Co-Creating Sustainable Personalized Input Solutions with Individuals with Cerebral Palsy

by

Raymond Liu

Submitted in partial fulfillment of the requirements
for the degree of Master of Design in Inclusive Design

OCAD University
Toronto, Ontario, Canada
2025

Abstract

When specialized assistive technology fails, users face a particular crisis: the original manufacturers and designers are no longer available, and no documentation exists for replacement. This research addresses this problem through participatory co-design with an individual with cerebral palsy whose decades-old custom accessible keyboard has become non-functional. Through three co-design sessions and reflexive thematic analysis, the research examines how the participant's embodied expertise, developed through sustained keyboard use, informs design requirements that observation alone cannot access. Findings show that the participant's body-based knowledge functions as design authority, that functional reliability takes priority over aesthetic considerations, and that spatial optimization reflects decades of single-hand typing adaptation. The project contributes both a functional personalized keyboard and a reproducible design package that addresses the sustainability gap in assistive technology by enabling future maintenance without specialized expertise.

Acknowledgements

I would like to express my sincerest gratitude to my mentor and supervisor, Jutta Treviranus, for her invaluable guidance and unwavering support throughout this research.

I also wish to thank the participants who generously shared their time, trust and experiences, making this research possible. A special thanks to Assistive Technologist Bert Shire of the Inclusive Design Research Center, for providing me with impeccable assistances at the times of need.

Finally, I am grateful to my family and friends for their encouragement and patience.

Contents

List of Figures

Chapter 1

Introduction

This chapter introduces the research context: the problem of assistive technology abandonment and the history of personalized keyboard design at the Inclusive Design Research Centre. It then presents the specific research problem (a long-term assistive technology user facing device failure with no viable replacement options), the research questions, and an overview of the remaining chapters.

1.1 Background

When specialized assistive technology fails, users who depend on it face a particular kind of crisis. Unlike mainstream devices that can be replaced with equivalent products from the market, assistive technology, which by the heterogeneous nature of disability must be highly personalized, is often irreplaceable: the original designers have moved on, manufacturers have ceased production, and the embodied knowledge built into the device exists nowhere else. This problem of device abandonment represents a systemic vulnerability in how assistive technology is currently designed and maintained. Because personalized devices can enable decades of successful use, the question of what happens when they fail carries significant consequences for the individuals who depend on them. This MRP addresses that question through a participatory co-design process that aims to create a functional device and develop a sustainable, reproducible approach to personalized assistive technology.

It is useful to distinguish between two forms of device abandonment. The first form, which has received considerable attention in the literature, is abandonment by the user: individuals stop using assistive technology because it fails to meet their needs, proves too difficult to use, or does not integrate well with their daily lives. High rates of user abandonment have been documented across assistive technology categories, often attributed to insufficient personalization during device selection and fitting. The second form, which this research addresses, is abandonment by the manufacturer or support system: devices that work well for their users become unavailable because producers cease manufacturing, replacement parts become unobtainable, or the expertise required for maintenance is no longer accessible. This second form of abandonment has received less research attention, perhaps because it is harder to study, yet it may be particularly consequential for users of highly personalized AT. When a device is sufficiently personalized to enable sustained, successful use over decades (as the King Keyboard was for Rick), its loss cannot be remedied by selecting an alternative from available products. The embodied expertise developed through years of use has no equivalent replacement.

For individuals with motor disabilities, specialized keyboards serve as a primary interface for digital participation. Work and communication (from professional tasks to civic engagement) increasingly depend on the ability to type, yet mainstream keyboards are designed with assumptions about motor control that many users cannot meet. Mainstream designs assume that users operate keyboards with two hands, that they possess fine motor precision, and that standard key spacing works for all bodies. These assumptions do not account for the diverse ways that bodies actually interact with input devices. While some commercial alternative keyboards (or keyboard alternatives) exist, they typically offer limited customization and cannot accommodate the highly specific motor patterns that develop over decades of use. As a result, individuals with significant motor disabilities often require specialized solutions that no mainstream device can provide. Yet the support systems designed to provide assistive technology (government programs, insurance coverage, institutional funding) are generally structured around catalogued products rather than custom design. When a user's needs fall outside what standardized AT can address, existing support systems prove inadequate.

Centres like the Inclusive Design Research Centre (IDRC) at OCAD University, along with small enterprise assistive technology companies, have worked on personalized assistive technology for decades, developing specialized solutions for individuals whose needs exceed what commercial products can offer. Among these solutions was the King Keyboard, developed at the Rehabilitation Technology Unit of the National Research Council of Canada. The keyboard was customized by Jutta Treviranus and colleagues for individuals with a specific type of cerebral palsy whose motor patterns required a completely different approach to keyboard design. The keyboards were then manufactured by TASH, a small enterprise assistive technology company. Figure 1.1 shows the original King Keyboard, with its distinctive hexagonal form factor and color-coded circular keycaps arranged specifically for left-hand typing patterns. This keyboard served its users' needs for decades, proof that deeply customized and personalized design, when grounded in actual motor patterns, can enable sustained independence. However, the unit that developed it was eventually shuttered, case files were kept only five years, and the manufacturer ceased production, leaving users without recourse when their devices required repair or replacement. Additionally, as operating systems evolved, maintaining compatibility with devices designed for earlier systems became an ongoing challenge that small manufacturers could not consistently address.

Figure 1.1: The original King Keyboard, a custom accessible keyboard developed with Jutta Treviranus's help that Rick has used for decades. The color-coded circular keycaps and distinctive hexagonal form factor accommodate Rick's motor patterns.

However, the same characteristics that made the King Keyboard successful, its high degree of customization and specialized manufacturing, also made it vulnerable. The manufacturer that produced the original units eventually ceased production due to economy-of-scale constraints: the market for highly customized keyboards could not sustain manufacturing. The participant was left with only a few remaining functional units, each degrading with daily use. Research on device abandonment suggests that this pattern is common across assistive and medical technologies: when devices are sufficiently customized, they fail because the systems that produce and maintain them cannot sustain long-term support rather than because users reject them. Okun et al. (2024) examine this problem in the context of implanted neurological devices. They identify maintenance challenges and support system fragility as primary drivers of abandonment. Although their focus is on implanted devices, the dynamics they describe parallel what occurs with external assistive technologies like specialized keyboards.

The King Keyboard's discontinuation reflects a broader pattern in the assistive technology industry. Specialized AT products face structural market challenges that mainstream devices do not. Treviranus (2018c) describes this as a "vicious cycle of exclusion and impoverishment": products needed by disabled users are not produced by the mainstream market and therefore have no economy of scale. When such products are available, they cost more, are less readily obtainable, require specialized skills to operate and maintain, and face ongoing compatibility challenges with evolving operating systems and applications. Small enterprises that attempt to serve this market (as TASH did with the King Keyboard) struggle to sustain production when the user base cannot support manufacturing costs. The result is that users who depend on highly personalized AT face a double vulnerability: their devices may be abandoned because the market structures that produce them cannot be sustained rather than because the devices fail to work.

The consequences of manufacturer abandonment extend beyond inconvenience. For alternative computer access systems, there is the added challenge of maintaining interoperability with the frequently updated operating systems. For individuals whose digital participation depends on specialized input devices, losing access to a functional keyboard means losing access to work and communication. The skills and adaptations developed over decades, the embodied expertise that makes effective use possible, cannot simply be transferred to a different device. A user who has learned to type through spatial relationships with one specific keyboard layout may find that their skills do not transfer to any commercially available alternative.

Figure 1.2 shows one of Rick's non-functional keyboards, with a diagnostic note reading "Has Power, but Switches aren't Working." The exposed circuit board visible in the photograph shows repair attempts that could not restore functionality. Without proper documentation and replaceable components, even dedicated repair efforts could not overcome the limits of aging technology.

1.2 Research Problem

The participant in this research is an individual with cerebral palsy who, for ethical confidentiality purposes, is referred to by the pseudonym Rick. He has used the King Keyboard for decades. During this time, he developed what Hamraie (2017) calls "access-knowledge." By this term, she means expertise that emerges from sustained engagement with technologies and environments, expertise that shows up in motor patterns and spatial memory, physical adaptations that cannot be easily expressed or transferred. Rick types exclusively with his left hand, navigating the keyboard through spatial relationships anchored to the spacebar at the center. Based on observations during our sessions, his typing speed and accuracy appeared considerable. His body has learned this specific keyboard in ways that might not transfer easily to other devices.

Figure 1.2: The non-functional King Keyboard with a diagnostic note reading "Has Power, but Switches aren't Working," illustrating the device abandonment problem that motivated this research.

When his remaining keyboards began to fail, Rick faced a problem that existing support systems could not address. Government assistive technology programs are structured around catalogued products with established suppliers; they cannot fund custom design for individual users. Commercial alternatives do not exist for keyboards with his specific layout and key-strike characteristics. The expertise embedded in the original King Keyboard design was no longer available: the unit within which the keyboard was designed was closed, the manufacturer had ceased production, and no documentation existed that would allow someone else to reproduce the device.

Faced with this situation, I approached Rick to offer a possible solution, initiating what would become this research project. This engagement shaped the research methodology from the outset. Because Rick came to the project with decades of expertise about his own accessibility requirements, the design process needed to center his knowledge rather than impose external assumptions about what he might need. Participatory co-design offered a framework for this kind of collaboration, treating Rick as a design partner whose embodied expertise constitutes a form of knowledge that observation or interview alone cannot access.

The core problem, however, extends beyond Rick's immediate need for a functional keyboard. The deeper issue is sustainability: one-of-a-kind devices create dependency on original designers, developers and producers, and when those designers and developers are unavailable, users are left without recourse. As I recognized early in this project, I could have simply built Rick a new keyboard using hand-wiring methods, but such a solution would recreate the same vulnerability. When I am no longer available, there would be no one to repair or reproduce the device. Thus, the research problem extends to developing a reproducible design approach: a complete package of design files, assembly instructions, and component specifications that would allow the keyboard to be manufactured and assembled without specialized expertise. This MRP documents the complete co-design process, from initial sessions through prototype development, leading to a sustainable final product with a reproducible design package that could enable long-term maintenance and eventual replacement.

1.3 Research Questions

This research addresses three interrelated questions:

1. **RQ1:** How does the participant's embodied expertise inform design requirements for a personalized accessible keyboard?
2. **RQ2:** What design values and spatial preferences emerge through participatory co-design with a long-term assistive technology user?
3. **RQ3:** How can assistive technology be designed for long-term sustainability and reproducibility?

1.4 MRP Overview

This MRP is organized into seven chapters that move from theoretical foundations through empirical findings and technical process documentation to practical implications.

Chapter 2 establishes the literature foundations for this research. The chapter draws on disability studies scholarship. Two concepts were particularly useful: Hamraie's (2017) concept of "access-knowledge" and Hendren's (2020) analysis of how bodies and tools adapt together through sustained use. Together, these concepts suggest that Rick's decades of keyboard use may have given him a form of knowledge that cannot be accessed through observation or interview alone. Assistive technology research situates the project within broader patterns of device success and abandonment, offering frameworks for understanding why personalized AT succeeds and why it fails. Together, these literatures position Rick as the primary authority on his own accessibility needs and establish the theoretical rationale for the inclusive design methodology employed in this research.

Chapter 3 describes the research design and methods. The study employs an inclusive design co-design methodology with a single primary co-designer, conducted over three co-design sessions spanning ten months. Data collection included video-recorded sessions, design artifacts, email exchanges, and researcher observations. The chapter explains the choice of reflexive thematic analysis and addresses the ethical considerations of working with a participant who approached the IDRC seeking help, a situation that required careful attention to the researcher's dual role as both designer and researcher.

Chapter 4 presents three themes that emerged from the analysis of Rick's contributions to the co-design process. The first theme, Embodied Expertise as Design Authority, documents how Rick's body-based knowledge informed design requirements in ways that observation alone could not reveal. The second theme, Function as the Sovereign Design Value, shows how Rick consistently prioritized functional reliability over aesthetic considerations. The third theme, Spatial Optimization for Single-Hand Access, details the specific layout preferences that emerged from his left-hand typing pattern. These three themes are grounded primarily in Rick's voice (75-90% participant voice), establishing him as the authority on his own accessibility requirements.

Chapter 5 documents the technical development journey through which Rick's requirements were translated into a manufacturable, sustainable design. This chapter presents a chronological narrative of the researcher's technical problem-solving process: learning PCB design from scratch, encountering and overcoming the dual-footprint obstacle, and ultimately discovering the button switch solution that enabled both sustainability and assembly accessibility. The chapter uses a hybrid voice (first-person for emotional and learning moments, third-person for technical descriptions) to document the complete technical process that Jutta Treviranus's original design expertise represented but documented knowledge was lost.

Chapter 6 synthesizes the parallel contributions documented in Chapters 4 and 5. The chapter examines how participant expertise and technical problem-solving converged to address the research questions, interprets these findings in relation to the literature, and considers the implications of this work for assistive technology design more broadly. The discussion addresses the implications of this research for inclusive design practice and acknowledges the limitations of a single-case study approach.

Chapter 7 summarizes the contributions of this research and identifies directions for future work. The MRP contributes both a functional accessible keyboard tailored to Rick's specific needs and a reproducible design package that addresses the sustainability gap identified in the research problem. The conclusion reflects on the broader implications of this work for inclusive design practice, particularly the value of treating long-term assistive technology users as design partners whose embodied expertise offers unique knowledge about accessibility requirements. Directions for future work include testing the reproducibility of the design package with different fabricators and exploring how the sustainability framework developed here might apply to other forms of personalized assistive technology.

Chapter 2

Literature Review

This literature review establishes the theoretical foundations for co-designing an accessible keyboard with an individual who has used personalized input devices for decades. Three areas of scholarship inform the research: disability studies and inclusive design, assistive technology research, and research ethics with vulnerable populations. These areas were selected because each addresses a distinct dimension of the research problem. Disability studies and inclusive design scholarship offers ideas about what counts as knowledge, and specifically why the co-designer's experiential knowledge matters; assistive technology research situates the project within patterns of device success and failure; and ethics literature guides how to build trust and work responsibly with a vulnerable population. Together, these literatures position Rick as the primary holder of expertise about his own accessibility needs, expertise developed through decades of embodied keyboard use.

2.1 Disability Studies and Inclusive Design

Recent disability studies scholarship has begun to reframe how some researchers understand the relationship between bodies, technologies, and access. The medical model locates disability within the individual body, treating it as a deficit to be fixed. The social model takes a different view: disability results from environmental barriers rather than bodily limitations. Several recent scholars have moved beyond both of these models. According to this newer work, access emerges through encounters between bodies, environments, and technologies. It is not fixed, but depends on the specific situation and the particular body-environment encounter.

Inclusive design offers one practical framework for applying these theoretical insights. Treviranus (2018b) articulates inclusive design through three interconnected dimensions. The first dimension concerns recognizing human diversity: design must account for "the full range of human diversity with respect to ability, language, culture, gender, age and other forms of human difference." This leads to what Treviranus calls "one-size-fits-one" design, solutions tailored to individual needs rather than averaged across populations. The framework operates as "a trellis for design teams to grow their design, not a check list of requirements or a prescriptive step-by-step recipe" (Treviranus, 2018b).

The second dimension concerns the role of the user in the design process. Treviranus (2018d) argues that individuals at the margins of design (those she terms "edge users") should participate "not as research participants and subjects of study and analysis, but as full-fledged design team members, or co-designers." This is the principle often expressed as "nothing about us without us," applied here to the design process itself. Edge users bring what Treviranus calls "the hardest challenge": their needs stretch design requirements beyond what mainstream users would reveal. When design accommodates edge users, the resulting systems become more robust and adaptable for everyone.

The third dimension concerns inclusive design as a systemic practice embedded in complex adaptive systems. Treviranus (2018c) observes that current assistive technology markets often trap disabled users in what she terms a "vicious cycle of exclusion and impoverishment":

> "Products he needs are not produced by the mainstream market, they have no economy of scale. Hence, when they are available they will cost more, be less readily available, require special skills to operate and maintain, and, as these compatibility issues aren't addressed by mainstream developers of operating systems and applications, they are likely to have integration and interoperability challenges." (Treviranus, 2018c)

This observation applies directly to Rick's situation. His original King Keyboard was manufactured by a small enterprise that could not sustain production when the limited market proved insufficient. The keyboard worked exceptionally well for decades, proof that personalized design can succeed, but its separation from mainstream manufacturing ecosystems made it vulnerable to exactly the dynamics Treviranus describes.

