function not merely as tools but as mediators of learning and meaning-making. From this perspective, interface design carries implicit pedagogical assumptions about how users should interpret information, learn new concepts, and make decisions. Health applications that support self-management or behavioral change therefore embed particular models of patient agency, health literacy, and appropriate help-seeking behaviors.

Taken together, these studies indicate that many of the challenges observed in digital health adoption cannot be fully explained through traditional usability metrics alone. Instead, they highlight the need for analytical frameworks capable of examining how health information is semiotically structured and communicated through digital interfaces.

2.7. Theoretical Framework Synthesis: The Semiotic Framework for Usability (SFU)

Synthesizing these theoretical foundations, we propose the Semiotic Framework for Usability (SFU) as an integrative model for analyzing and designing health interface communication. The framework builds upon the theoretical traditions discussed in previous sections—semiotic theory, affective communication, and usability research—by integrating them into a unified analytical structure capable of examining how meaning, emotion, and action are coordinated within digital health interfaces.

In contrast to conventional usability frameworks that primarily evaluate performance outcomes, SFU focuses on the interpretive processes through which users construct meaning from interface signs. This perspective recognizes that usability emerges not only from technical efficiency but from the successful alignment between interface communication and users' cognitive, cultural, and emotional interpretive frameworks.

SFU is structured across three classical semiotic dimensions, here operationalized specifically for interface analysis:

Syntactic Dimension

This level analyzes the formal organization and structural relationships among interface elements—layout hierarchies, navigation patterns, information architecture, visual consistency, and interaction sequencing. From a semiotic perspective, this dimension corresponds to the structural grammar of the interface, shaping how visual and interactive elements are arranged to guide perception and interaction.

Syntactic Analysis Asks

- Are interface elements organized according to coherent structural principles?
- Do recurring patterns facilitate learning?
- Are relationships among elements clearly indicated?

Semantic Dimension

This level examines how meaning is encoded in and decoded from interface signs—icon symbolism, color associations, metaphorical mappings, gestural conventions, and linguistic choices. At this level, the interface functions as a system of signs through which health-related concepts are communicated to users. The effectiveness of interface communication therefore depends on the degree to which these symbolic representations correspond to users' existing conceptual and cultural knowledge structures.

Semantic analysis asks

- What meanings are interface elements intended to convey?
- Are these meanings successfully communicated across diverse user populations?
- Where do semantic ambiguities or cultural misalignments occur?

Pragmatic Dimension

This level investigates how interface signs function in actual contexts of use—how user characteristics (age, cultural background, health literacy, technological experience, accessibility needs), situational factors (location, time pressure, emotional state), and usage goals shape interpretation and action. This dimension recognizes that meaning is not produced solely within the interface itself but emerges through interaction between the system and the user's real-life circumstances and experiences.

Pragmatic Analysis Asks

- How do contextual variables affect sign interpretation?
- Do interface communications appropriately account for use contexts?
- How do users integrate interface meanings with their lived health experiences?

Together, these three dimensions enable a systematic examination of interface communication across structural, symbolic, and contextual levels. By articulating syntactic organization, semantic interpretation, and pragmatic use conditions, the SFU framework provides a comprehensive analytical lens for understanding how usability emerges through the interaction between interface design and user meaning-making processes. This triadic structure aligns with classical semiotic theory, particularly the tradition established by Morris and later developed in communication and interface studies, where syntactic relations organize signs, semantic relations establish meaning, and pragmatic relations connect signs to their users and contexts of interpretation.

To operationalize these analytical dimensions within a design-oriented perspective, the Semiotic Framework for Usability (SFU) is represented graphically in Figure 2. The diagram illustrates how syntactic, semantic, and pragmatic layers interact within the broader communicative ecosystem of interface design, conceptualized here as a design semiosphere. Rather than functioning as isolated analytical levels, these dimensions operate as interdependent processes that guide the transformation of signs into functional interface systems capable of supporting meaningful user interaction.

SFU additionally integrates Jakobson's (1960) six communicative functions as analytical categories for evaluating how interface elements fulfill communicative purposes: referential (conveying medical information), emotive (expressing or eliciting emotional responses), conative (directing user action), phatic (maintaining contact or engagement), metalinguistic (explaining interface conventions), and poetic or aesthetic (creating affective tone and cultural resonance).

Building on this communicative perspective, interface components can be interpreted not only as structural elements but also as communicative acts directed toward users. Table 1 operationalizes Jakobson's six communicative functions by mapping each function to its specific role and representative manifestations within digital health interface design.

Figure 2: Framework for the Development of Systems from a Semiotic Perspective.

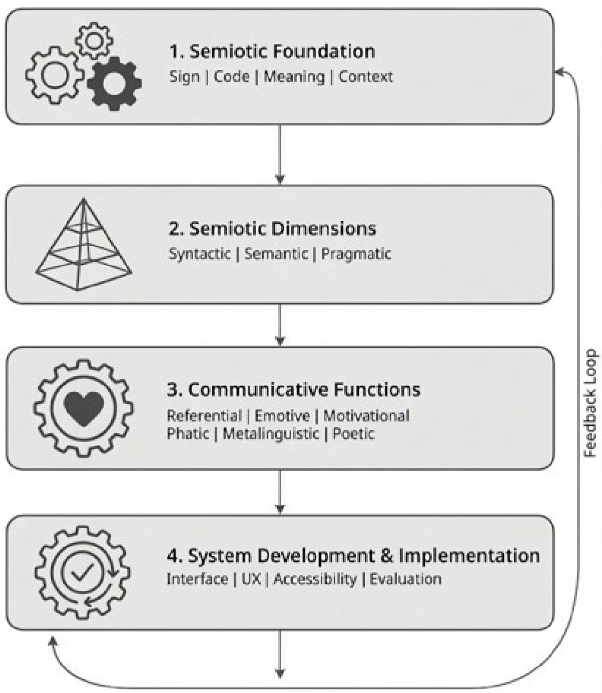


Table 1: Functions of communication in the perspective of semiotics.

Function	Role in Health App Interface	Example
Referential	Conveys medical facts or advice	"Take 1tablet every 8 hours"
Emotive	Express user's or app's emotional tone	Emojis, color changes, notifications
Motivational	Encourages user action	"Schedule your next appointment now"
Phatic	Maintains interaction	Alerts, confirmation sounds
Metalinguistic	Explains meaning of icons/symbols	Tooltip explaining a heart icon
Poetic	Adds aesthetic/emotional value	Transitions, animations, metaphors

The framework explicitly conceptualizes the interface as embedded within a design semiosphere—a bounded meaning-space structured by technological constraints, usability requirements, regulatory standards, cultural norms, and health communication ethics. The success of interface communication depends on the degree to which this design semiosphere successfully translates across the boundary into users' diverse lived semiospheres. This translation requires explicit attention to potential barriers: semantic ambiguities, syntactic inconsistencies, pragmatic misalignments, and affective incongruence.

This framework is further enriched by research on multimodality as a foundational principle of digital communication. Studies by Area-Moreira and Pessoa (2012) emphasize the role of new technologies in enabling multimodal representation, while Edwards-Groves (2012) highlights the integration of linguistic, visual, spatial, gestural, and auditory meanings into unified communicative processes. Together, these perspectives support the argument that app development—particularly in health contexts—cannot be reduced to technical implementation but must be informed by semiotic principles that account for the full spectrum of communicative functions and sign systems.

3. Research Methodology

3.1. Research Design and Rationale

This study employs a convergent mixed-methods design combining qualitative semiotic analysis with quantitative experimental validation. This approach is justified by the research objectives: understanding the nature and impact of semiotic barriers requires interpretive depth that qualitative methods provide, while demonstrating the effectiveness of semiotic design interventions requires the rigor and generalizability of experimental comparison. The convergent design allows these complementary data types to be collected and analyzed in parallel, then integrated during interpretation to provide comprehensive answers to the research questions.

The methodological design is directly aligned with the Semiotic Framework for Usability (SFU) proposed in the theoretical section, enabling systematic examination of interface communication across syntactic, semantic, and pragmatic dimensions. Through this alignment, the study operationalizes semiotic theory within an empirical usability research context.

The study was organized in three phases:

(1) Exploratory semiotic analysis identifying communication patterns and barriers across existing applications;
(2) Intervention development and controlled comparison testing enhanced interfaces against standard versions; and
(3) Triangulated synthesis integrating quantitative usability metrics, qualitative user interpretations, and systematic semiotic evaluation.

This sequential structure ensures that the semiotic observations identified during exploratory analysis directly inform the design of interface improvements tested in the experimental phase.

This three-phase structure ensures that findings are both empirically robust and theoretically grounded.

3.2. Participant Recruitment and Characteristics

Participants were recruited through purposive sampling designed to ensure diversity across dimensions relevant to interface interpretation: age, gender, educational background, technological experience, health literacy, and accessibility needs. Recruitment occurred through mental health support organizations, university health centers, and community health clinics in three urban areas representing different socioeconomic profiles.

The final sample comprised 30 participants (15 women, 15 men) aged 18-72 (M=38.4, SD=15.7). Educational backgrounds ranged from secondary education incomplete (N=4) through postgraduate degrees (N=7). Self-reported technological experience ranged from minimal (smartphone use only, N=8) through advanced (professional technology work, N=6). Health literacy was assessed using the eHealth Literacy Scale (eHEALS), with scores ranging from 18 to 40 (M=28.6, SD=6.3), indicating moderate to high health literacy across the sample.

Crucially, the sample included participants with diverse accessibility needs: 7 participants reported color vision deficiency, 5 reported motor coordination challenges affecting touch precision, 4 reported mild cognitive difficulties affecting working memory or processing speed, and 3 reported visual acuity requiring assistive magnification. This diversity was intentional, as one research objective was to examine how semiotic interventions differentially affect users with varying perceptual and cognitive profiles.

Including participants with heterogeneous perceptual and cognitive characteristics was methodologically important for evaluating how interface signs are interpreted across diverse interpretive frameworks, a core concern of semiotic usability analysis.

All participants provided informed consent following protocols approved by institutional review boards. Participants received modest compensation (equivalent to USD $25) for their participation, which involved approximately 4 hours total across multiple sessions. No personally identifiable health information was collected.

3.3. Application Selection and Description

The study analyzed 11 mobile health applications selected to represent functional, cultural, and technological diversity within the digital health ecosystem. Selection criteria required that applications:

1. Were currently available on major platforms (iOS/Android);
2. Had substantial user bases (>100,000 downloads);
3. Maintained average ratings >3.0 stars;
4. Represented different health domains; and
5. Employed different interface paradigms.

Selected applications included: nutrition and lifestyle platforms (Lifesum, MyFitnessPal) emphasizing personalized goal-setting and food logging; system-level health hubs (Google Health Connect, Apple HealthKit) designed to centralize and share health data across applications; device-linked monitoring tools (Salud de Honor) integrating biometric tracking from wearables; comprehensive fitness environments (Health Infinity) combining multiple health functions; mental health and wellbeing applications (Calm) foregrounding emotional regulation and guided meditation; medical professional platforms (Medscape, GNU Health) targeting healthcare providers; patient management tools (CareZone) supporting medication tracking and care coordination; and clinical record systems (OpenMRS Android Client) designed for low-connectivity contexts.