Hamraie (2017) introduces a concept that I found useful for thinking about this research. She calls it "access-knowledge." What she means by this term is a kind of knowing and making that "emerged from interdisciplinary concerns with what users need, how their bodies function, how they interact with space, and what kinds of people are likely to be in the world" (p. 5). Through this concept, Hamraie argues that disabled people have historically "positioned themselves as experts credentialed by their lived experiences to remake the world" (p. 5). This framing challenges the notion that accessibility is merely a matter of keeping disabled users "in mind" and rejects the assumption that accessible design is merely accommodating or compensatory. The implication is that disabled people can actively contribute to design rather than simply receiving it. Rick's decades of keyboard use represent what might be understood as access-knowledge: embodied expertise that observation, simulation, or expert design alone may not fully capture. His fingers know which key positions work, and his muscle memory encodes spatial relationships that guide efficient typing. His embodied knowledge actively contributed to generating design solutions in our co-design sessions.

The concept of access-knowledge has important predecessors. Treviranus (1994) anticipated many of these ideas in earlier work on alternative computer access, arguing that controlling assistive technology should become "as automatic as touch-typing or speech." She identifies two prerequisites to this skill acquisition: understanding and trust. Understanding refers to the mental models users construct of their access systems, models that allow them to "make sense of the world, to predict what will happen next, and to determine how to respond" (Treviranus, 1994). Trust refers to the user's confidence that the system will behave predictably: "If trust is broken or mistakenly assigned the process of regaining trust is slow and difficult, the whole learning process may be jeopardized and the user may abandon the use of the tool" (Treviranus, 1994).

This early work also identified a problem that directly parallels Rick's situation. Treviranus observed that "once a user has developed skill in using an access system, that skill is jeopardized if the access method is not supported by the manufacturer, if upgrades to the technology are not compatible with the access system that has been learned" (Treviranus, 1994). She noted that mainstream manufacturers preserve familiar interfaces (like the QWERTY keyboard layout) because of large user bases with established skills, but alternative access designers face no such market pressure. As a result, "many skilled users of directed scanning, quadrant scanning or reed switch keyboards must abandon years of skill development and relearn a new access technique because those techniques are no longer supported by commercially available alternative access systems" (Treviranus, 1994). This parallels what Rick faced: decades of embodied expertise jeopardized by manufacturer abandonment.

His situation illustrates the vulnerability that Treviranus identified over thirty years ago.

Hendren (2020) makes a related observation through narrative case studies of prosthetic limb users. She writes that "tools don't run the show; they work together with bodies in a mutual exchange of adaptation" (p. 9). Disabled individuals often need "a whole panoply of these extensions, where the work is distributed among multiple objects chosen for the fine-motor calibrations needed to get the job done...a series of objects that are just right and just in time" (p. 25), rather than "a single miraculous replacement" or "a solitary universal arm." Rick's case seems to show something like what Hendren describes. It seems unlikely that any universal keyboard, however well-designed, could accommodate the specific spatial relationships and embodied habits he has developed over decades of use.

Hendren also reconceptualizes independence in ways that I found useful for thinking about this research. Drawing on the Independent Living Movement, she distinguishes independence-as-self-sufficiency from independence-as-self-determination. Disability activist Judith Heumann articulated this distinction: "To us, independence does not mean doing things physically alone. It means being able to make independent decisions. It is a mind process not contingent on a normal body" (p. 117). The participant's keyboard maintains his self-determination, his ability to choose how he works and participates in digital life. The co-design process tries to follow this principle by centering his decisions about what his keyboard should become.

Östlund and Frennert (2021) provide a historical analysis of how users have been represented in assistive technology design. Their analysis reveals how assumptions about users persist despite decades of critique. They observe that "any attempts to generalise the needs or demands of older people into a universal one-size-fits-all formula have long been criticised" (p. 235), yet such approaches continue to dominate AT design practice. They also write that technology "reveals its true significance when situated in the environment of its use" (p. 230). What I take from this is that the technology only makes full sense when you see it being used in its actual context. This observation seems relevant to Rick's case: his original King Keyboard is perhaps best understood in the context of the decades of daily use that shaped his relationship with it. Its significance emerged through embodied practice. No generic replacement can remedy its loss.

2.2 Assistive Technology: Personalization and Sustainability

Research on assistive technology documents broader patterns of AT success and failure that inform this project. Desmond et al. (2018) frame assistive technology as an interface between a person and the life they wish to lead. This framing shifts evaluation criteria from narrow functionality (can the user perform specific tasks?) to broader participation (does the technology enable the life the user wants?). The participant's keyboard mediates his relationship to work, communication, and digital citizenship. Its failure means exclusion from the digital participation that contemporary life increasingly requires.

The phenomenon of device abandonment provides direct motivation for this research. Okun et al. (2024) define device abandonment as "failure to actively support medical needs of patients who...do not possess the medical, technical, or financial capabilities to maintain the safe and effective use of a durable implanted neurotechnological device" (Okun et al., 2024, p. 2). While their focus is implantable devices, the pattern applies equally to external assistive technologies like keyboards. When manufacturers discontinue products or cease operations, users are left without support for devices they depend on. This is precisely the participant's situation with the King Keyboard. The original manufacturer ceased production. Replacement parts became unavailable. Technical documentation for rebuilding the device did not exist in accessible form. The participant experienced abandonment through systemic failure of the production and support infrastructure; the device itself still functioned.

Buehler et al.'s study of assistive technology designs shared on Thingiverse documents emerging alternatives to commercial AT provision. They observe that "DIY or self-designed AT can address several of the pitfalls of traditional or off-the-shelf AT. Devices and modifications can be tailor-made in a way that is often unavailable or pricey for standard AT fittings, end-user involvement can increase buy-in and reduce user abandonment" (Buehler et al., 2015, p. 526). One item on Thingiverse "was designed because its commercial vendor had gone out of business and was no longer available to consumers" (Buehler et al., 2015, p. 528), a direct parallel to the participant's situation. The open-source, documentable design approach this research adopts responds directly to device abandonment by ensuring the keyboard can be reproduced if it fails or wears out.

Profita et al.'s research on aesthetic customization of hearing devices offers a counterpoint to functionality-focused AT design. Many hearing device users invest considerable effort in making their devices visually distinctive, using customization as "a medium for self-expression" (Profita et al., 2016, p. 224). This research complicates any assumption that AT users uniformly prioritize function over form. The participant articulates a different priority: the keyboard's appearance matters far less than its reliable function. "The shape of the keyboard is less important to me than the relevant position of the keys," he states. "The most important thing is the relevant position of the keys." His preference is individual, underscoring that AT design must assess each user's priorities rather than assuming either aesthetic or functional concerns dominate. Yet regardless of individual priorities, all users of specialized AT face the systemic challenge Treviranus (2018a) identifies: small companies creating alternative access systems have "the impossible challenge of maintaining interoperability with a huge number of applications and services," and "given the precarity of the specialized niche market, the equipment... could become unavailable at any time, leaving her without access."

2.3 Gap in Literature

Disability studies and assistive technology research provide useful theoretical and methodological resources. This research addresses several gaps in the existing literature.

Standard AT design approaches tend to design for rather than with disabled individuals, positioning them as recipients of expert-designed solutions rather than as co-designers whose expertise shapes design decisions. Inclusive design challenges this framing, yet documented cases of extended one-on-one co-design partnerships with individuals who have decades of device-use history are uncommon in the literature.

AT co-design research has examined prosthetics, mobility aids, and sensory devices extensively, yet keyboard and input device design with users who have motor disabilities remains underexplored. The specific challenges of incorporating decades of embodied typing expertise into design, and of using open-source mechanical keyboard practices for accessible input devices, have not been systematically addressed.

The device abandonment literature identifies sustainability as a problem; maker literature suggests DIY solutions. Few studies explicitly center reproducibility as a primary design goal from the outset. This research develops methodology for designing with sustainability as a first-order concern, using off-the-shelf components and documented fabrication processes to ensure the keyboard can be rebuilt without the original designer's involvement.

The transition from user-initiated design to formal research (when a disabled person's independent making becomes an institutional study) also remains underexamined. The participant initiated contact seeking practical help; the research formalizes this request within ethical and scholarly frameworks. How this transition shapes participation and outcomes deserves explicit attention.

Literature on trust in co-design typically assumes trust must be built from scratch. The participant's long relationship with the IDRC precedes this research; the researcher inherits an established trust relationship. What this pre-existing trust enables and constrains in the co-design process is rarely discussed.

Chapter 3

Methodology

This chapter describes the research design, participant engagement, data collection methods, analytical approach, and ethical considerations that guided this co-design study. Each methodological choice reflects the particular demands of co-designing with a single participant whose expertise is embodied rather than abstractly articulable. The methodology centers on participatory principles that position the participant as the primary holder of expertise about his own accessibility needs, expertise developed through decades of embodied keyboard use.

This is an Inclusive Design MRP. A design challenge was identified: Rick needed a functional keyboard, and no existing solution could meet his needs. The research question emerged from this practical challenge, and the co-designer (Rick himself) determined the research direction alongside the researcher.

As Treviranus (2018b) explains, inclusive design operates through three interconnected dimensions, the first of which establishes that design must recognize "the full range of human diversity with respect to ability, language, culture, gender, age and other forms of human difference." This recognition leads to "one-size-fits-one" design rather than "one-size-fits-all" solutions. The framework comes with three important provisos: the one-size-fits-one design "cannot be separate or segregated" from the general market; it must "enable the design of something smarter" for everyone; and it must be "the optimal fit for each individual within the current constraints" (Treviranus, 2018b).

The first proviso carries particular significance for this research. If personalized assistive technology is separate from the mainstream market, it will cost more, be less readily available, require specialized skills to maintain, and face ongoing compatibility challenges with evolving systems. This parallels what happened with Rick's original King Keyboard: a highly personalized solution that worked well, but whose separation from mainstream manufacturing made it unsustainable when the small-enterprise manufacturer ceased production. The sustainability framework developed in this MRP attempts to address this challenge by designing personalized technology using components and methods that connect to, rather than separate from, broader manufacturing ecosystems.

3.1 Research Design

This research adopts a qualitative, interpretivist approach grounded in inclusive design co-design methodology. As I understand it, interpretivism is the idea that knowledge is constructed through interaction rather than discovered objectively. This orientation matters here because knowledge about accessibility needs seems to emerge through collaborative meaning-making between researcher and co-designer. What spatial arrangements support Rick's typing? Which design decisions matter most? These questions require engaging with his lived experience.

Inclusive design provides both the methodological framework and ethical basis for this research. Because Rick's expertise is embodied and contextual, a co-design approach offered the most appropriate way to collaborate with him. Hamraie (2017) has a term for this kind of expertise: she calls it "access-knowledge," by which she means knowledge derived from lived experience. Rick was a co-designer whose expertise shaped every aspect of this project rather than a research subject. Treviranus (2018b) makes a related argument about how edge users should be involved in design. She argues that they should participate "not as research participants and subjects of study and analysis, but as full-fledged design team members, or co-designers." This positioning has practical implications (Rick holds knowledge essential to successful design that observation cannot access) and ethical implications (he has the right to shape technologies that affect his daily life).

The research employs a single-case study design, prioritizing depth over breadth. A reviewer might reasonably ask whether findings from one participant can yield broader insights. This concern deserves a direct response: in inclusive design research, the goal is to stretch the design space to encompass the needs of someone who was previously excluded from it rather than to produce findings that can be replicated across populations. As Treviranus (2018b) argues, "Inclusive design begins with no predetermined end point and no generalized success criteria." Success is measured by whether the design genuinely serves the individual it was created with. Single-case designs are appropriate when the case itself is revelatory (Yin, 2018), when it offers access to phenomena rarely available for systematic study. Rick's decades of daily keyboard use, combined with his articulate reflections on what works and why, make his case this kind of revelatory opportunity.

This does not mean the research lacks broader value. The documentation provided here (Rick's articulated preferences, the reasoning behind design decisions, the sustainability framework developed) enables other designers to assess which approaches might apply to their own work. Geertz (1973) uses the term "thick description" to describe detailed accounts that let readers evaluate transferability to their own contexts. That is what I have tried to provide here. More importantly, in inclusive design, scaling happens through diversification and localization rather than through replication. Each edge user who participates in co-design stretches the design space further, making systems more adaptive to human diversity. Rick's case does not generalize to other users; it expands what keyboard design can accommodate.

The research draws on Participatory Action Research (PAR) principles. I chose this framework because PAR explicitly connects research with practical action, which aligns with this study's goal of producing a functional keyboard. Baum et al. (2006) describe PAR as research that leads to action, where reflection and action intertwine in repeated cycles of praxis. This research embodies praxis over its ten-month duration: formal co-design sessions generate insights that inform design decisions, which produce prototypes Rick evaluates between sessions, generating new insights that reshape subsequent design iterations. The cycles of reflection and action extended beyond formal data collection moments into ongoing exchanges that sustained the collaboration. I came to understand Rick's needs while creating his keyboard; these concurrent activities shaped each other across the full arc of the partnership.

A distinctive feature of this methodology is the researcher's active participation in implementation. While this dual role of researcher and designer may seem unconventional, the practical demands of this project required it: the participant needed someone who could both understand his requirements and physically build the device. This study therefore positions the researcher as designer-implementer who translates Rick's articulated preferences into technical specifications and physical prototypes. This role requires transparency about how the researcher's expertise shapes what becomes possible. My background in mechanical keyboard design and electronics fabrication enables certain solutions (hot-swap sockets, custom PCB layouts) while potentially foreclosing others I lack expertise to implement. Reflexivity about this shaping influence is essential throughout the analysis.

The researcher's relationship with the principal investigator, Professor Jutta Treviranus, requires reflexive attention. I want to be transparent about this relationship because it shapes the research context in ways that may not be immediately obvious. Professor Treviranus designed Rick's original King Keyboard decades ago; the research therefore involves co-designing with Rick while engaging with a design lineage in which my supervisor is a central figure. This relationship provides access to historical context and design rationale, but creates dynamics I must acknowledge: the new keyboard is designed in dialogue with a predecessor my supervisor created. I have tried to navigate this dynamic carefully, drawing on the historical knowledge while ensuring Rick's current needs, not the original design's logic, guide the new keyboard.

3.2 Participant

This section introduces the participant whose embodied expertise the methodology aims to access. The primary participant, referred to by the pseudonym Rick, is an individual with cerebral palsy who has used accessible keyboards for decades. Rick contacted the Inclusive Design Research Centre (IDRC) seeking assistance after his King Keyboard, a custom accessible keyboard developed by Jutta Treviranus, became non-functional and irreplaceable. The original manufacturer had ceased production and replacement parts were unavailable; no commercial alternative matched Rick's highly specific spatial and functional requirements developed over decades of daily use.

This participant-initiated engagement distinguishes the research from typical recruitment scenarios. Rick approached the IDRC with a concrete need, and his request became the foundation for this study. While Sarmiento-Pelayo (2015) describes "User-Initiated Design" (UID) as the phenomenon of disabled people transforming their own environments without professional intervention, Rick's case represents a related but distinct pattern: user-initiated collaboration, where the disabled person identifies the need and seeks partnership with designers rather than modifying the environment independently. Both patterns share the characteristic that the disabled person, not the designer, defines what problem requires solving. The transition from informal help-seeking to formal research raises questions this methodology must address: how does institutional framing change the dynamics of assistance? What does Rick gain and lose when his request becomes a study?

Rick's expertise derives from embodied practice. His fingers know which key positions work; his muscle memory encodes spatial relationships that guide efficient one-handed typing; his body has learned which activation forces feel natural and which cause fatigue. Hamraie (2017) would probably call this "access-knowledge," her term for expertise that emerges from navigating accessibility challenges over time. Simulation or expert analysis cannot replicate it. It exists in his body and emerges through his engagement with keyboards.