This heterogeneous selection enabled examination of semiotic usability across multiple healthcare communication scenarios, including preventive health, self-monitoring, clinical information management, and emotional wellbeing support.

This diverse sample enabled examination of semiotic usability across varying domains—preventive health, chronic disease management, mental health support, professional practice, and institutional care—while maintaining a consistent analytical lens grounded in SFU.

Each application was independently evaluated by three trained coders over multiple sessions spanning three months, generating approximately 10,000 interaction events for analysis.

3.4. Data Collection Instruments

Data collection employed multiple instruments designed to capture different dimensions of interface communication and usability:

Semiotic coding protocol: A structured codebook was developed based on SFU dimensions (syntactic, semantic, pragmatic) and Jakobson's communicative functions. Coders systematically analyzed interface elements (icons, colors, gestures, text, metaphors, layout) recording their apparent intended meaning, observed user interpretations, identified ambiguities, and classified communication barriers.

The coding protocol also incorporated indicators for identifying communicative misalignment, defined as cases where the intended meaning of an interface sign differed from the interpretation reported by users.

Coding was conducted in NVivo 12, with intercoder reliability established through independent coding of 20% of interactions (Cohen's κ=0.82, indicating strong agreement).

A/B experimental comparison: For four selected applications representing different health domains, semiotic-enhanced versions were developed incorporating visual glossaries, metaphorical alignment, redundant coding (visual + textual), and adaptive feedback. Participants were randomly assigned to interact with either standard or enhanced versions while completing matched task sets. Task completion rates, time-on-task, and error frequencies were recorded.

These semiotic enhancements were specifically designed to address the types of communication barriers identified during the exploratory semiotic analysis phase.

NASA Task Load Index (NASA-TLX): Cognitive load was assessed using the validated NASA-TLX instrument, which measures six dimensions of workload: mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants completed NASA-TLX immediately following each task set, allowing comparison of cognitive load between standard and enhanced interfaces.

Satisfaction and comprehension surveys

Custom 5-point Likert scales assessed:

- Overall satisfaction
- Perceived ease of use
- Confidence in understanding
- Trust in information accuracy
- Emotional comfort
- Likelihood of sustained use

Additionally, comprehension was directly tested through questions asking participants to explain the meaning of specific interface elements (icons, colors, gestures) they had encountered.

This comprehension component allowed direct measurement of whether interface signs were interpreted as intended by designers.

Longitudinal usage Diaries

Participants maintained structured diaries over two weeks, recording each interaction instance, purposes, encountered difficulties, emotional responses, and interpretation uncertainties. Diaries provided longitudinal data on how understanding evolves and where persistent confusion remains.

Semi-structured Interviews

Individual interviews (45-60 minutes) explored participants' interpretive processes, cultural associations with interface signs, comparisons between standard and enhanced versions, and suggestions for improvement. Interviews were audio-recorded, transcribed, and thematically analyzed using template analysis.

3.5. Analytical Procedures

Data analysis proceeded through three integrated stages corresponding to the convergent mixed-methods design:

Stage 1—Qualitative Semiotic Analysis: NVivo-coded interface evaluations, interview transcripts, and diary entries were analyzed using template analysis. Initial templates derived from SFU categories were iteratively refined as emergent themes revealed additional communicative patterns.

Special analytical attention was given to identifying recurring semiotic barriers and classifying them according to their syntactic, semantic, or pragmatic origin within the SFU framework.

Analysis focused on identifying recurrent semiotic barriers, characterizing their types (syntactic/semantic/pragmatic), and documenting how different user profiles interpreted identical interface signs.

This stage produced a comprehensive taxonomy of semiotic barriers observed across the 11 applications.

Stage 2—Quantitative Comparison Analysis: A/B experimental data (task completion rates, error frequencies, completion times) and NASA-TLX scores were analyzed using mixed-effects models accounting for repeated measures and participant characteristics. Independent variables included interface version (standard vs. enhanced), application domain, and user accessibility profile.

This statistical model allowed estimation of the specific contribution of semiotic interface improvements to observed usability outcomes.

This stage produced quantitative effect sizes for semiotic design interventions across different usability dimensions.

Stage 3—Triangulated Integration: Qualitative and quantitative findings were systematically integrated through explanation-building triangulation. Quantitative patterns (e.g., "enhanced interfaces reduce cognitive load by 39%") were explored and explained through qualitative data revealing mechanisms (e.g., "visual glossaries eliminate interpretive uncertainty"). Conversely, qualitative themes (e.g., "users with color blindness experience semantic exclusion") were validated and quantified through experimental comparisons.

This triangulated interpretation ensured that statistical outcomes could be linked to identifiable semiotic mechanisms within interface communication.

Statistical analyses employed R 4.3.1 with packages lme4 (mixed models), ggplot2 (visualization), and psych (reliability). Effect sizes are reported as Cohen's d for mean differences and as odds ratios for categorical outcomes. Significance threshold was set at $\alpha=0.05$ with Holm-Bonferroni correction for multiple comparisons. Qualitative analysis-maintained audit trails documenting coding decisions, theme development, and interpretive warrants to ensure transparency and dependability.

4. Results and Findings

Results are organized by research questions, progressing from identification of semiotic barriers (RQ1) through experimental validation of design interventions (RQ2), differential effects across user profiles (RQ3), and systematic design guidelines (RQ4). All statistical comparisons report effect sizes alongside significance tests to support practical interpretation.