Secondary participants were recruited through snowball sampling from Rick's personal network and the IDRC community. These included Rick's spouse, colleagues familiar with his keyboard use, and IDRC researchers and engineers who worked on the original King Keyboard or related projects. Secondary participants provided contextual information about Rick's keyboard use in different settings and historical perspective on the original design decisions. All provided informed consent under the same ethical protocols as Rick.

The research received ethics approval from OCAD University's Research Ethics Board (File No: 102721) under the supervision of Professor Jutta Treviranus as Principal Investigator. The consent process acknowledged the study's participatory nature, emphasizing that Rick's involvement would shape design decisions. Given the participant-initiated nature of the engagement, the consent documentation noted that Rick's withdrawal would terminate the study entirely; the research exists because of his request and cannot proceed without his continued participation.

3.3 Data Collection

The co-design partnership extended over ten months (February 2025–December 2025), encompassing ongoing communication and iterative prototyping alongside formal research activities. Within this extended engagement, three structured co-design sessions served as primary data collection moments, each video-recorded and transcribed for systematic analysis. The sessions marked key moments in the collaboration rather than making up its entirety; design work continued between them through email exchanges, prototype sharing, and informal feedback on emerging solutions.

This distinction between the formal sessions and the broader partnership matters methodologically, because it clarifies what data were subjected to systematic analysis and what context informed that analysis. The three sessions produced the transcribed data subjected to thematic analysis; the ongoing relationship provided context, enabled iterative validation, and allowed design decisions to be tested and refined over time. Rick's responses to prototype iterations (shared via photographs and discussed in emails, then evaluated during his visits to the IDRC) informed the analysis even when those exchanges occurred outside formal data collection.

The three formal sessions combined structured discussion with hands-on exploration of keyboard components and collaborative design activities. Both in-person and remote formats were used based on Rick's availability and preferences, with remote sessions conducted via Microsoft Teams.

3.3.1 Session One: Understanding Current Use

The first co-design session focused on documenting Rick's current keyboard use and preferences. Video recording captured Rick demonstrating his typing technique on existing keyboards, revealing patterns not easily articulated verbally: his exclusive use of his left hand, the spacebar's role as a spatial anchor for finger positioning, and the distinctive rhythm of his keystrokes.

Key insights from Session One included Rick's emphasis on key strike accuracy over aesthetic considerations. "The shape of the keyboard is less important to me than the relevant position of the keys," he explained. "The most important thing is the relevant position of the keys." This prioritization of function over form counters assumptions that assistive technology users always value aesthetic customization. Individual assessment of priorities must guide design.

Session One revealed that Rick's muscle memory operates relative to the spacebar position. His fingers locate keys by their relationship to the spacebar, meaning the overall keyboard position matters less than maintaining consistent spatial relationships between keys. This insight directly informed later design decisions about layout flexibility.

3.3.2 Session Two: Design Exploration

The second session moved from documentation to design exploration. Rick examined keyboard components including mechanical switches, stabilizers of various sizes, hot-swap sockets, and keycaps in different profiles. Physical samples helped the researcher and participant develop shared understanding. Clarke et al. (2021) discuss how physical objects can serve as "material resources" that support trust-building in co-design. Having actual components to handle allowed Rick to assess tactile qualities and physical dimensions that photographs or descriptions could not convey.

Key insights from Session Two included Rick's interest in hot-swap socket technology, which allows switch replacement without soldering. Given that Rick cannot perform soldering himself, hot-swap sockets transform keyboard maintenance from

Figure 3.1: Rick typing during Co-Design Session One, showing his left-hand-only technique with fingers positioned relative to the spacebar.

a repair that requires an expert to something Rick or a caregiver could accomplish. This fits with the sustainability goals behind the project: designing a keyboard that Rick can maintain and repair.

Session Two explored stabilizer options for the larger keys Rick prefers. Standard keyboard stabilizers prevent wobble on wide keys like the spacebar; Rick's custom layout requires stabilizers in non-standard positions to support his larger keycaps. Photographs documented the exploration process and the design concepts that emerged.

3.3.3 Session Three: Feedback Systems and Refinement

The third session addressed feedback systems and refined earlier design decisions. Rick clarified the relative importance of different feedback modalities. When asked about an OLED display for status indicators, he responded: "Why do you need a little display on the keyboard?" His question revealed that visual feedback was unnecessary; auditory feedback through programmed beeps was critical:

> "The beep is critical, it's there when it was completed. That beep and the tone of that beep tells me everything, right? Like when I use the sticky key, the beep is different than the regular. When I hit a regular key, I don't want to hit that key when the different beep happens."

This insight reframed priorities. The beep provides confirmation that a keypress registered, eliminating the need to look at the screen. Different tones for sticky keys

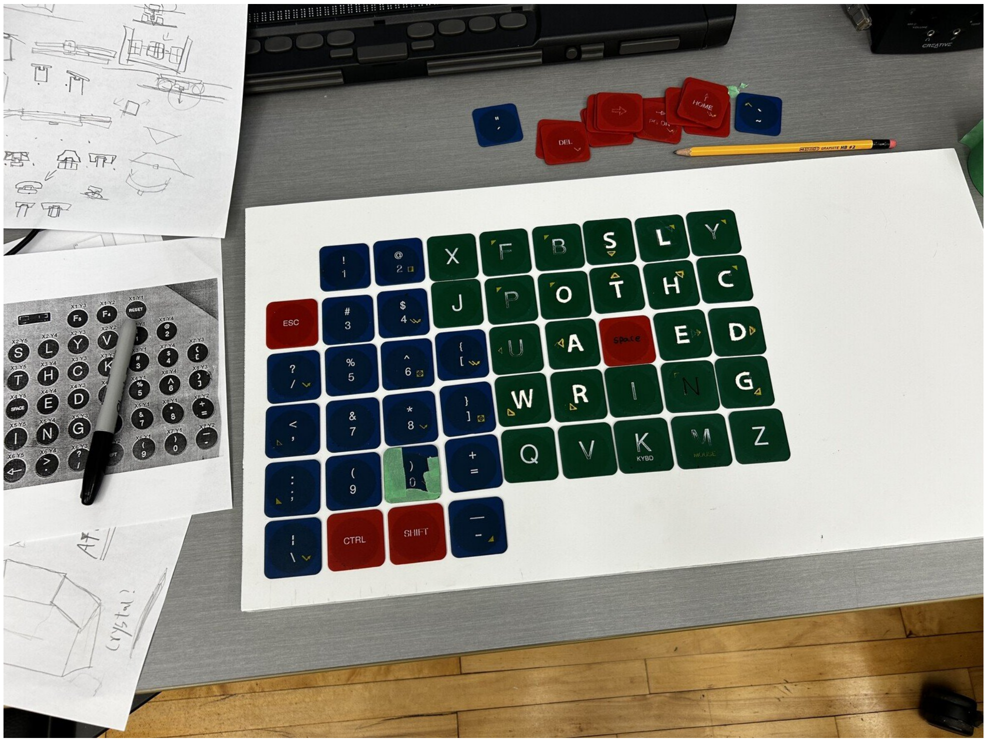

Figure 3.2: Layout proposals reviewed during Co-Design Session Two. The printed reference sheet of the original King Keyboard layout (left) was used alongside proposed redesigns with numbers relocated to the left side.

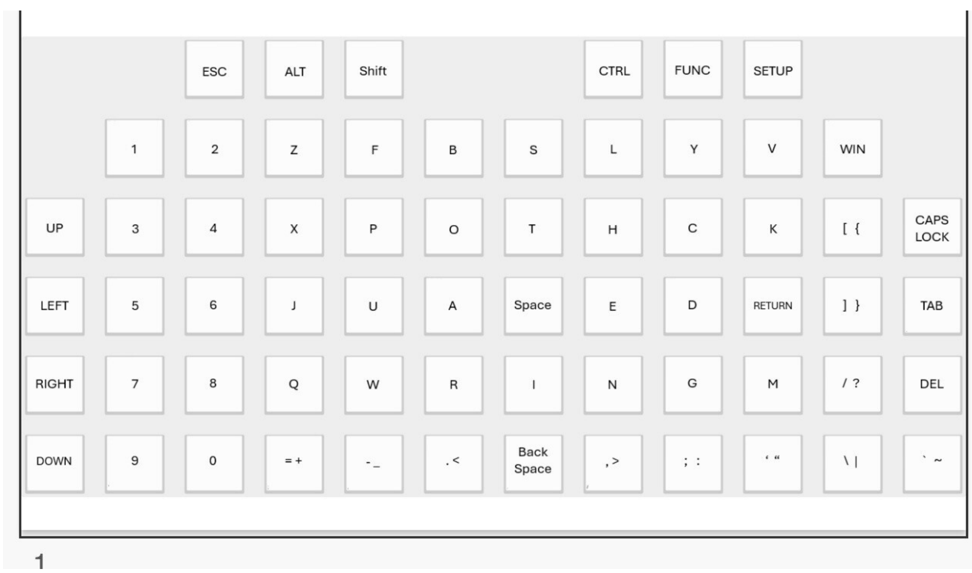

Figure 3.3: Key placement layout produced by Rick after the second co-design session, showing his ideal positions for the new keyboard design. Numbers are grouped on the left side, arrow keys positioned for easy left-hand access, and the spacebar remains central. This layout represents Rick's direct contribution to the design process.

versus regular keys communicate modifier state. Rick noted he would like to adjust the beep volume ("it drives other people around me crazy!"), suggesting a future implementation consideration.

Session Three also confirmed Rick's layout preferences from Session Two. He identified three priority areas: the number keys must be grouped together on the left, the spacebar must remain central, and the letter cluster around the spacebar must maintain its relative positions. Other keys could be rearranged as needed.

Rick raised a future possibility: Bluetooth connectivity enabling the keyboard to work with tablets and phones. He acknowledged this exceeded the current project scope but noted its relevance as technology evolves: "I would imagine, in 10 years there won't be desktops." This forward-looking perspective informed the sustainability framework's emphasis on adaptable design.

3.3.4 Data Types and Documentation

Given the participatory nature of this research, multiple data types were collected to capture both verbal exchanges and material artifacts. The following data types were gathered across sessions:

- **Video recordings** documented Rick's keyboard demonstrations and co-design discussions. Per REB requirements, raw video files were deleted immediately following transcription; only transcribed text was retained for analysis.
- **Audio recordings** captured verbal exchanges during sessions, particularly useful when video was impractical. These were similarly deleted post-transcription.
- **Photographs** documented co-design artifacts, component explorations, and design sketches. Unlike recordings, photographs were retained as visual data for analysis.
- **Session notes** recorded observations, decisions, and emerging questions during and immediately after sessions.
- **Design artifacts** including layout sketches, CAD screenshots, and prototype iterations constituted both outputs of the co-design process and data for analysis.

Accessibility accommodations shaped data collection throughout the research process. Rick's cerebral palsy affects his speech, so data collection required patience and attentive listening during verbal exchanges. Automatic transcription tools proved ineffective for Rick's speech patterns; thus, all transcription was performed manually with careful attention to context and clarification of ambiguous passages. Session pacing was similarly adapted to accommodate Rick's communication needs, allowing adequate time for him to formulate and express complex thoughts. These accommodations were necessary conditions for collecting accurate data rather than departures from rigorous methodology.

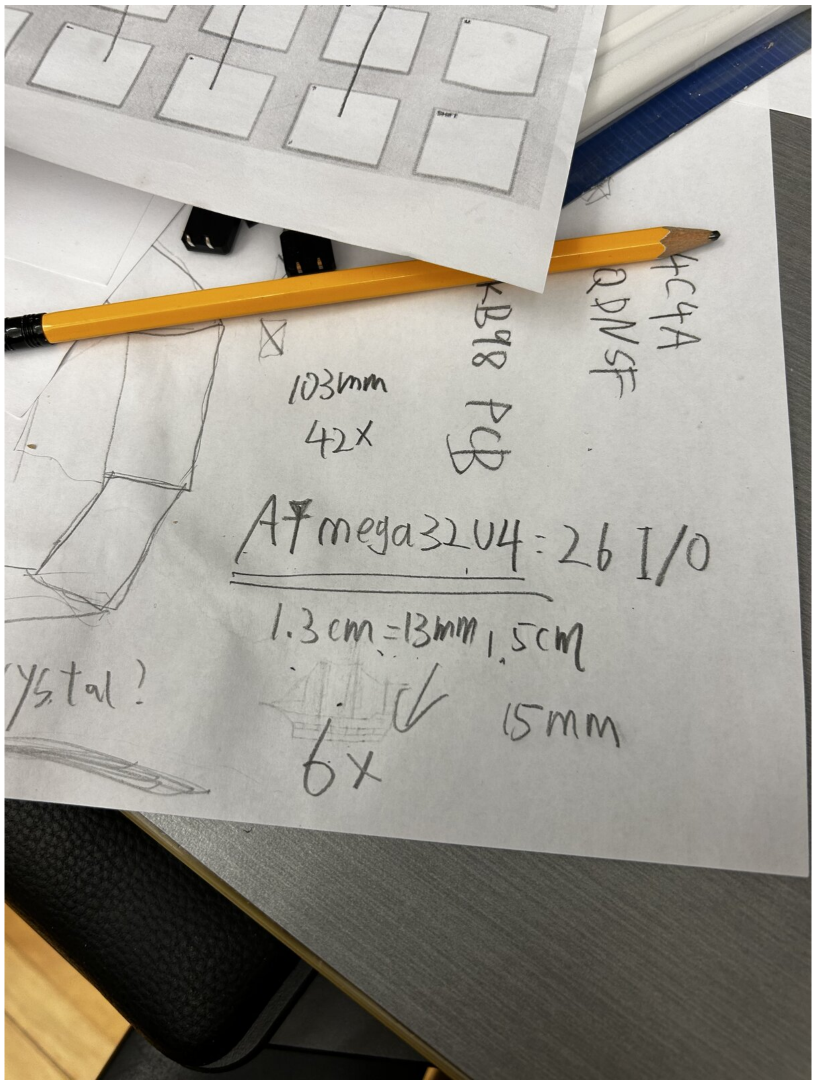

Figure 3.4: Initial matrix calculation sketch exploring keyboard matrix dimensions and the resulting I/O pin requirements. This early calculation was one of the first steps in the project, determining which microcontroller could provide sufficient pins for the keyboard design.

3.4 Data Analysis

Data analysis employed reflexive thematic analysis, following the approach developed by Braun and Clarke (2006, 2019). Braun and Clarke's framework is widely used in qualitative research because it provides clear procedural guidance while acknowledging the researcher's active role in constructing themes. That is to say, themes do not wait to be discovered; rather, the researcher develops them through interpretive engagement with data. I selected this approach, rather than more mechanical coding procedures, because the research questions concern meanings that emerge through relationship rather than frequencies that can be counted. I recognize, of course, that another analyst might reasonably have made different choices; my selection reflects what seemed most appropriate given the participatory orientation of the research. This reflexive stance aligns with the participatory methodology: just as Rick's expertise shapes design decisions, my interpretive perspective shapes how data becomes findings.

In terms of procedure, the analysis followed the six-phase process outlined by Braun and Clarke (2006). These phases provided a systematic structure for moving from raw data to interpreted themes:

1. **Familiarization**: Repeated reading of transcripts and review of photographs and artifacts to develop intimate familiarity with the data corpus.

2. **Initial coding**: Systematic generation of codes capturing features of interest across the dataset. Codes included both semantic codes (explicit content) and latent codes (underlying meanings and assumptions).

3. **Searching for themes**: Collating codes into candidate themes, examining how codes cluster around central organizing concepts.

4. **Theme review**: Checking candidate themes against coded extracts and the full dataset, refining theme boundaries and assessing coherence.

5. **Theme definition**: Developing clear names and definitions for each theme, articulating the specific aspect of data each theme captures.

6. **Writing**: Integrating themes into a coherent analytical narrative that addresses the research questions.

Through the initial theme generation process, I identified five candidate themes from seventy-seven codes. During theme review (Phase 4), I assessed each candidate theme for coherence and distinctiveness. This assessment led me to conclude that one candidate theme, initially termed Evolved Accessibility Needs, lacked sufficient independence from Theme 1. The temporal and social dimensions of Rick's accessibility requirements (his accumulated adaptation over decades, his social awareness of how his practices affect others, and his forward-looking technology thinking) represent extensions of his embodied expertise rather than a separate phenomenon. I integrated these elements into Theme 1, which strengthened its conceptualization of embodied expertise as historically accumulated, socially situated, and temporally aware.

Four final themes emerged from this analysis, each capturing a distinct dimension of the co-design process:

1. **Embodied Expertise as Design Authority**: Rick's deep, body-based knowledge developed through decades of continuous keyboard use (manifested as spatial memory anchored on the spacebar, complete left-hand reliance, non-visual typing, precise self-awareness of motor patterns, adaptive software practices, social awareness of how his practices affect others, and forward-looking technology thinking) positions him as the primary authority on design requirements. (Approximately 75% participant voice)

2. **Function as the Sovereign Design Value**: Rick's consistent and explicit prioritization of reliable key registration over all other considerations including aesthetics and ergonomics, establishing an unambiguous value hierarchy where function is paramount. (Approximately 90% participant voice)

3. **Spatial Optimization for Single-Hand Access**: Rick's specific keyboard layout proposals (numbers relocated to left side, shift key repositioned, cross-body reaching eliminated) following a consistent logic derived from his embodied expertise: optimize for efficient left-hand-only access while preserving relational key positions that protect muscle memory. (Approximately 85% participant voice)

4. **Sustainability as Researcher Contribution**: The technical framework emphasizing reproducibility, zero-soldering assembly, modular component replacement, and long-term user agency. This theme represents the researcher's intellectual contribution to the co-design, validated through Rick's confirmation of solutions that met his functional requirements. (Approximately 85% researcher voice)

Given the co-design methodology, tracking whose voice generated each insight seemed important. The voice attribution reflects systematic tracking of speaker attribution throughout the coding process. Given this systematic attribution, the distribution itself is a finding about participation dynamics: Themes 1–3 emerge predominantly from Rick's direct statements (participant voice), while Theme 4 draws on design artifacts, technical decisions, and Rick's confirmations of proposed solutions (researcher framework validated by participant). This distribution suggests that different parties may contribute different forms of expertise to genuine co-design: the participant contributes embodied authority on requirements; the researcher contributes systemic thinking on sustainability.

Scholars of qualitative research generally agree that quality and rigor depend on transparency and systematic engagement with data. Member checking, the practice of sharing interpretations with participants to assess whether those interpretations resonate with participants' own understanding, served as a key validation strategy in this research. The ten-month partnership enabled member checking to occur iteratively throughout the research process rather than as a single post-analysis verification. Each design decision embodies an interpretation of Rick's needs; his engagement with prototypes (shared between sessions, discussed via email, and evaluated during informal visits) validated or challenged those interpretations over time. When my interpretation of Rick's spatial preferences produced a layout proposal, his response to the physical prototype constituted direct validation of that interpretation. This iterative validation through prototype engagement represents what Birt et al. (2016) frame as the broader purpose of member checking: ensuring that "participants' own meanings and perspectives are represented and not curtailed by the researchers' own agenda and knowledge" (p. 1803). While Birt et al.'s "synthesized member checking" technique involves returning analyzed findings to participants post-analysis, the co-design methodology enabled continuous validation: each prototype served as a tangible interpretation that Rick could directly assess and refine.

Reflexive journaling documented my evolving understanding and decision-making throughout analysis. Thick description in the findings chapter provides sufficient contextual detail for readers to assess the credibility of interpretations and their potential transferability to other contexts.

3.5 Ethical Considerations

The research received ethics approval from OCAD University's Research Ethics Board (File No: 102721), with Professor Jutta Treviranus serving as Principal Investigator. Standard ethical protections included informed consent, the right to withdraw at any time without penalty, confidentiality protections, and secure data storage on OCAD University's OneDrive system with five-year retention. Access to research data was restricted to the student investigator and principal investigator only.

Waycott et al. (2015) make a useful distinction between two forms of ethics in research. "Procedural ethics" refers to the institutional requirements satisfied through application and approval, the formal steps described above. "Ethics in practice," by contrast, refers to the ongoing ethical judgment that fieldwork demands. This second form matters especially for research with vulnerable populations. Munteanu et al. (2015) argue for what they call "situational ethics" in HCI research, recognizing that fieldwork generates ethical moments that formal protocols cannot anticipate.

Several features of this research required ongoing ethical attention beyond procedural compliance. It should be acknowledged that navigating these features involved judgment calls, situations where I had to make decisions and where reasonable researchers might have made different choices. The participant-initiated nature of the engagement created mutual obligations: Rick sought practical assistance, and the research must deliver tangible benefit: a functional keyboard. The pre-existing trust relationship between Rick and the IDRC, built over decades, created expectations I inherited and must honor. The intimacy of one-on-one co-design over an extended period generated a relationship exceeding typical researcher-participant boundaries.

The direct benefit to Rick, a personalized accessible keyboard, distinguishes this research from studies where participant benefit is indirect or uncertain. This benefit is not incidental to the research; it is the purpose of participation. Rick's involvement shapes what the keyboard becomes. Ensuring the keyboard genuinely serves Rick's needs remains an ongoing ethical commitment that extends beyond formal study completion. I hope to fulfill this commitment, though I am aware that the ultimate measure of success lies with Rick himself.

This framing reflects a fundamental shift in how this research positions Rick: as an active agent in the design process rather than a subject of research. Traditional research ethics frameworks conceptualize participants as subjects to be protected from researcher harm. Inclusive design reframes this relationship. Rick is someone I design with rather than someone I study. His expertise drives design decisions; his priorities determine what matters. The ethical commitment extends beyond protection to genuine partnership, where Rick's agency shapes both process and outcome. This distinction, between subject and agent, carries methodological implications throughout the research design.

Chapter 4

Findings: Participant Expertise

Thematic analysis of co-design session transcripts and researcher documentation revealed three distinct themes emerging mainly from the participant's direct statements, specifically his embodied expertise and his design values. These themes capture what Rick brought to the co-design process, namely the body-based knowledge and functional priorities that only he could provide. The researcher's technical contribution, documenting how these requirements were translated into a sustainable, reproducible design, is presented separately in Chapter 5. This structural separation reflects the different forms of expertise that each party contributed to the collaboration.

The three themes relate hierarchically. Embodied Expertise as Design Authority (Theme 1) provides the foundational knowledge from which the other themes emerge. This theme encompasses Rick's body-based spatial and motor knowledge, along with the temporal dimension of decades of accumulated adaptation and his awareness of how his accessibility practices affect those around him. Function as the Sovereign Design Value (Theme 2) and Spatial Optimization for Single-Hand Access (Theme 3) express this expertise as values and concrete proposals. Together, these participant-voiced themes address the first two research questions: how embodied expertise informs design requirements (RQ1) and what design values and spatial preferences emerge through co-design (RQ2). The third research question, how assistive technology can be designed for sustainability, is addressed through the technical development process documented in Chapter 5 and synthesized in Chapter 6.

4.1 Theme 1: Embodied Expertise as Design Authority

Rick possesses deep, body-based knowledge developed through decades of continuous keyboard use. His expertise positions him as the primary authority on design requirements. This expertise manifests as spatial memory anchored on the spacebar, complete left-hand reliance, non-visual typing ability, and precise self-awareness of his motor patterns. His body holds knowledge that external observation cannot access. This knowledge emerges only through his direct expression.

4.1.1 The Spacebar Anchor

Central to Rick's embodied expertise is a sophisticated spatial memory system that uses the spacebar as its origin point. Rick navigates through relational awareness anchored to this single reference point:

> "That's all linked to the space key. So my memory is all linked to the space key because you can't see. It doesn't matter because I know the relatives to the space key."

This statement introduces two critical elements of Rick's embodied expertise. The spacebar functions as an "origin point" in what can be understood as a coordinate system; every other key's position is defined in relation to it. Rick types without visual guidance ("you can't see"), relying entirely on this internalized spatial map developed over decades of practice. He elaborates on this relational system:

> "So the muscle memory is relative to the centre. It's not really relative to the actual position of the keys. It's more relative centre."

The distinction between "relative centre" and "actual position" challenges design assumptions about fixed keyboard layouts. A redesigned keyboard that preserves relative positions will function effectively for Rick, even if the overall layout changes. One that disrupts relative positions will fail. Ergonomic optimization matters less than relational fidelity. This insight cannot be accessed through observation alone.

4.1.2 Complete Left-Hand Reliance

Rick's computer interaction operates entirely through his left hand, a fundamental constraint that shapes all design decisions. When asked about switching between hands, his response is emphatic and unequivocal:

> [Raymond] "Are you more comfortable with typing with one hand or sometimes switching from left to right?"
> [Rick] "Only one. Only one."
> [Raymond] "Only left hand?"
> [Rick] "Yeah."

The repetition ("Only one. Only one") signals the totality of this constraint. Any keyboard must function under this condition. Implications extend beyond typing to all computer interaction. When asked about mouse use:

> [Raymond] "So you also used the mouse with your left hand. That's the same arm that you use for typing."
> [Rick] "Everything."

4.1.3 Self-Awareness and Adaptation

Rick's embodied expertise includes precise awareness of his own motor patterns, expressed with unusual clarity:

> "I never hit the keys at the same place twice."

Because Rick's strikes vary in location across the key surface, the keyboard must register keystrokes reliably regardless of where on the key they land.

Rick's non-visual typing depends on feedback mechanisms beyond sight. I observed in the Design Journey Summary:

> "He also rely heavily on the feedback from the keyboard (the tactile sound from the mechanical keys and the beep sounds from after hitting the keys)."

The mechanical keyboard's tactile click confirms each keystroke; the computer's beep confirms each character entry. Together, these feedback channels replace visual monitoring. This dependence on non-visual feedback shaped technical decisions throughout the project. Low-profile, quiet switches (common in compact keyboards) would remove the tactile feedback Rick requires for accurate typing.

Rick has developed adaptive software practices that layer onto his embodied knowledge:

> "I use the sticky key, I don't use the shift here. A shift on this key is like one sticky key. So right first shift and it's going to give me to the next letter."

Sequential input (pressing shift, then pressing a letter) replaces simultaneous input (holding shift while pressing a letter), an adaptation Rick has fully integrated into his practice over years of use.

4.1.4 Challenged Assumptions

My initial encounter with Rick's typing challenged my expectations. I recorded in the Design Journey Summary:

> "I had the opportunity to observe him operating the keyboard in person, his typing is truly unique to himself, otherwise I would have never expected someone with several motor loss to be able to type this accurate and with this much consistency."

This admission matters methodologically. I arrived with assumptions about what cerebral palsy means for keyboard use, assumptions that Rick's demonstrated competence overturned. The observation "I would have never expected" reveals prior deficit thinking that direct engagement corrected. Rick's expertise became visible only through watching him type: forty words per minute with near-perfect accuracy, achieved through body-based knowledge I could not have anticipated.

Rick himself positions his case as unusual:

> "And also I'm probably very rare, right."

This self-assessment acknowledges what the findings confirm: Rick's specific combination of motor patterns, spatial memory, and decades of practice produces expertise that cannot be generalized to all keyboard users with cerebral palsy. His expertise is both extensive and particular. The design requirements emerging from this knowledge apply to his body, his practice, his accumulated experience.

4.1.5 Temporal Dimensions of Embodied Expertise

Rick's embodied expertise has accumulated over decades of continuous adaptation. His current accessibility practices represent the sedimentation of years of learning, with each adaptation building on previous ones and each workaround becoming habituated into muscle memory. The equipment failure history documented across sessions provides concrete evidence of this accumulated adaptation:

> "He hits the keyboard really hard, which is why some of his key caps shattered into pieces due to prolonged usage."

This observation, recorded in my Design Journey Summary, captures how Rick's motor patterns have materially shaped the equipment he uses. His keyboards fail in patterns reflecting his specific use. The shattered keycaps represent accumulated physical evidence of how his body interacts with technology: decades of strikes, each slightly different ("I never hit the keys at the same place twice"), eventually exceeding material tolerances.

This accumulated adaptation has practical implications for the new keyboard design. Rick's requirements are tested conclusions drawn from decades of use. When he specifies that key strike reliability is paramount, that priority emerges from direct experience with what happens when keys fail to register consistently.

Rick's perspective extends beyond current technology to anticipate future evolution. During Session 3, he reflected on the trajectory of computing platforms:

> "Because I would imagine, in 10 years there won't be desktops, I don't see the desktops surviving."

Rick anticipates that desktop computers, the platform his keyboard serves, may become obsolete, replaced by mobile devices and alternative interfaces. This awareness informed his earlier interest in Bluetooth connectivity.

4.1.6 Social Dimensions of Embodied Expertise

Rick's accessibility practices exist within social contexts, a dimension he articulated with striking clarity when discussing the beep feedback central to his typing:

> "Now what I would love to do is be able to change the volume of that beep, because it drives other people around me crazy!"

Rick's beep-reliant typing practice, essential to his function, affects others sharing his environment. He is aware of this impact and would modify it if possible.

This social awareness extends the analysis beyond Rick's individual needs to the relational context of accessibility. His adaptations do not exist in isolation; they occur in shared spaces where others are affected. The volume adjustability request represents a concrete design implication: the beep that Rick requires for functional confirmation should be controllable so he can minimize its impact on others when appropriate.

4.2 Theme 2: Function as the Sovereign Design Value

Theme 1 established that Rick possesses embodied expertise developed through decades of keyboard use. This second theme documents how that expertise expresses itself in a clear value hierarchy. Rick consistently and explicitly prioritizes functional requirements (particularly reliable key registration) over all other design considerations including aesthetics and ergonomics.

This prioritization reflects a deeper philosophy about motor function maintenance. Rick actively works to preserve his physical capabilities, pushing his limits rather than accommodating decline. From my initial observations, it became clear that he approaches his motor function as something to be actively maintained through continued use and challenge. This philosophy explains why he insists on a physical keyboard requiring deliberate, forceful keystrokes rather than assistive technologies that might reduce physical engagement. Function is sovereign as part of Rick's broader commitment to maintaining his embodied capabilities.

4.2.1 The Central Statement

The clearest expression of Rick's design values appears in a single statement that contains the complete priority hierarchy:

> "I never hit the keys at the same place twice, the key strike is critical, that's the critical part of this keyboard is the key strike. The layout, the look, the size is less important than the key strike."

The word "critical" appears twice, signaling unmistakable emphasis. Rick first connects to Theme 1: the variable strike pattern he knows from embodied self-awareness. He then establishes the design imperative: key strike reliability must be paramount because his motor patterns require it. Everything else (layout, look, size) is explicitly subordinated. Function holds sovereign authority.

Importantly, Rick does not say these factors are unimportant; he says they are "less important than the key strike." A clear-eyed assessment of design priorities, not a dismissal of other considerations.

4.2.2 Explicit Subordinations

Rick reinforces this hierarchy consistently across multiple exchanges throughout the co-design sessions. Regarding shape:

> "The shape of the keyboard is less important to me than the relevant position of the keys."

Regarding size:

> "It's best to reach each key quickly, right? If this keyboard is bigger or smaller, it wouldn't make too much difference."

And when asked to confirm:

> [Raymond] "So it doesn't really matter what shape of the case look like?"
> [Rick] "No, the most important thing is the relevant to the keys' position."

The repetition across different sessions and different phrasings demonstrates consistency.

4.2.3 Rejection of Standard Ergonomics

Rick's prioritization of function extends to rejecting conventional accessibility accommodations that might seem obvious to a designer working from general principles. When asked about tilting angle, a standard ergonomic consideration in accessible keyboard design:

> [Raymond] "What about the tilting angle? Is that also less relevant?"
> [Rick] "Doesn't matter."

Tilting angle is a feature often included in accessible keyboard design based on general ergonomic principles. Rick's dismissal signals that his needs are specific. Standard accessibility accommodations designed for a general population may be counterproductive if they disrupt established patterns.

Equipment failure history further reinforces this primacy. I observed:

> "He hits the keyboard really hard, which is why some of his key caps shattered into pieces due to prolonged usage."

Rick's force patterns have materially damaged previous keyboards. This history provides concrete rationale for prioritizing durable, reliable key registration.