Consistent with the Semiotic Framework for Usability (SFU), results are interpreted through the interaction between syntactic, semantic, and pragmatic dimensions of interface communication. In addition, findings are discussed in relation to the semiotic perspectives of Yuri Lotman and Roman Jakobson, particularly regarding the role of sign interpretation within communicative systems and the potential for misalignment between encoded and decoded meanings.

4.1. RQ1: Types and Frequency of Semiotic Barriers

Systematic semiotic coding across 11 applications and approximately 10,000 interaction events identified 347 distinct instances of communication barriers that impeded user comprehension, increased cognitive load, or resulted in task errors. These barriers were classified according to SFU dimensions with the following distribution: semantic barriers (42%, N=146), pragmatic barriers (31%, N=108), and syntactic barriers (27%, N=93).

This distribution confirms that most usability failures in digital health interfaces occur not at the level of technical interaction but at the level of meaning construction, supporting the semiotic hypothesis that usability problems often emerge from interpretive misalignment between system designers and users.

Semantic barriers constituted the most frequent obstacle to interface comprehension. These involved four primary subtypes:

Ambiguous iconography (38% of semantic barriers): Icons whose intended meanings were not reliably interpreted across users. For example, a "leaf" icon was interpreted variously as nutrition, environmental health, organic food, nature therapy, or freshness depending on user background and application context.

From a semiotic perspective, these variations illustrate what Lotman conceptualizes as interpretive plurality within a semiosphere, where identical signs generate multiple possible readings depending on the cultural and cognitive background of interpreters.

Cultural color coding (27%): Color associations that varied across cultural groups. Red signals for health metrics were interpreted as "danger/stop" by Western users but as "vitality/celebration" by some East Asian users, leading to opposing emotional responses to identical information.

This finding reflects the culturally embedded nature of semiotic codes and demonstrates that color functions as a culturally mediated signifier rather than a universal signal.

Metaphorical misalignment (22%): Extended metaphors (e.g., "journey," "garden," "dashboard") that either lacked internal consistency or conflicted with users' health conceptualizations.

Users with chronic conditions sometimes rejected "journey" metaphors as implying temporary challenges rather than ongoing management.

Such mismatches reveal tensions between designer-intended narrative framing and the lived experiential models of users.

Technical jargon (13%): Medical or technical terminology presented without adequate contextual explanation, creating accessibility barriers for users with lower health literacy or non-native language speakers.

This barrier type illustrates breakdowns in Jakobson's referential function of communication, where the informational message fails to be decoded accurately by the receiver.

Pragmatic barriers reflected mismatches between interface assumptions and actual use contexts:

Contextual inappropriateness (41% of pragmatic barriers): Interface communications assuming circumstances not matching users' realities. For example, motivational messages encouraging "outdoor exercise" that failed to account for mobility limitations, unsafe neighborhoods, or climate constraints.

Literacy level mismatch (29%): Content complexity exceeding users' processing capacity, particularly under stress or emotional distress when applications were most likely to be consulted.

Temporal misalignment (18%): Interaction patterns requiring sustained attention or multi-step processes that conflicted with typical usage contexts (brief, interrupted sessions during daily routines).

Cultural frame conflicts (12%): Assumptions about health models, help-seeking behaviors, or emotional expression norms that diverged from users' cultural frameworks.

From Jakobson's perspective, these pragmatic mismatches correspond to disruptions in the contextual and conative functions of communication, where interface messages fail to align with the user's situational and behavioral context.

Syntactic Barriers Involved Structural Organization Issues

Inconsistent interaction patterns (47% of syntactic barriers): Gestures, navigation structures, or control locations that varied across application sections, requiring users to relearn interaction conventions.

Information hierarchy ambiguity (31%): Visual organization that failed to clearly indicate relative importance or functional relationships among interface elements.

Gestural convention violations (22%): Touch interactions conflicting with platform conventions or learned patterns from other applications.

These syntactic failures reflect breakdowns in the formal organization of the interface sign system, where structural inconsistencies disrupt users' ability to anticipate interaction patterns.

Table 2: Average User Ratings by Question Category.

		Average Values			
Apps	Open MRS	6.0	9.5	10.0	6.0
	HealthKit	8.3	7.0	4.0	3.7
	Medsscape	8.0	8.5	7.0	6.0
	CareZone	8.0	9.0	6.7	6.7
	Lifesum	8.0	9.0	Nan	10.0
	GNU Health	5.0	7.0	4.0	8.0
	Myfitnesspal	8.2	8.3	7.9	5.4
	Health Connect	7.5	7.7	5.8	4.7
	Salud de Honor	8.7	6.7	7.0	4.2
	Health Infinity	7.1	7.6	6.4	5.3
	Calm	7.5	7.0	5.7	6.2
		Q1	Q2	Q3	Q4
	Questions				
Total records: ~10,000 interaction events.					

4.2. RQ2: Effects of Semiotic Design Interventions

A/B experimental comparison between standard and semiotic-enhanced interface versions revealed statistically significant improvements across all measured usability dimensions. Enhanced interfaces incorporated four primary design interventions derived from SFU analysis: visual glossaries providing contextual definitions for icons and symbols, metaphorical coherence ensuring consistent conceptual frameworks, redundant multimodal coding combining visual and textual information, and adaptive feedback responding to interaction patterns and user characteristics.

These interventions were designed to reduce interpretive ambiguity by strengthening the communicative alignment between interface signs and user meaning-making processes.

Cognitive Load: NASA-TLX composite scores decreased significantly for enhanced interfaces ($M=42.3$, $SD=8.7$) compared to standard versions ($M=69.1$, $SD=11.2$), representing a 39% reduction in reported cognitive load ($t(29)=8.34$, $p<.001$, Cohen's $d=2.68$). The largest individual subscale improvements occurred in Mental Demand (-44%) and Frustration (-47%), while Physical Demand showed minimal difference (-3%), confirming that improvements specifically targeted interpretive rather than motor challenges.