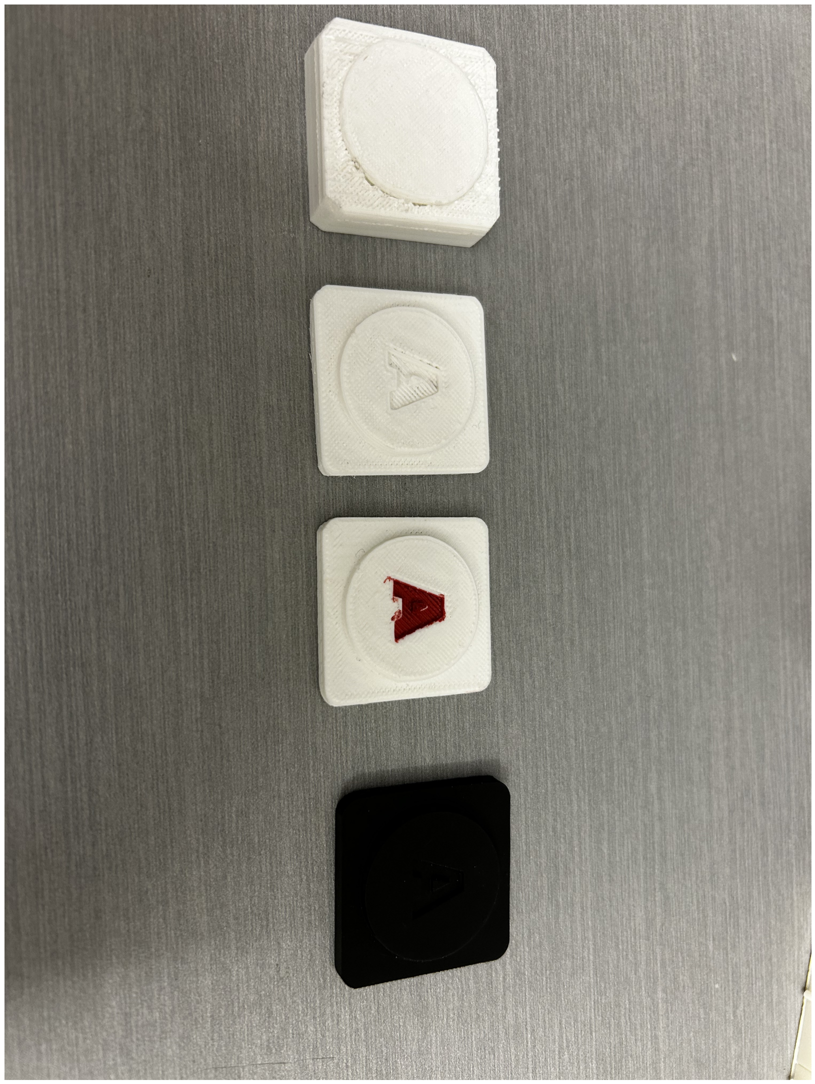

Figure 4.1: Keycap prototype evolution showing iterative refinement: (1) initial white prototype with circular indent, (2) arrow symbol variant for directional keys, (3) two-color inlay experiment with red arrow, and (4) final black keycap design using black resin material.

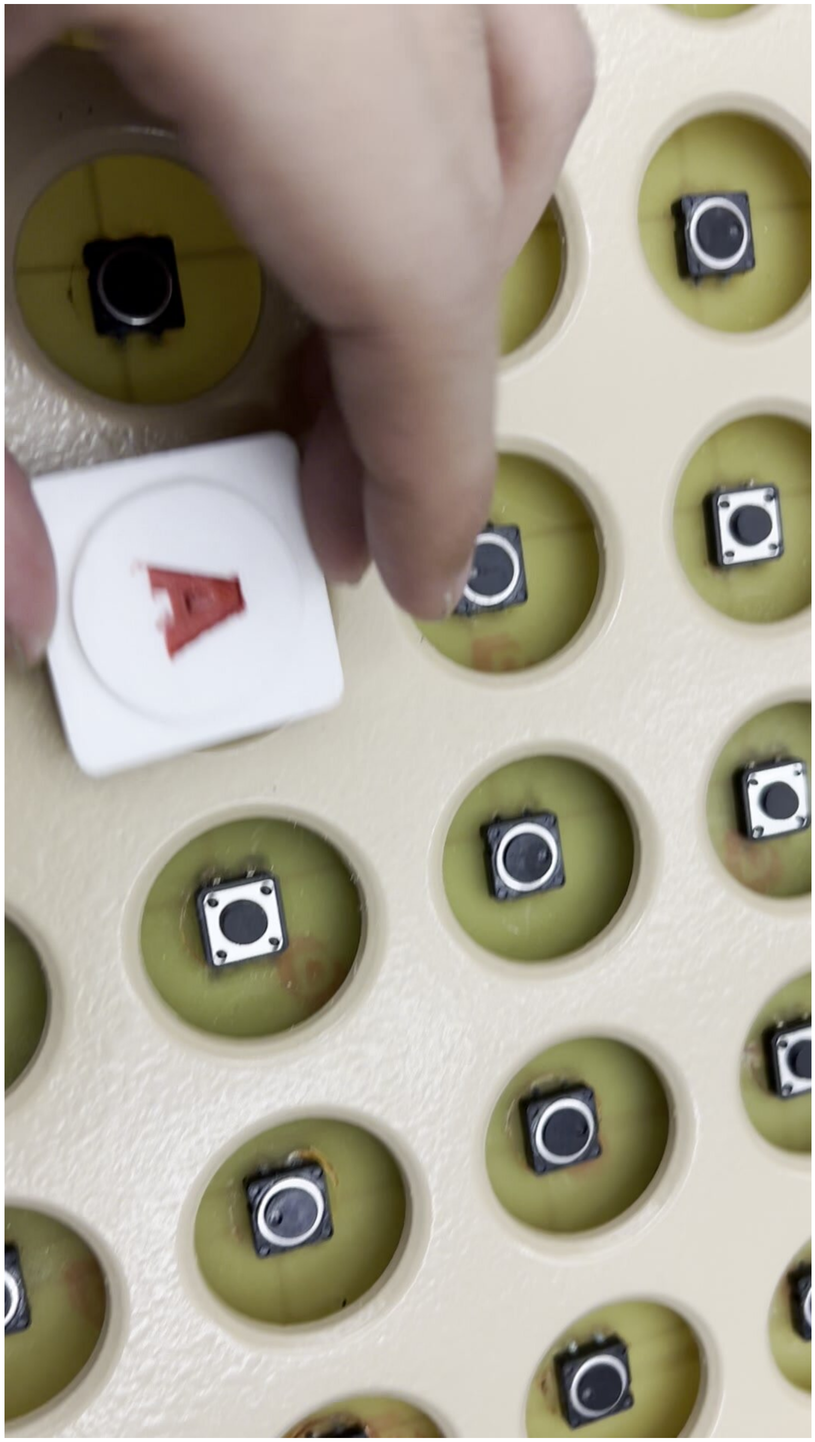

Figure 4.2: Testing the 3D-printed prototype keycap (with red arrow inlay) on button switches mounted in the original King Keyboard housing.

4.3 Theme 3: Spatial Optimization for Single-Hand Access

Where Theme 2 documented Rick's values, Theme 3 documents his concrete design proposals. Rick proposes specific keyboard layout changes that follow a consistent logic: optimize for efficient left-hand-only access while preserving the relational key positions that protect his muscle memory. Theme 3 captures Rick as designer, generating detailed solutions that express his embodied expertise in concrete spatial terms.

4.3.1 The Mirroring Proposal

Rick's most detailed spatial proposal involves reorganizing the keyboard layout through a mirroring principle:

> "Ideally these three columns would be on this side [the left side], basically mirrored, right? So the numbers here [gestures by hand] and the arrows here. Basically you would shift the keyboard over one row, right? Because you got three columns here, there are two columns here, so all of the alphabet would shift to the right, right?"

Rick identifies specific components (numbers, arrows), specifies their new positions (left side), names the organizing principle (mirroring), and calculates the resulting implications (alphabet shifting right to accommodate).

4.3.2 Eliminating Physical Burden

Rick describes the problem that the mirroring proposal addresses:

> "Just so I don't have to reach over to the right side."

And elaborates on the current burden imposed by standard keyboard layouts:

> "I usually have to position my body because when I do numbers a lot, all I'm doing is numbers, right? So formulas, whatever it is, usually we round up numbers, it's only numbers."

The phrase "position my body" reveals that current keyboard layout forces whole-body compensation, repositioning the entire torso. Rick's proposed reorganization would eliminate this full-body adjustment, reducing keyboard use to hand movement alone.

4.3.3 Precise Preferences

Rick describes precise positional preferences for individual keys. For the shift key:

> "That key put it below M. That's a better place for me, here."

The specificity ("below M") demonstrates that Rick's expertise includes exact knowledge of optimal positions derived from his spatial memory system. Rick provided detailed verbal feedback on key placements during the session, which I documented and translated into the layout proposal shown in Figure 3.3. His specifications (numbers grouped on the left, shift key below M, spacebar remaining central) guided the finalized arrangement.

4.3.4 Beyond Personal Need

Rick's design thinking extends beyond his own situation. During Session 1, he proposed a feature with other users in mind:

> "If not designing for me, it will be designed for other users, the ideal would be to train the keyboard in a way that you could customize these so they are like stickers, you can put reprintable stickers..."

Rick proposes modular key labeling, namely stickers that users could customize, as a feature for other users, not himself. His spatial proposals emerge from his specific needs; his design thinking includes people whose needs differ from his own.

4.4 Summary

The three themes emerging from this analysis capture Rick's contribution to the co-design process. Embodied Expertise as Design Authority (Theme 1) establishes Rick's decades-long body-based knowledge, including its temporal accumulation and social dimensions, as the irreplaceable source of design requirements. Function as the Sovereign Design Value (Theme 2) reveals Rick's explicit prioritization of reliable key registration over all other considerations. Spatial Optimization for Single-Hand Access (Theme 3) shows Rick's embodied expertise and functional values expressed in concrete layout proposals that position him as designer.

Together, these participant-voiced themes address the first two research questions. Rick's embodied expertise informs design requirements through a sophisticated spatial memory system and precise self-awareness of motor patterns (RQ1). Design values and spatial preferences emerge through the co-design process, with function as the sovereign priority and explicit subordination of aesthetics and ergonomics, expressed through concrete layout proposals optimized for left-hand access (RQ2). The third research question is addressed in Chapter 5.

Chapter 5

Process: Technical Development Journey

Chapter 4 documented the expertise Rick brought to the co-design process, specifically his embodied knowledge and functional priorities. This chapter documents my contribution as the researcher-designer: the technical problem-solving journey through which Rick's requirements were translated into a manufacturable, sustainable design. Two guiding principles shaped every technical decision throughout this process.

The first principle, which I termed "Lego-like assembly," required that the final keyboard could be assembled without soldering or specialized electronic knowledge. Rick cannot perform soldering, and his caregivers lack physical computing expertise. Any solution requiring electrical skills would recreate the dependency problem that brought Rick to this project: when the person with those skills became unavailable, the keyboard would become irreparable.

The second principle, sustainability through reproducibility, required that the design exist as a complete documentation package rather than a singular artifact. If I built Rick a keyboard through hand-wiring methods, the knowledge to repair or reproduce it would exist only in my head. The sustainability framework demanded that anyone with access to standard PCB fabrication services could manufacture and assemble an identical keyboard without my involvement.

These principles were not arbitrary constraints. They emerged from analyzing why Rick's original King Keyboard had become irreplaceable: specialized manufacturing knowledge that was never documented, custom components that could not be sourced, and assembly techniques that required expertise no longer available. The technical development journey documented here represents my attempt to solve these problems systematically.

5.1 Pre-REB Exploration: Orienting to the Domain

Before formal data collection began, I engaged in preparatory technical exploration to orient myself with the domain of accessible keyboard design. Because Rick had used mechanical keyboards for decades, I began by researching mechanical keyboard construction, component types, and production methods.

This initial exploration ruled out membrane keyboards as a viable approach. Membrane keyboards, while common in consumer products, presented two significant barriers. First, their soft, quiet key response would not provide the tactile and auditory feedback Rick depends upon for typing confirmation, the “beep noise” he identified as critical to knowing whether a key had registered. Second, membrane technology requires industrial precision manufacturing that cannot be replicated through the accessible fabrication methods central to the sustainability framework. A membrane keyboard would be just as irreplaceable as the original King Keyboard.

Mechanical keyboards, by contrast, offered a path forward. Their modular construction (separate switches, keycaps, stabilizers, and PCBs) suggested the possibility of replaceable components. Their manufacturing, while still technical, could potentially be achieved through PCB fabrication services accessible to anyone with design files. I began learning KiCad, an open-source PCB design software, with no prior experience in circuit board design.

5.2 Understanding Keyboard Architecture

Learning PCB design required understanding how keyboards actually work at the electrical level. A keyboard is fundamentally a matrix, a grid of rows and columns where each key position corresponds to a unique row-column intersection. When a key is pressed, it completes a circuit between its row and column, and the microcontroller detects this connection.

For a 64-key keyboard like Rick’s, the most obvious arrangement would be a 12×6 matrix (twelve rows, six columns), requiring eighteen GPIO (general-purpose input/output) pins on the microcontroller. However, I would later discover that Jutta Treviranus’s original design used an optimized 8×8 matrix requiring only sixteen pins, a detail that became important when selecting the microcontroller.

The microcontroller, the "brain" of the keyboard, presented its own choices. The ATMEGA32U4, used in many commercial mechanical keyboards, was an obvious candidate. However, the sustainability principle argued for more widely available alternatives. The Raspberry Pi Pico, with its RP2040 processor and built-in USB capability, offered equivalent functionality at lower cost with broader availability, both important considerations for long-term reproducibility.

During this learning phase, I discovered hotswap sockets: small receptacles that allow mechanical switches to be inserted and removed without soldering. This technology seemed to answer the "Lego-like assembly" requirement perfectly. If switches could simply plug into sockets, maintenance would be transformed from expert-dependent repair to something Rick or a caregiver could accomplish.

5.3 The Stabilizer-Hotswap Theory

A complete keyboard design requires more than just key switches. Large keys (spacebar, enter, shift) need mechanical stabilizers to prevent wobbling and ensure even key travel. These stabilizers are separate components that mount to the PCB alongside the switches.

My initial theory combined hotswap sockets with mechanical stabilizers: the sockets would enable tool-free switch replacement, while the stabilizers would provide the mechanical support Rick's heavy keystrokes required. This combination seemed elegant. Users could replace worn switches without soldering, and the stabilizers would ensure reliable operation under sustained force.

I began creating design files in KiCad, building the schematic (the logical representation of electrical connections) and attempting to assign footprints (the physical component patterns) to each key position. This is where the technical journey encountered its first major obstacle.

5.4 The Dual-Footprint Problem

KiCad, like most PCB design software, enforces a fundamental constraint: each schematic symbol can have only one footprint. A "footprint" in PCB design is the physical pattern of solder pads, mounting holes, and copper traces that corresponds to a component. When you place a key switch symbol in your schematic, you must assign it exactly one footprint, either a hotswap socket footprint or a stabilizer-compatible footprint, but not both.

The problem crystallized: I needed to combine two incompatible elements on the same key positions. Hotswap sockets required their own footprint (the socket mounting points and contact pads). Mechanical stabilizers required different footprints (the stabilizer mounting holes and switch mounting positions). No standard library contained a combined configuration.

What followed were months of frustration. I searched for tutorials covering this specific problem and found almost nothing. The mechanical keyboard hobbyist community had produced extensive documentation on standard keyboard builds, but the combination I needed (hotswap sockets with stabilizer support in a fully documented, manufacturable format) remained elusive.

Eventually, I discovered a forum post from several years earlier where a hobbyist described a similar design challenge. I contacted the author directly, hoping to learn how he had achieved the combined configuration. His response was both helpful and discouraging: his solution relied on fully custom schematics, a complete custom component library he had built himself. To replicate his approach, I would need to recreate this work from scratch.

5.5 A Partial Solution: Custom Mounting Holes

Studying the hobbyist's design revealed an insight. Mechanical stabilizers mount through holes in the PCB but require no electrical connection; they simply need physical space. The mounting holes exist purely for mechanical attachment and carry no electrical signals.

I realized I could create custom mounting hole footprints at the correct spacing for stabilizers, then position these alongside hotswap socket footprints. The mounting holes would provide the physical attachment points for stabilizers, while the adjacent hotswap sockets would provide the electrical connections for the switches. The approach was inelegant (each key position would require manual placement of multiple footprints), but theoretically workable.

I built a 3×3 number pad prototype using this method to validate the concept. When the PCB was produced and assembled, the prototype confirmed the electrical theory: keys registered correctly. The hotswap sockets worked as intended; switches could be inserted and removed cleanly.

However, the approach introduced significant problems. Every key position required manual placement of multiple footprints with precise alignment, and the margin for error was high. Most critically for sustainability, the resulting design files would be difficult for others to modify or reproduce. Someone attempting to create a variant of the keyboard, perhaps with a different layout, would need to understand and replicate my custom footprint arrangement. This complexity directly threatened the sustainability goals.

5.6 The Button Switch Breakthrough

The actual solution emerged unexpectedly, months into the struggle with the dual-footprint problem. During a casual conversation with a colleague at the IDRC who had previously worked on keyboard repair, I was describing my frustrations with the hotswap-stabilizer combination. The colleague asked a simple question that reframed the entire problem: why use mechanical keyboard switches at all?

The question forced me to reconsider assumptions I had not examined. Mechanical keyboard switches are designed for user installation; they are meant to be inserted into sockets and replaced when worn. But Rick was not going to replace his own switches. The "user-replaceable" feature of hotswap sockets solved a problem Rick did not have. What he needed was reliable key registration with minimal maintenance, not the ability to swap switches himself.

Button switches, the kind found in industrial control panels and simple electronic devices, could be factory-soldered directly to the PCB during manufacturing. Unlike mechanical keyboard switches designed for user installation, button switches are meant for permanent mounting. They would arrive already attached to the board, requiring no assembly by the end user.

The implications crystallized immediately. If a PCB factory could solder button switches during assembly, the end user would receive a fully functional keyboard requiring no electrical work whatsoever. The "Lego-like assembly" principle could be achieved completely: users would only need to attach the casing and keycaps. The months of struggling with dual-footprint workarounds had been addressing the wrong problem.

I checked KiCad's standard component library. Button switch footprints existed. I contacted JLCPCB, a major PCB fabrication service, to confirm they offered assembly services that included through-hole component soldering. They did. Within days, I had redesigned the entire PCB layout around button switch footprints.

> "Finally I see some hope throughout this months long struggle."

The button switch approach solved both the sustainability problem and the assembly problem simultaneously.

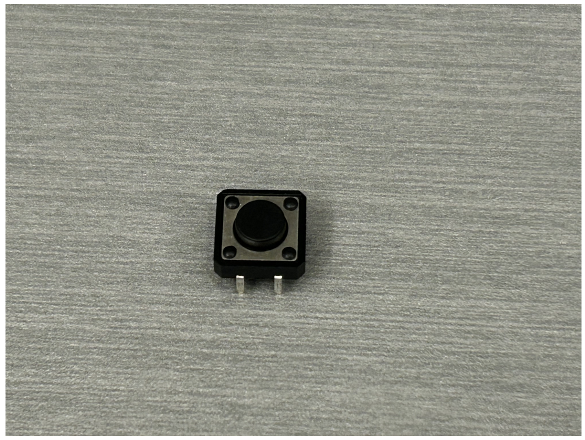

Figure 5.1: The 12mm button switch that enabled the breakthrough solution. Unlike mechanical keyboard switches requiring hotswap sockets for user replacement, button switches are designed for permanent factory soldering, enabling the “Lego-like assembly” principle where end users receive a fully functional PCB requiring no electrical work.

5.7 From Theory to Validation

The button switch design needed validation before committing to full production. Fortunately, the original King Keyboard, sent to the IDRC for repair, provided a testing platform. Though the keyboard was non-functional, its copper traces still connected all sixty-four keys to the board’s edge connector.

I traced each wire to identify column and row assignments, documenting the matrix configuration. This reverse-engineering revealed Jutta Treviranus’s original design efficiency: an 8×8 matrix (sixteen I/O pins) rather than the more obvious 12×6 arrangement (eighteen pins). This optimized configuration demonstrated sophisticated design thinking worth preserving.

I connected the original keyboard’s matrix to a Raspberry Pi Pico development board, hand-wiring the connections to test whether the modern microcontroller could successfully read the thirty-year-old key matrix. Using QMK (Quantum Mechanical Keyboard) open-source firmware, I configured the matrix assignments and flashed the firmware to the Pico.

When I pressed keys on the original keyboard, the Raspberry Pi Pico successfully registered keystrokes. A new device appeared in Windows settings, and the modern

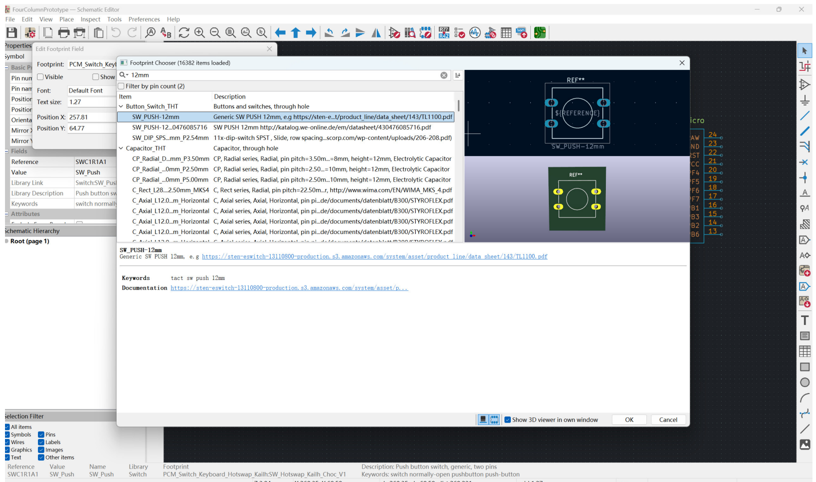

Figure 5.2: Button switch footprint in KiCad's standard component library. The discovery that this footprint existed, and that PCB fabrication services could factory-solder these components, resolved months of struggling with the dual-footprint problem.

circuit was communicating through the old board. This hybrid setup confirmed that the new PCB design would function as intended.

5.7.1 QMK Firmware Configuration

With the hardware validated, the keyboard needed programming to function. I found this aspect fairly simple thanks to QMK (Quantum Mechanical Keyboard), an open-source firmware framework designed for custom keyboards. The setup process involved three steps: first, selecting the microcontroller type dedicated to the keyboard; second, choosing a preset keyboard layout from the firmware's library; and third, extracting the configuration code via Visual Studio Code for customization.

Before beginning the configuration, I verified the QMK MSYS development environment by comparing the downloaded executable's SHA256 hash against the official checksum (Figure 5.3). I took this verification step because firmware tools handle low-level hardware communication; thus, confirming the tools had not been tampered with during download seemed prudent.

Once I extracted the preset, I could modify the keyboard configuration to match the matrix I had designed. The customization options included fine-tuning the matrix assignments, editing which coordinates on the matrix correspond to which key, adjusting the timing of key presses, and adding features such as sound response. Figure 5.4 shows the keymap configuration file where each key position in the matrix is assigned

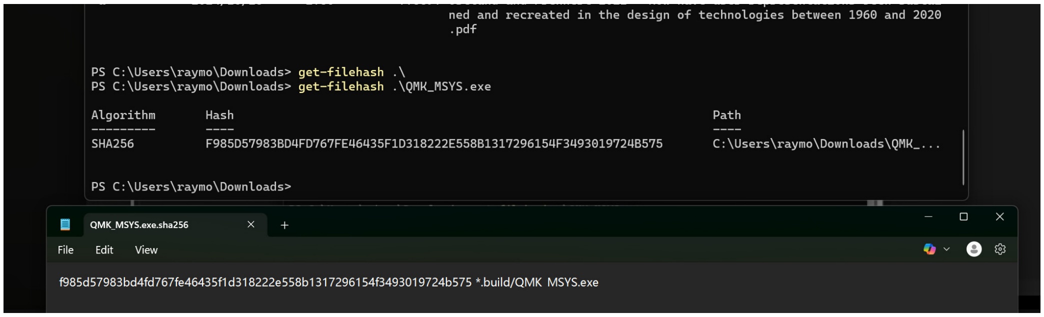

Figure 5.3: Verification of the QMK MSYS development environment. PowerShell's **get-filehash** command generates the SHA256 hash of the downloaded executable, which matches the official checksum displayed in the text file below.

its corresponding keycode; this is where the physical layout becomes functional.

Figure 5.4: The `keymap.c` configuration file in Visual Studio Code. The `LAYOUT` macro maps each position in the matrix to a keycode (e.g., `KC_ESC` for Escape, `KC_SPC` for Space). This file defines what each physical key position produces when pressed.

After completing the configuration, I compiled the firmware and transferred it to the microcontroller. The QMK MSYS terminal compiles the keyboard configuration into a `.uf2` firmware file (Figure 5.5). The Raspberry Pi Pico uses a particular flashing method: when connected to a computer via USB while holding its boot button, the Pico appears as a removable drive. Copying the compiled `.uf2` file to this drive programs the microcontroller, and the device automatically reboots as a functional keyboard.

This firmware approach supports the sustainability framework. The keyboard's key mappings and matrix configuration are stored in version-controlled text files that can be modified and reflashed as needs change. Accordingly, if Rick's requirements evolve (different key assignments, adjusted timing, or added features), the firmware can be updated without hardware modifications.

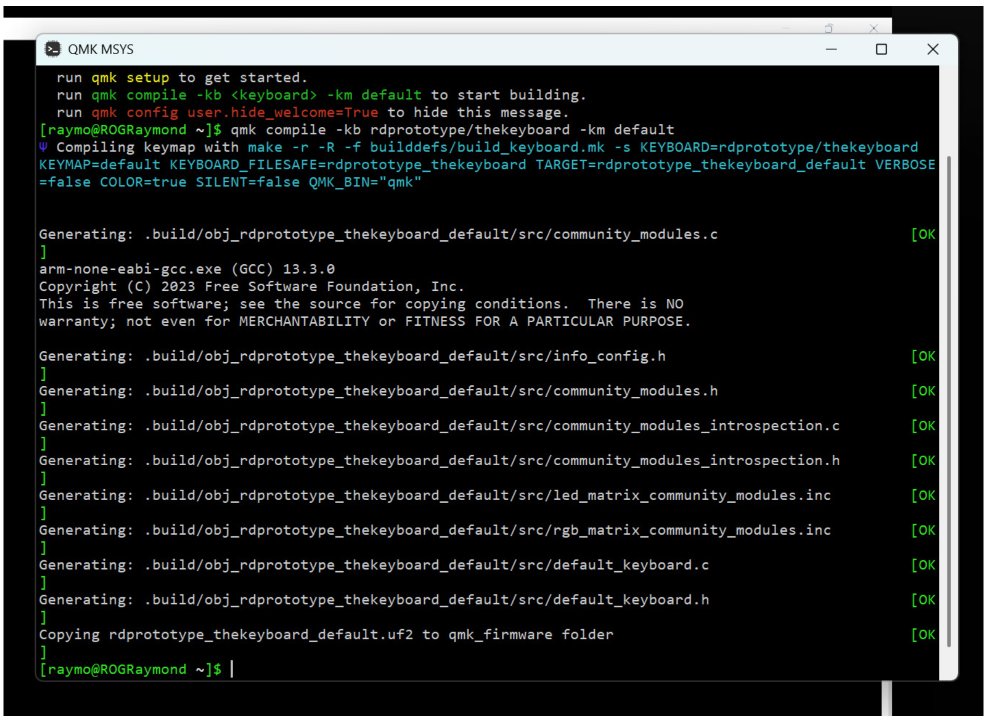

Figure 5.5: QMK MSYS terminal during firmware compilation. The command `qmk compile -kb rdprototype/thekeyboard -km default` builds the firmware, generating various source files (each marked `[OK]`). The final line shows the compiled `rdprototype_thekeyboard_default.uf2` file being copied to the firmware folder, ready for transfer to the Raspberry Pi Pico.

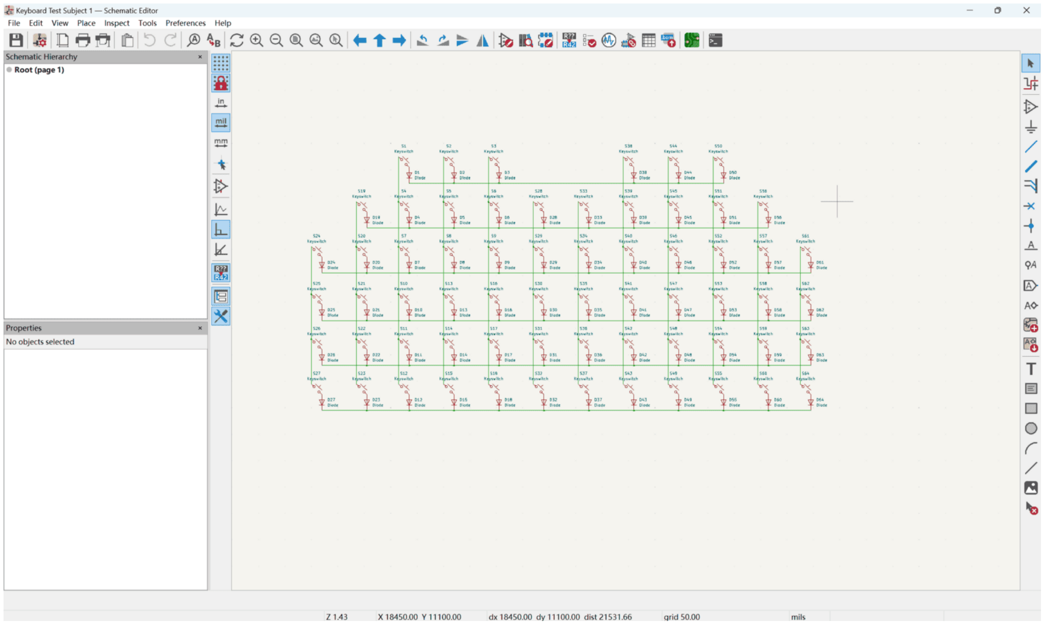

Figure 5.6: Initial KiCad schematic design created early in the learning process. This early version assumed the schematic should mirror the keyboard's physical shape, but the matrix logic proved more complicated, requiring significant revision.

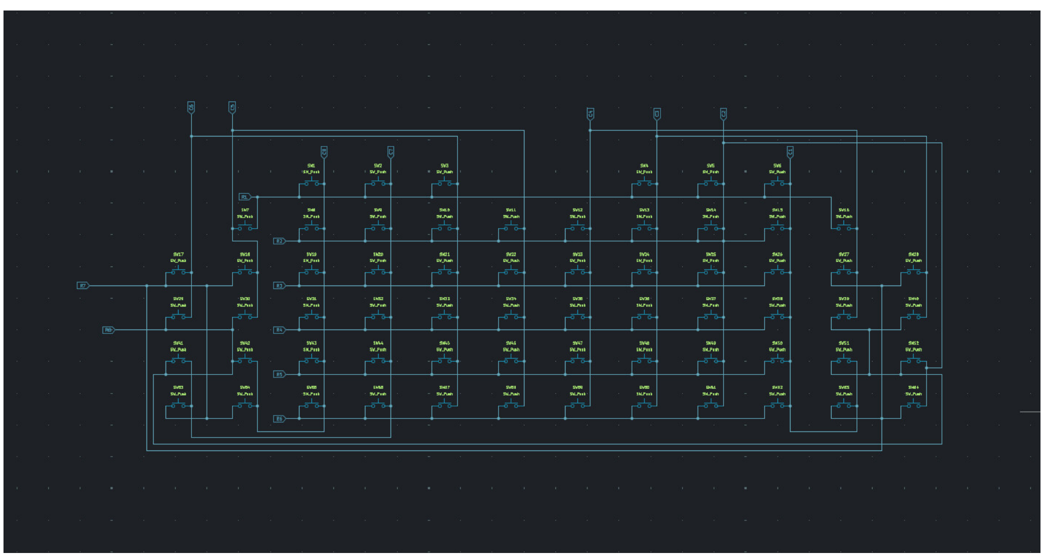

Figure 5.7: Final keyboard schematic design in KiCad. Unlike the initial version, this schematic reflects the correct matrix logic with the 8×8 column-row connections visible as the complex routing pattern connecting all 64 switches.