This pattern reinforces the semiotic interpretation that cognitive burden in interface interaction often arises from meaning negotiation rather than physical interaction complexity.

Task Completion: Enhanced interfaces achieved 92.3% task completion rates compared to 70.8% for standard versions ($\chi^2(1)=23.7$, $p<.001$, $OR=4.82$). Error frequencies similarly decreased: enhanced interfaces averaged 1.4 errors per task set ($SD=1.1$) versus 3.8 errors for standard versions ($SD=2.3$), $t(29)=5.12$, $p<.001$, $d=1.31$.

Error reduction was particularly pronounced for semantic errors (interpretation mistakes) rather than motor errors (mis-taps), confirming that improvements addressed meaning-making specifically.

User Satisfaction: Overall satisfaction ratings increased from 6.8/10 ($SD=1.9$) for standard interfaces to 9.1/10 ($SD=1.1$) for enhanced versions, representing a 2.3-point improvement ($t(29)=6.89$, $p<.001$, $d=1.44$). Confidence in understanding interface communications showed even larger gains: from 5.9/10 ($SD=2.1$) to 9.3/10 ($SD=0.9$), a 58% increase ($t(29)=8.91$, $p<.001$, $d=2.03$).

Symbolic Understanding: Direct comprehension tests asking participants to explain icon meanings revealed substantial improvements.

For standard interfaces:

- 71% icon comprehension (SD=18%)
- 68% color comprehension (SD=16%)

Enhanced versions achieved:

- 92% icon comprehension (SD=9%)
- 90% color comprehension (SD=10%)

Representing 25–30% relative improvements.

These results empirically confirm that semiotic clarity directly enhances symbolic comprehension, strengthening the communicative effectiveness of interface signs.

Table3: Semiotic Comprenhension (pre/post).

Indicator	Pre-redesign Post-redesign	Pre-redesign Post-redesign
Color Understanding (Semantics)	68 %	90 %
Understanding Abstract Icons	71 %	92 %
Overall average satisfaction (1–10)	6.8	9.1 %
Assistance for users with color blind- ness	0 %	100 %

4.3. RQ3: Differential Effects Across User Profiles

Mixed-effects modeling examined whether semiotic design improvements differentially benefited users with varying characteristics. Three user profile dimensions showed significant interaction effects with interface version: accessibility needs, technological experience, and health literacy.

Accessibility Needs: Users reporting color vision deficiency, motor coordination challenges, or cognitive processing difficulties showed significantly larger improvements from enhanced interfaces than users without these needs (interaction effect: $F(1,28)=12.4$, $p=.001$, $\eta^2=0.31$).

For users with accessibility needs:

- Cognitive load reduced by **52%**
- Task completion improved by **38%**

Compared to:

- **31%** cognitive load reduction for other users
- **24%** completion improvement.

This differential benefit demonstrates that semiotic design interventions function not only as usability improvements but also as mechanisms of inclusive interface communication.

Technological Experience: Paradoxically, users with minimal technological experience (smartphone-only use) showed larger satisfaction improvements (+2.8 points) than technologically advanced users (+1.7 points), though both groups improved significantly (interaction: $F(1,28)=6.8$, $p=.014$, $\eta^2=0.20$).

Qualitative evidence suggests that experienced users developed compensatory strategies for ambiguous interfaces, whereas novice users relied more directly on explicit semiotic cues provided by enhanced designs.

Health Literacy: Users with lower health literacy (eHEALS scores <26) showed equivalent task completion improvements to high-literacy users when using enhanced interfaces.

Standard version completion:
Low literacy 62.3%
High literacy 76.1%
Difference = 13.8 points
Enhanced version completion:
Low literacy 90.8%
High literacy 93.4%

Difference = 2.6 points

This convergence indicates that improved semantic transparency can partially neutralize disparities produced by knowledge or literacy differences.

4.4. RQ4: Systematic Design Guidelines

ntegration of semiotic analysis findings with experimental validation results yielded eight evidence-based design guidelines for digital health interfaces.

These guidelines translate semiotic theory into practical interface design principles.

1. **Multimodal redundancy:** Communicate critical information through multiple complementary modes (visual + textual + auditory when possible).
2. **Contextual glossaries:** Provide on-demand explanations for icons, symbols, colors, and terminology within the interaction context.
3. **Metaphorical consistency:** Ensure conceptual coherence when extended metaphors structure interface design.
4. **Cultural color awareness:** Avoid relying exclusively on color-based signification.
5. **Progressive disclosure:** Structure interaction complexity according to users' evolving interpretive competence.
6. **Explicit conventions:** Provide orientation for gesture meanings and navigation patterns.
7. **Emotionally calibrated aesthetics:** Align visual tone with the emotional context of healthcare interactions.
8. **Iterative interpretation testing:** Evaluate interface signs with diverse users to ensure that intended meanings are effectively decoded.

Taken together, these guidelines illustrate how semiotic analysis can inform systematic design strategies capable of improving usability, inclusivity, and communicative clarity in digital health environments.

5. Discussion

This research provides the first systematic empirical validation that semiotic principles, when operationalized through the Semiotic Framework for Usability (SFU), yield measurable improvements in digital health interface effectiveness. Rather than treating usability exclusively as a technical or ergonomic property of systems, the present findings demonstrate that interface effectiveness is fundamentally grounded in communicative processes through which designers encode meaning and users interpret it within specific cultural and cognitive contexts. The findings challenge conventional assumptions that usability is primarily a technical-functional concern, demonstrating instead that interface success depends fundamentally on communicative effectiveness—the degree to which designer intentions are successfully translated into user understanding across diverse interpretive contexts.