5.8 Peripheral Development

The button switch approach required custom keycap design. Standard mechanical keyboard keycaps would not fit the button switch profile. More critically, Rick's history of shattered keycaps demanded more durable materials than the thin injection-molded plastic used in previous generations.

I developed keycap variants in Blender, designing for resin 3D printing. Resin offers smooth surface finish and superior durability compared to FDM (fused deposition modeling) printing. The designs incorporated increased thickness and density to withstand Rick's forceful keystrikes, as his previous keycaps had shattered under sustained heavy use. Figure 5.8 shows the dimensional specifications developed during this design phase.

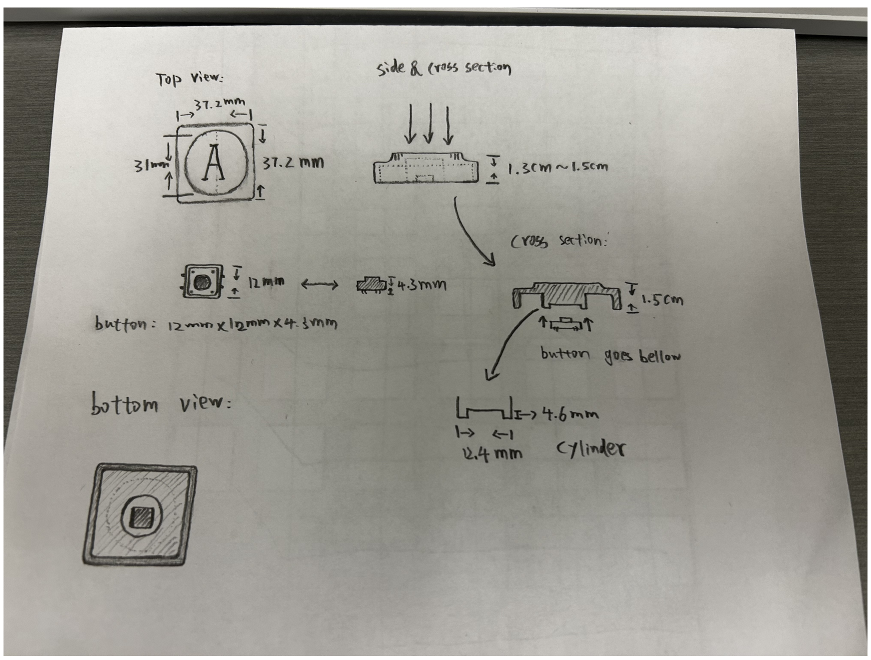

Figure 5.8: Hand-drawn keycap design sketch with dimensional specifications. Top view shows 37.2mm square keycap with circular indent matching the original King Keyboard aesthetic; cross-section details the button switch mounting geometry with the switch positioned below the keycap surface.

Samples printed at OCAD's rapid prototyping lab were presented to Rick during the third co-design session. He confirmed satisfaction with the tactile quality and hardness. The keycaps felt substantial enough to survive his use patterns.

Examining the original King Keyboard revealed another critical design detail: numerous mounting holes distributed across the PCB. These served as structural reinforcement, creating a grid of anchor points that prevented the board from flexing

Figure 5.9: Resin keycap prototype printed at OCAD University's rapid prototyping lab. Rick responded positively to its sturdiness, confirming the material choice would withstand his forceful keystrikes.

under repeated force. The PCB itself is fragile; without adequate mounting, sustained impacts would eventually cause warping or cracking.

The original keyboard's screws had loosened over time, likely because they were too short for secure anchoring. The new design specifies longer screws and a denser mounting hole pattern to ensure structural integrity under Rick's use patterns.

The modular architecture emerged from considering practical failure scenarios. USB ports can bend from repeated cable insertions. Microcontrollers can fail from prolonged use or accidental damage. If these components were permanently integrated into the main PCB, their failure would render the entire keyboard unusable.

The design separates the keyboard into replaceable modules: the main key switch PCB, the microcontroller board (a Raspberry Pi Pico), and the case components. If the microcontroller fails, only that module needs replacement, not the entire keyboard.

5.9 Summary

The technical development journey documented in this chapter transformed Rick's requirements (reliable key registration, left-hand optimization, preserved spatial relationships) into a manufacturable, sustainable design. The button switch breakthrough, emerging from a casual conversation after months of struggling with the wrong technical approach, resolved both the sustainability problem and the assembly accessibility problem simultaneously.

The resulting design package includes complete KiCad source files, component specifications, assembly instructions, and validated QMK firmware. If the fabricated keyboard fails, the documentation enables reproduction without requiring the original designer's involvement.

The voice distribution in this chapter differs from Chapter 4. Where those themes drew primarily on Rick's direct statements, this chapter documents my technical problem-solving process: the learning curve, the failures, and the eventual breakthrough. Rick's embodied knowledge defined what the keyboard needed to accomplish; my technical knowledge determined how to accomplish it sustainably. Chapter 6 integrates these parallel contributions.

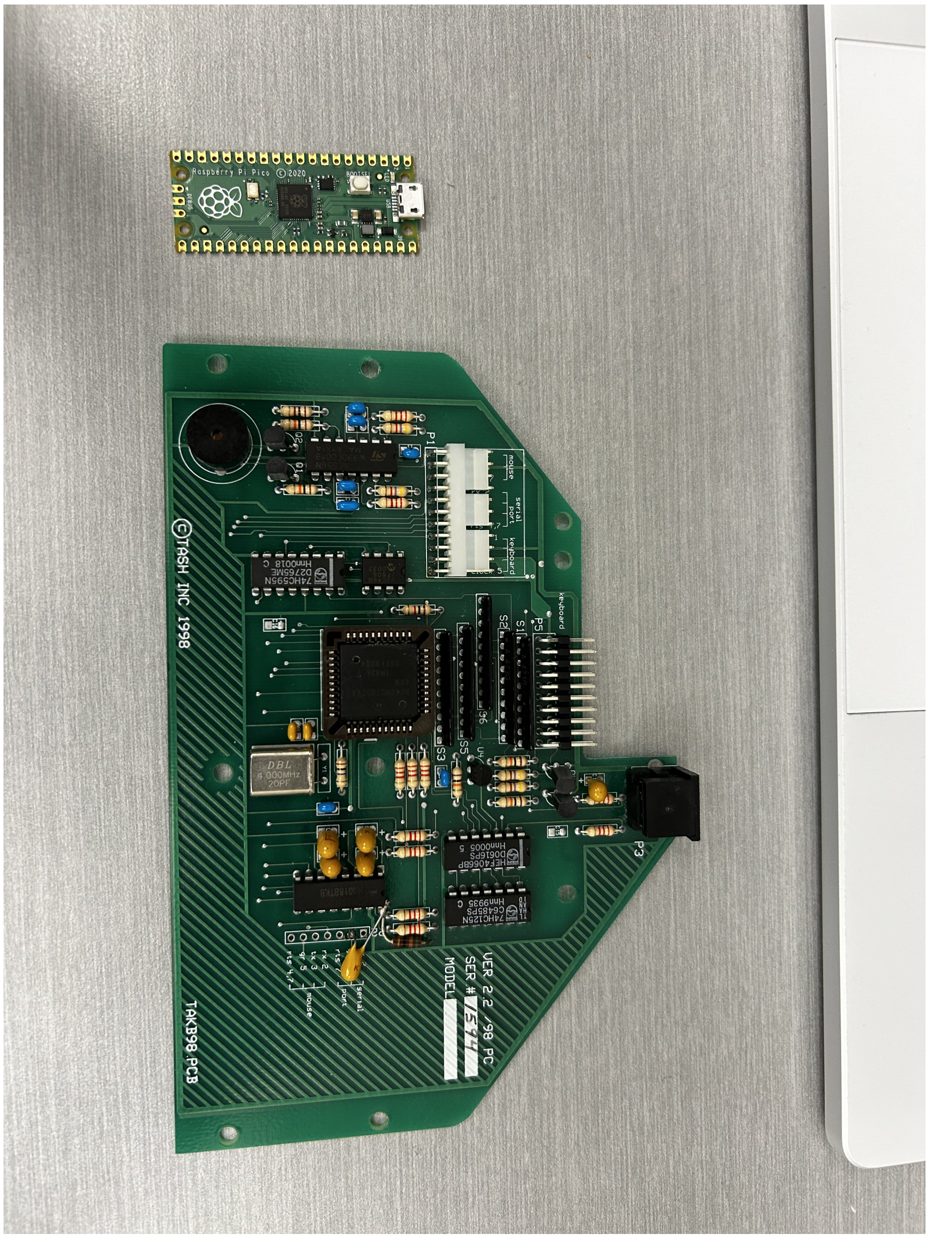

Figure 5.10: Generational comparison: the Raspberry Pi Pico microcontroller (top) alongside the original TASH Inc. King Keyboard PCB (bottom). The modern controller provides equivalent functionality in a fraction of the size, enabling the sustainability framework's goal of using commercially available, replaceable components.

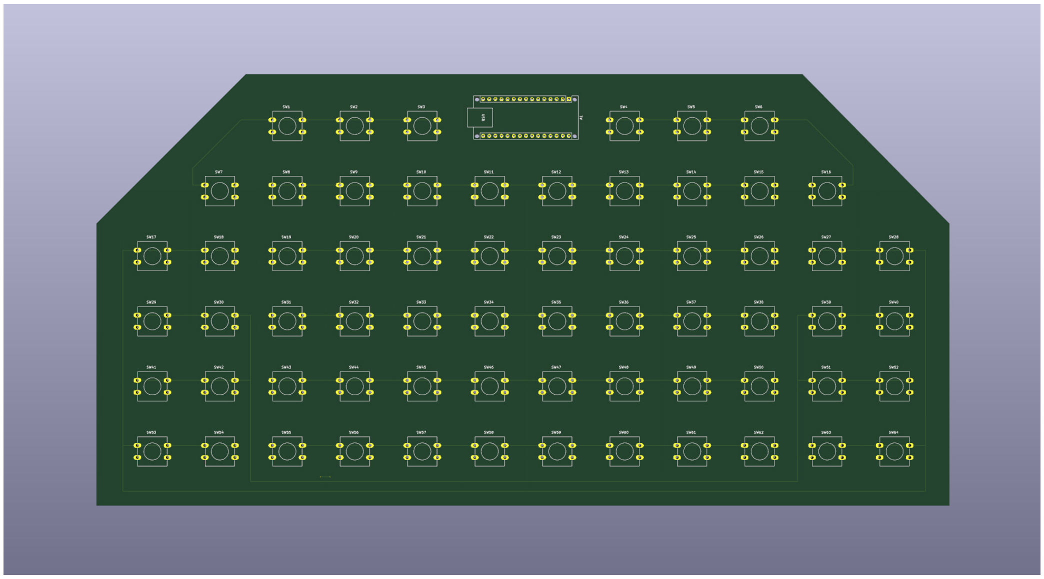

Figure 5.11: Final keyboard PCB design rendered in KiCad's 3D viewer (front view). The hexagonal form factor preserves the original King Keyboard's distinctive shape while incorporating button switches at each of the 64 key positions. The Raspberry Pi Pico mounting location is visible at the top center.

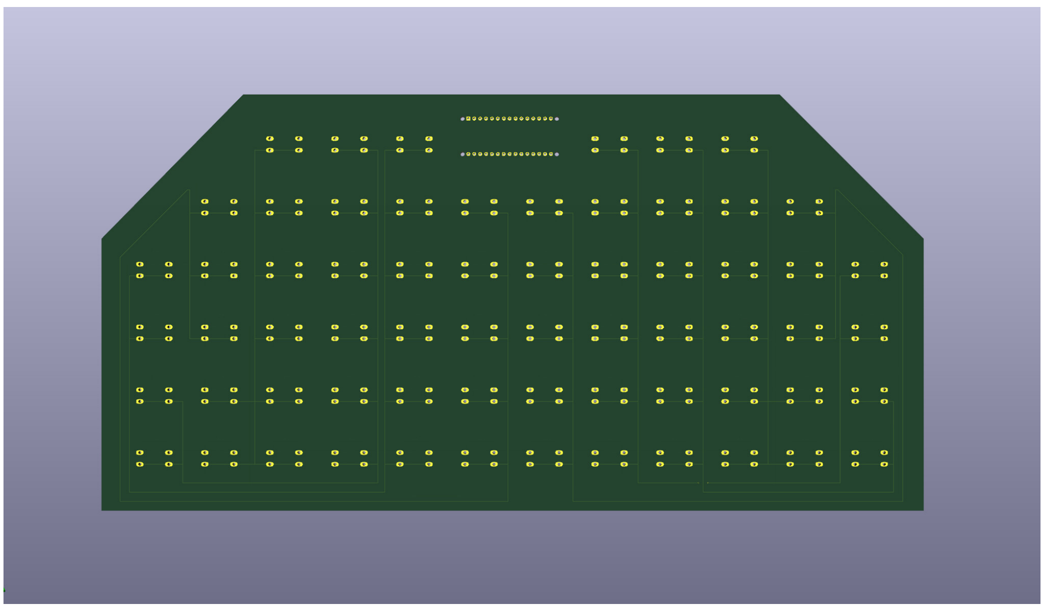

Figure 5.12: Final keyboard PCB design (rear view) showing the through-hole button switch pins and trace routing. This view reveals the manufacturing simplicity enabled by the button switch approach: all components mount from one side, simplifying factory assembly.

Chapter 6

Synthesis: Designing for Sustainability

This chapter synthesizes the parallel contributions to the co-design process: Rick's embodied expertise documented in Chapter 4 and my technical development journey documented in Chapter 5. It examines how co-designer expertise and technical problem-solving converged to address the research questions.

6.1 The Convergence: Expertise Meets Technical Solution

The co-design process revealed a productive division of expertise. Rick held authority over requirements, knowledge his body provided through decades of keyboard use. I held authority over implementation, technical knowledge of PCB design, fabrication services, and component selection. Neither form of expertise alone could have produced the design outcome.

Rick's requirements shaped every technical decision. His spacebar-anchored spatial memory (Theme 1) meant the new keyboard had to preserve the exact relative positions of keys. His prioritization of reliable key registration (Theme 2) meant that switch selection could not compromise tactile feedback for easier manufacturing. His left-hand optimization proposals (Theme 3) meant the layout had to accommodate his specific motor patterns. The technical development documented in Chapter 5 operated within these constraints.

Conversely, technical constraints shaped what could be offered to Rick. The button switch solution emerged from manufacturing realities, specifically what fabrication services could actually produce at accessible cost. The modular architecture responded to component availability, using commercially available Raspberry Pi Pico boards rather than custom microcontroller designs. The sustainability framework itself was a response to the technical analysis of why the original King Keyboard had become irreplaceable.

6.1.1 Participation Dynamics

The evidence structure across chapters reveals how different parties contributed different forms of expertise. Themes 1-3 in Chapter 4 draw primarily on Rick's direct statements (75-90% participant voice). Chapter 5 draws primarily on my technical documentation and design artifacts (approximately 85% researcher voice). This distribution is not a flaw in participatory methodology; it reflects the legitimate structure of expertise in this collaboration.

Rick contributes embodied authority on requirements, knowledge only his body can provide. I contribute systemic thinking on sustainability, conceptual frameworks that ensure long-term accessibility. Rick did not state sustainability as an explicit priority; he stated functional requirements (reliable key registration and left-hand optimization within preserved spatial relationships). I translated these requirements into a technical system designed for reproducibility and long-term maintenance. Rick validated these technical solutions by confirming they met his functional needs.

The sustainability framework serves Rick's stated priorities, as it ensures the keyboard he needs remains available over time. The framework emerged from my expertise in physical computing and fabrication, applied to requirements Rick's expertise defined.

6.2 Sustainability as Emergent Achievement

The project's sustainability framework did not exist at the outset. It emerged through the technical development process as I recognized what had made Rick's original keyboard irreplaceable and designed against those failure modes.