The finding that semantic barriers constitute 42% of identified usability obstacles aligns with and extends de Souza's (2005) Semiotic Engineering thesis that interfaces function as designer-to-user metacommunications. Within this perspective, digital interfaces can be interpreted as structured communicative artifacts through which designers explain their understanding of users, tasks, and system logic. Our results provide quantitative evidence that when these metacommunications fail—when signs are ambiguous, culturally misaligned, or contextually inappropriate—usability degrades measurably even when technical functionality remains intact. This empirical confirmation reinforces the argument that usability breakdowns often emerge not from system malfunction but from communicative misalignment between design intention and user interpretation. This validates treating interface design as fundamentally a communicative rather than merely an engineering challenge.

The differential effectiveness of semiotic interventions across user profiles (RQ3 findings) empirically confirms Lotman's (1990) theoretical proposition that meaning emerges at semiotic boundaries requiring translation. Users with accessibility needs, lower technological experience, or different cultural backgrounds can be conceptualized as occupying different positions within the semiosphere—positions from which the translation demands of standard interfaces are greater. From this perspective, usability barriers represent moments where translation between semiotic subsystems fails or becomes cognitively costly. Enhanced interfaces employing explicit semiotic support effectively reduce translation burden, enabling more equitable access to interface meaning. In this sense, semiotic design interventions operate as mediating mechanisms that stabilize meaning circulation within the broader communicative ecosystem of the interface semiosphere.

The integration of Roman Jakobson's communicative functions into the SFU framework further clarifies how interface signs operate as purposeful communicative acts. Results show that usability barriers frequently correspond to failures in specific communicative functions: referential breakdowns when information is unclear, conative failures when users cannot infer required actions, phatic disruptions when engagement collapses, and emotive inconsistencies when interface tone generates unintended affective responses. By mapping interface elements to Jakobsonian functions, the analysis demonstrates that effective interface design requires maintaining functional coherence across these communicative dimensions. Consequently, digital health interfaces should be understood not only as technical systems but also as structured communicative environments in which multiple functions operate simultaneously to support comprehension, action, and engagement.

Our findings also contribute to multimodality theory (Kress & van Leeuwen, 2006) by demonstrating that redundant multimodal coding—presenting information simultaneously through visual, textual, and interactive modes—produces additive rather than merely redundant effects. The 39% cognitive load reduction observed with multimodal enhanced interfaces suggests that different semiotic modes scaffold interpretation, with textual elements stabilizing potentially ambiguous visual signs. Rather than representing unnecessary duplication, multimodal redundancy functions as an interpretive support mechanism that distributes meaning across complementary sign systems. This challenges design approaches that prioritize visual minimalism without accounting for interpretive certainty.

Our findings are consistent with Islam et al.'s (2020) observation that traditional usability methods overlook meaning-making challenges in mHealth applications. However, we extend their work by demonstrating not merely that semiotic problems exist, but that systematic semiotic analysis enables targeted interventions producing substantial effect sizes (d=1.31 to 2.68 across different metrics). These effect magnitudes indicate that semiotic clarity constitutes a central determinant of interface effectiveness rather than a marginal design refinement. This moves beyond critique to solution, providing concrete evidence that semiotic frameworks can guide practical design improvement.

The magnitude of improvement in symbolic understanding (25% for icons, 33% for color coding) exceeds effects reported in prior interface optimization studies typically focused on layout or navigation (Nasr et al., 2023). This finding suggests that interpretability of signs may represent a more powerful usability lever than structural optimization alone.Particularly in health contexts, where misinterpretation may influence health decisions, semantic clarity becomes not only a usability concern but also a matter of communicative responsibility in health information design.

Our results both align with and complicate Torous et al.'s (2021) findings on mental health application engagement challenges. While they documented that 68% of applications employed inadequately explained terminology, our controlled comparisons demonstrate that providing semiotic support (glossaries, redundant coding) substantially mitigates these problems. However, our qualitative data revealed that some users actively preferred interfaces that allowed them to construct personal meanings rather than being told definitive interpretations. This observation introduces an important theoretical nuance: effective semiotic design may not eliminate interpretive flexibility but rather structure the conditions under which interpretation can occur productively. This suggests that optimal semiotic design may involve supporting rather than dictating interpretation—a tension that warrants further theoretical and empirical exploration.

The differential benefits for users with accessibility needs validate and quantify observations by Xie et al. (2025) regarding inclusive design. Our finding that accessibility-focused users showed 52% cognitive load reduction (compared to 31% for others) provides specific evidence that semantic clarity interventions function as accessibility accommodations, effectively reducing interpretive barriers analogous to physical accessibility barriers addressed by WCAG guidelines. In this sense, semiotic accessibility emerges as a complementary dimension to technical accessibility, emphasizing interpretability alongside perceptibility and operability.

5.1. Practical Implications for Design and Development

For UX/UI design practice, these findings establish that semiotic analysis should be integrated into standard design workflows rather than treated as an optional theoretical perspective. The eight derived design guidelines (Section 4.4) provide actionable principles that can be incorporated into design systems, evaluation checklists, and team training. Importantly, these guidelines do not require specialized semiotic expertise—once principles like "multimodal redundancy" or "contextual glossaries" are understood, they can be implemented using standard design tools and tested using conventional usability methods supplemented with interpretation verification. Integrating semiotic evaluation into iterative design cycles would allow designers to detect communicative breakdowns early in development rather than after deployment.

For software engineering education, the research demonstrates that interface design competency requires more than technical implementation skills or aesthetic sense. Engineering curricula should integrate communicative literacy—understanding how signs function, how meaning is culturally situated, and how to systematically evaluate interpretability. This aligns with broader calls (Clear et al., 2020) for more humanistic and socially informed computing education that prepares engineers to design systems that work for diverse human populations. Embedding semiotic literacy within technical training would therefore strengthen designers' ability to anticipate interpretive diversity among users.

For health informatics and digital health policy, the findings support establishing semiotic clarity as a regulatory consideration alongside functional performance and data security. Just as applications must demonstrate technical reliability and privacy protection, they should demonstrate symbolic accessibility—evidence that interface communications are interpretable across target populations. The SFU framework provides a methodology for such evaluation that could be integrated into approval processes for clinical health technologies. In regulated health environments, communicative transparency may be as critical as functional accuracy.

Implementation criteria derived from this research include:

(1) All critical health information should be encoded multimodally (visual + textual minimum);

(2) Icon and symbol libraries should be iteratively tested with representative populations including users with diverse accessibility needs;

(3) Applications targeting multicultural populations should either provide culturally adapted versions or employ culture-neutral semiotic strategies;

(4) Onboarding processes should explicitly teach interface conventions rather than assuming transferability from other applications; and

(5) Cognitive load should be assessed using validated instruments (NASA-TLX or equivalent) with target <50 composite scores for health applications intended for general populations.

5.2. Limitations and Constraints

Several limitations constrain the generalizability and interpretation of these findings. First, the sample size (N=30), while sufficient to detect the large effect sizes observed and consistent with qualitative and mixed-method usability research, limits statistical power for detecting smaller effects or more complex interaction patterns among user variables. Future studies with larger samples would allow more detailed modelling of how multiple user characteristics jointly influence semiotic interpretation processes.

Second, the six-month study period provides evidence of short-term usability improvements but does not allow definitive conclusions regarding long-term engagement or health outcomes. Although two-week usage diaries captured evolving user understanding and interpretive adaptation, longitudinal research following users over extended periods is necessary to determine whether improved interface comprehension translates into sustained behavioral change and measurable health outcomes.

Third, the application sample, while functionally diverse, included only eleven mobile health applications and primarily reflected Western design conventions. Because semiotic systems are inherently culture-dependent, the interpretation of interface signs, metaphors, and symbolic structures may vary significantly across cultural contexts. Replication in non-Western healthcare environments is therefore essential to assess the cross-cultural robustness of the Semiotic Framework for Usability (SFU).

Fourth, the controlled A/B testing design, although methodologically rigorous, inevitably created somewhat artificial usage conditions. Participants interacted with the applications in research environments rather than naturalistic contexts where distractions, time pressure, and emotional states may influence interpretive processes. Complementary field studies observing real-world use would strengthen ecological validity and provide additional insights into situated meaning-making.

Finally, this study examined current mainstream interaction paradigms, particularly touchscreen-based mobile graphical interfaces. Emerging modalities such as voice interfaces, augmented reality environments, or brain–computer interfaces may introduce new semiotic challenges that require extending the SFU framework. While the core analytical structure—syntactic, semantic, and pragmatic analysis—should remain applicable, future work may need to adapt the design guidelines to these evolving technological contexts.

5.3. Future Research Directions

Several research directions emerge from the present findings.

First, longitudinal investigations examining sustained application use and objective health outcomes would provide stronger evidence regarding the practical impact of semiotically optimized interfaces. Future studies could integrate objective indicators such as medication adherence records, clinical assessments, or behavioral tracking data alongside self-reported user experiences.

Second, cross-cultural comparative research would allow systematic evaluation of the universality of the Semiotic Framework for Usability (SFU). Studies conducted in culturally diverse healthcare contexts could help distinguish between universal interpretive principles and culturally specific symbolic conventions. Particularly valuable would be research involving medical systems grounded in different epistemological traditions, such as traditional Chinese medicine, Ayurvedic practice, or indigenous health frameworks.

Third, applying the SFU framework to emerging digital health technologies could significantly expand its analytical scope. Telehealth consultation platforms, AI-based symptom checkers, wearable health monitoring dashboards, and remote patient management systems all rely heavily on interface-mediated communication. These environments provide fertile ground for investigating how semiotic structures influence user trust, interpretability, and decision-making.

Fourth, future work should explore whether semiotic clarity affects different health domains in distinct ways. Mental health applications, for instance, rely heavily on symbolic communication related to emotion and subjective experience, whereas chronic disease management tools emphasize monitoring and behavioral compliance. Domain-specific adaptations of SFU may therefore improve the framework's practical relevance for different health contexts.

Finally, the development of automated or semi-automated semiotic evaluation tools could increase the practical accessibility of the framework. Computational approaches, including machine learning models trained to detect common semiotic barriers such as ambiguous icons, inconsistent metaphors, or accessibility conflicts, could assist designers in identifying potential interpretive problems during early stages of interface development. Such tools would facilitate the routine integration of semiotic analysis into contemporary UX design workflows.

6. Conclusions

This study provides the first systematic empirical validation of the Semiotic Framework for Usability (SFU) as an analytical and design methodology capable of improving the effectiveness of digital health interfaces. Through the analysis of eleven real-world applications and experimental testing with thirty diverse participants, the study demonstrates that usability problems in digital health environments are fundamentally semiotic in nature. Semantic barriers—ambiguities in the interpretation of interface signs—accounted for 42% of identified usability obstacles, followed by pragmatic misalignments between interface assumptions and user contexts (31%) and syntactic structural inconsistencies (27%).

Experimental comparison further demonstrated that interfaces redesigned according to SFU principles—incorporating multimodal redundancy, metaphorical coherence, contextual explanations, and adaptive feedback—produced substantial and consistent improvements across multiple usability dimensions. Enhanced interfaces achieved a 39% reduction in cognitive load, 30% higher task completion rates, 25–33% improvement in symbolic comprehension, and significantly higher user satisfaction scores. Importantly, these improvements were particularly pronounced among users with accessibility needs, who experienced a 52% reduction in cognitive load, indicating that semiotic clarity functions as a mechanism for reducing interpretive inequality in digital health environments.

From a theoretical perspective, these findings support the proposition that usability in digital health systems should be understood primarily as a communicative achievement rather than merely a functional or technical property. By empirically demonstrating that improvements in semiotic clarity yield effect sizes substantially larger than those typically reported for interface layout or navigation optimizations, the study strengthens the relevance of semiotic approaches to human–computer interaction research. In this sense, the results extend the principles of semiotic engineering and multimodal communication into the empirical domain of digital health usability research.

Methodologically, the Semiotic Framework for Usability provides a structured approach for integrating semiotic analysis into existing design and evaluation processes. The framework operationalizes interface analysis across three complementary levels—syntactic organization, semantic clarity, and pragmatic alignment—while integrating communicative functions derived from linguistic theory. This structure allows design teams to identify and address communication breakdowns systematically rather than relying on intuition or purely aesthetic criteria. Because the framework can be integrated into established evaluation standards such as ISO usability quality models and accessibility guidelines, it offers a practical pathway for embedding semiotic analysis within contemporary UX design workflows.

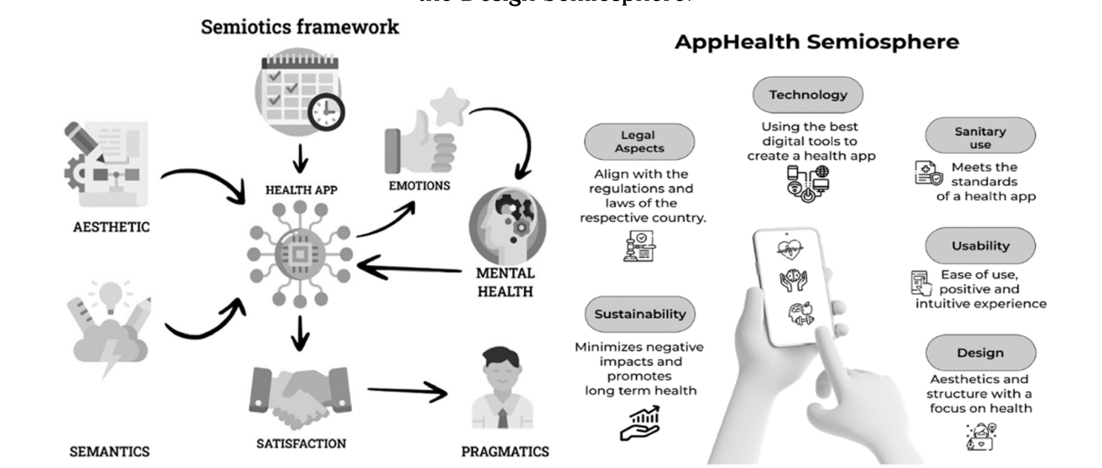
The practical contribution of this research lies in the eight evidence-based design guidelines derived from the empirical analysis, which emphasize multimodal communication, contextual explanation, metaphorical consistency, cultural sensitivity, progressive disclosure, explicit interface conventions, emotional calibration, and iterative interpretation testing. Together, these principles demonstrate that effective interface design depends not only on functionality or visual simplicity but on the systematic management of meaning across diverse interpretive contexts.

Beyond specific design recommendations, the findings suggest a broader shift in how digital health interfaces should be conceptualized. Applications intended to support health management operate within emotionally sensitive contexts where misunderstanding can affect trust, adherence, and patient well-being. Consequently, interpretive clarity should be recognized not merely as a usability concern but as an essential component of digital health safety and accessibility.

Taken together, the theoretical insights, empirical evidence, and methodological contributions of this study converge in a unified perspective: digital health interfaces function as communicative environments in which users interpret signs, construct meanings, and make decisions that directly influence their health experiences.

To synthesize these contributions, Figure 3 presents the integrated semiotic and communicative framework emerging from this research, illustrating how syntactic structures, semantic interpretation processes, and pragmatic user contexts interact within a broader design semiosphere for digital health application development.

Figure 3: Integrated Semiotic and Communicative Framework for HealthApp Development Within the Design Semiosphere.



6.1. Concluding Statement

In an era characterized by the rapid expansion of digital health technologies, the effectiveness of interfaces cannot be assumed to arise automatically from technical functionality. This research demonstrates that systematic attention to the communication of meaning—through icons, colors, metaphors, gestures, and interaction structures—can produce substantial improvements in comprehension, usability, and user satisfaction.

More fundamentally, the findings suggest that interface design in healthcare contexts should be understood as both a communicative and ethical responsibility. Individuals engage with health applications during moments of uncertainty, vulnerability, or illness. In these contexts, interfaces function not merely as technological tools but as mediators of meaning between complex medical systems and everyday human experience.

When interface signs communicate clearly, consistently, and empathetically, digital health systems can support users in navigating complex health information and making informed decisions. When communication fails, even technologically sophisticated systems risk becoming sources of confusion, mistrust, or exclusion.

The Semiotic Framework for Usability offers researchers, educators, and design practitioners a structured approach for addressing this challenge. By integrating semiotic theory with empirical usability evaluation, the framework enables the development of digital health interfaces that function not only as technically effective systems but also as coherent communicative partners in the broader ecosystem of healthcare and human well-being.

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