The "design package" concept captures this reorientation. Rather than delivering a single keyboard, the project produces a reproducible system: design files, component specifications, assembly instructions, and firmware code that enable future fabrication without the original designer's involvement. The button switch breakthrough enabled this framework to achieve its fullest expression. Factory-assembled switches eliminate the primary technical skill barrier. The end user receives a functional PCB requiring only mechanical assembly: no soldering, no electrical knowledge, no specialized tools. The "Lego-like assembly" principle, articulated early in the design process, found technical realization through this unexpected solution.

The design prioritizes commercially available components: standard button switches with existing KiCad footprints, widely available Raspberry Pi Pico microcontrollers, common screw sizes for mounting. If any single supplier discontinues production, equivalent components remain available from alternatives. This supply chain resilience addresses a vulnerability in Rick's original keyboard, namely custom components that could not be sourced when replacements were needed.

6.3 Interpretation of Findings

The thematic findings offer responses to each of the three research questions, responses grounded, as much as possible, in the empirical evidence of this co-design partnership.

6.3.1 RQ1: How Does Embodied Expertise Inform Design Requirements?

Given the thematic analysis presented in Chapter 4, it appears that embodied expertise informs design requirements through a sophisticated spatial memory system, a system that cannot be accessed through conventional design research methods. Rick's decades of keyboard use have produced what might be termed body-based knowledge, an intimate understanding of motor capabilities, limitations, and adaptations that exists primarily in muscle memory rather than conscious articulation. As Rick explained during the co-design sessions, his spatial navigation centers entirely on the spacebar: "My memory is all linked to the space key... the muscle memory is relative to the centre." This finding, that spatial memory anchors on the spacebar, significantly influenced the design approach. It established that any keyboard reconfiguration must preserve the spacebar as an anchoring reference point from which all other key positions derive their meaning.

Hamraie (2017) introduces a concept she calls "access-knowledge." She uses this term to describe expertise that disabled people develop through sustained engagement with built environments and technologies. For Hamraie, access-knowledge represents a form of understanding that emerges from lived experience rather than formal training. This positions disabled individuals as experts on their own accessibility requirements. The finding described above seems to fit within this framework. Rick's ability to articulate precisely how his muscle memory operates, which keys require problematic reaches, and how his left-hand-only typing technique shapes spatial needs demonstrates this access-knowledge in action. Conventional user research methods such as observation or task analysis would capture only surface behaviors; the co-design dialogue enabled Rick to externalize tacit knowledge that he himself may not have consciously examined before articulating it.

Rick's embodied expertise extends beyond the keyboard itself to encompass an integrated accessibility system. Hendren (2020) writes about how disabled individuals often need what she calls "a whole panoply of these extensions, where the work is distributed among multiple objects chosen for the fine-motor calibrations needed to get the job done" rather than "a single miraculous replacement." Rick's computing practice seems to show something like this. The keyboard does not function in isolation; rather, it functions alongside sticky keys software, auditory beep feedback, and decades of accumulated motor adaptations. Designing for Rick means designing within this existing system rather than replacing it wholesale.

Ostlund et al. (2021, p. 230) make what seems to be a related point. They write that assistive technology "reveals its true significance when situated in the environment of its use." What I understand them to mean is that the technology only makes sense when you see it being used in context. Rick's original King Keyboard cannot be understood apart from the decades of daily practice that shaped his relationship with it. The keyboard's significance emerged through embodied use; no specification document or ergonomic analysis could have predicted how Rick's spatial memory would anchor itself to the spacebar. This idea (that meaning emerges from context of use) may have implications for design method. It suggests that requirements might be better elicited through engagement with actual use contexts rather than derived solely from general principles.

Rather than positioning keys according to ergonomic guidelines developed for two-handed typists or accessibility standards assuming generic motor limitations, the design process could optimize specifically for Rick's established patterns. Theme 3 (Spatial Optimization for Single-Hand Access) documents the concrete requirements that emerged: numbers consolidated on the left side, shift key relocated to minimize awkward reaches, and overall layout organized around maintaining the spacebar as the spatial anchor.

6.3.2 RQ2: What Design Values and Spatial Preferences Emerge Through Co-Design?

The co-design process revealed what appears to be a clear hierarchy of design values, with function positioned as the sovereign priority above all other considerations. Theme 2 documents Rick's explicit articulation of this hierarchy: "The key strike is critical, that's the critical part of this keyboard... the shape of it and the aesthetics I can live with any shape." This finding may challenge certain assumptions present in some assistive technology literature regarding the importance of aesthetic acceptability (Profita et al., 2016; Williams et al., 2015). While research has documented stigma associated with medical-looking assistive devices and user preferences for mainstream-appearing technology, Rick's priorities diverge from this pattern. For him, reliable functional performance takes precedence over visual design.

This divergence does not indicate that aesthetics are universally unimportant for assistive technology users, but rather demonstrates the value of individual co-design over assumptions based on aggregate research findings. Rick's explicit subordination of aesthetics reflects his specific situation: after decades of using a keyboard that worked reliably, followed by an extended period without functional equipment, reliable key registration represents the most urgent need.

The process through which these values emerged merits attention. Clarke et al. (2021) discuss how trust develops in co-design. They observe that trust and distrust can be mediated "through both interpersonal relationships and material resources." In my understanding of their argument, this means that physical objects can help build trust between designers and participants. In this project, physical keyboard components (switches, stabilizers, keycap samples) served as shared reference points enabling dialogue across the different expertise domains of participant and researcher. When Rick handled actual switch samples during Session 2, he could assess tactile qualities and physical dimensions that verbal descriptions could not convey. His value hierarchy emerged through material engagement rather than abstract deliberation.

The spatial preferences emerging through co-design proved equally specific to Rick's embodied expertise. Rick's detailed verbal specifications from Session 2, documented by the researcher in layout diagrams, captured concrete spatial proposals: all number keys grouped on the left side to eliminate cross-keyboard reaches, shift key repositioned to the bottom-left corner, and frequently-used keys clustered within comfortable left-hand access. Treviranus (2018b) argues that inclusive design should position edge users as "full-fledged design team members, or co-designers." Rick's participation fits this description: he actively designed a configuration optimized for his specific motor patterns rather than choosing from a menu of predefined layouts.

6.3.3 RQ3: How Can Assistive Technology Be Designed for Sustainability?

Theme 4 addresses the sustainability question through two complementary design principles that emerged from this project: zero-soldering assembly and design package thinking. The original King Keyboard's failure mode, becoming irreparable when the sole technician who could maintain it was no longer available, illustrates the sustainability challenge facing custom assistive technology.

Rick's situation parallels patterns documented in the maker community literature. Buehler et al. (2015, p. 528) describe one assistive device on Thingiverse that "was designed because its commercial vendor had gone out of business and was no longer available to consumers." This situation sounds very similar to the King Keyboard's fate. Buehler et al. also point out that open-source documentation can help address this kind of vulnerability. They write: "DIY or self-designed AT can address several of the pitfalls of traditional or off-the-shelf AT. Devices and modifications can be tailor-made in a way that is often unavailable or pricey for standard AT fittings, end-user involvement can increase buy-in and reduce user abandonment" (p. 526). I tried to apply some of these ideas to the keyboard context in this project.

The design response achieves sustainability through reproducibility. Rather than delivering a single physical keyboard, this project produces a "sustainability package" comprising design files, component specifications, assembly instructions, and firmware code. Okun et al. (2024) discuss why people stop using assistive technology. One of the main reasons they identify is that devices become unusable when maintenance is too difficult or when parts cannot be found. By specifying commonly available commercial components (standard mechanical keyboard switches, a Raspberry Pi Pico microcontroller, off-the-shelf stabilizers), the design avoids dependence on custom or obsolete parts.

The zero-soldering assembly principle emerged from analyzing barriers to maintenance. A key development during the design process eliminated the primary technical skill requirement: factory-assembled button switches arrive pre-soldered to PCB contact pads, meaning the end user receives a board requiring only mechanical assembly. This reduces the technical knowledge required to assemble or repair the keyboard from basic electronics competency to what I termed a "LEGO-like" process of fitting standardized components together. Combined with hotswap sockets that allow switch replacement without desoldering, the design prioritizes accessibility of maintenance over manufacturing elegance.

6.3.4 Participation Dynamics as Methodological Finding

Beyond the substantive findings addressing each research question, the analysis revealed an important methodological pattern: different participants contributed different forms of expertise across themes. Themes 1 through 3 draw primarily on Rick's direct statements: approximately seventy-five to ninety percent of the supporting evidence comprises Rick's articulations of his embodied knowledge (including its temporal and social dimensions), functional priorities, and spatial preferences. Theme 4, conversely, draws approximately eighty-five percent of its evidence from my engineering decisions, design artifacts, and technical problem-solving, with Rick's contribution primarily taking the form of validating proposed solutions.

This voice distribution reflects a participation structure shaped by the project's origins. Sarmiento-Pelayo (2015) writes about something he calls "User-Initiated Design" (UID). What he means by this is that people with disabilities often transform their own environments to improve accessibility without professional intervention. While Rick's case differs (he sought collaborative assistance rather than modifying his environment independently), his approach seems to share one important characteristic with what Sarmiento-Pelayo describes: the disabled person, not the designer, identified the problem requiring solution. Rick recognized his accessibility problem, identified potential collaborators, and initiated contact seeking specific assistance. This user-initiated engagement influenced the participation dynamics throughout. Rick arrived with clear requirements derived from decades of use; the research task was to realize what he already knew rather than to discover what he needed.

The voice distribution reflects the different expertise each party brought to the collaboration rather than indicating diminished participation in Theme 4. Rick holds embodied expertise regarding his accessibility requirements; I hold technical expertise regarding keyboard engineering, PCB design, and manufacturing constraints. Some inclusive design scholars describe this kind of arrangement as complementary expertise. For example, Hamraie (2017) argues that co-designers contribute what she calls access-knowledge derived from lived experience, while designers contribute expertise in materializing solutions. The voice distribution across themes seems to show something like this relationship. Rick exercised authority over requirements (his capacity to define needs), while I exercised authority over technical implementation within those requirements. Both forms of expertise proved necessary; neither alone would have produced the design outcome.

6.4 Implications

The findings from this co-design project carry implications for inclusive design practice, assistive technology development, and participatory research methodology. This section considers each domain in turn, identifying how insights from this single-participant case study might inform broader practice while acknowledging the limits of generalization from individual cases.

6.4.1 Implications for Inclusive Design Practice

Inclusive design contests standard assistive technology research and development processes. As Treviranus (2018b) argues, inclusive design recognizes "the full range of human diversity" and leads to "one-size-fits-one" solutions that cannot emerge from conventional methods designed to produce population-level generalizations. The centrality of embodied expertise in this project demonstrates why: Rick's articulation of his spacebar-centered spatial memory system emerged through extended co-design dialogue, the kind of sustained conversation that observation, surveys, or brief interviews would not have enabled. Inclusive design practice requires methods capable of accessing body-based knowledge that conventional research techniques cannot surface, positioning users not as subjects to be observed or respondents to be queried, but as collaborators whose expertise guides design direction.

Given the finding that Rick's priorities diverge from patterns documented in AT aesthetics literature, this divergence suggests that individual engagement may be more important than population-level assumptions in some cases. Design guidelines derived from aggregate research provide useful defaults, yet individual users may hold different values. This finding does not invalidate the aesthetics research (many AT users do, after all, prioritize mainstream appearance), but it suggests that co-design dialogue should remain open to individual variation rather than assuming that documented patterns apply universally. Both Hamraie (2017) and Treviranus (2018b) argue that users should be treated as co-designers whose lived experience shapes design decisions. Following this principle seems to require genuine openness to requirements that may not match researcher expectations.

6.4.2 Implications for Assistive Technology Development

The sustainability framework developed in this project offers what I hope might serve as one approach to addressing assistive technology abandonment. The device abandonment literature identifies multiple factors contributing to AT disuse, including maintenance challenges, changing needs, and device-user mismatch (Okun et al., 2024; Desmond et al., 2018). Given these documented factors, this project's response (prioritizing reproducibility, specifying commercial components, and eliminating skill barriers to assembly) represents one possible operationalization of sustainability thinking in AT development.

The "design package" concept, a term I use to describe this approach, extends the deliverable beyond a physical artifact to include the documentation enabling future reproduction. For custom assistive technology serving individual users, this approach attempts to address a fundamental tension: devices customized to individual needs cannot be mass-produced, yet singular artifacts become vulnerable when the original creator becomes unavailable. The design package model attempts to resolve this tension by making the design knowledge, not just the physical device, the primary deliverable.

The zero-soldering assembly principle may have broader applicability beyond this specific keyboard project. Many maker-community AT solutions require electronics skills that users and their support networks may not possess (Buehler et al., 2015). Designing for factory assembly of skilled components while preserving user-accessible modification and repair could, in principle, expand the population capable of maintaining custom AT. This suggests, then, that AT designers might consider both whether a device meets functional requirements and who can feasibly assemble, modify, and repair it.

6.4.3 Implications for Co-Design Methodology

The voice distribution analysis across themes suggests what might serve as a methodological tool for assessing participation quality in co-design research. Braun and Clarke (2006, 2019) describe reflexive thematic analysis as a method that pays attention to researcher positionality and the interpretive nature of qualitative analysis. Building on their approach, adding explicit attention to voice attribution (tracking whose statements, artifacts, and decisions ground each theme) could provide additional transparency regarding how co-design authority was exercised and by whom.

This analytical attention to voice emerged from the unusual evidence structure in

Theme 4, where my engineering decisions rather than Rick's statements comprised the primary data source. Initially, this pattern raised concerns about whether Theme 4 represented genuine co-design or researcher-imposed design decisions. The resolution I arrived at, recognizing that different expertise domains warranted different voice distributions, validated through Rick's confirmation of proposed solutions, suggests that equal voice distribution may not always be the appropriate metric for evaluating co-design partnerships.

The three-session structure proved sufficient for this particular project, though different co-design contexts might require different configurations. The sessions served distinct functions: initial exploration and relationship-building (Session 1), detailed design specification (Session 2), and prototype review with refinement (Session 3). This structure emerged pragmatically rather than from methodological prescription. I offer it tentatively as a possible template for similar projects: an initial session to establish shared understanding, a middle session for substantive design work, and a later session for validation and refinement.

6.4.4 Broader Contributions

Beyond the immediate domains of inclusive design, AT development, and co-design methodology, this project may contribute to ongoing conversations about expert knowledge in design contexts. There is an ongoing tension between professional design expertise and user experiential expertise. Treviranus (2018b) argues that edge users should participate as "full-fledged design team members, or co-designers" rather than as research subjects. This case study may offer one illustration of how such tensions can play out. In this collaboration, different forms of expertise seemed to operate in complementary domains rather than competing for authority over the same decisions. Rick held authority over requirements derived from embodied expertise; I held authority over technical implementation within those requirements; both parties contributed to validating the resulting design.

The project also suggests that meaningful co-design can occur with a single participant over limited sessions. While participatory design literature often emphasizes community involvement and extended engagement (Baum et al., 2006), constraints of time, resources, and participant availability may preclude such approaches. This project achieved what I would characterize as substantive participant contribution and genuine shared authority within three ninety-minute sessions.

Finally, Hendren (2020) makes a distinction that seems relevant here. She distinguishes between what she calls "independence-as-self-sufficiency" and "independence-as-self-determination." The first means being able to do everything yourself. The second means being able to make decisions about your own life. Rick cannot manufacture or solder a keyboard himself, yet through this co-design process he determined what his keyboard should become. His inability to perform certain physical tasks did not diminish his authority over design decisions.

6.4.5 Challenging Standard AT Research and Development

This research implicitly challenges conventional approaches to assistive technology research and development. Standard AT development typically follows a pattern familiar from mainstream product design: identify average user needs, design for that average, and scale through mass production. This approach assumes that understanding the "typical" user of a device category provides sufficient guidance for design. Inclusive design contests this assumption.

Treviranus (2018d) observes: "If you want innovation or even design improvement, the best people to have at the design table are people that have difficulty with a current design." Edge users (individuals whose needs fall outside what current designs accommodate) reveal limitations that designing for the average cannot expose. Treviranus describes one of the "distressing phenomena" she observed during her career: "the degree to which excelling in the respected design methods often led to worse design for the individuals that most depended on a good design" (Treviranus, 2018d). Conventional methods, by averaging across users, systematically exclude those whose needs diverge most from the mean.

The alternative that inclusive design offers is to redirect rigor rather than abandon it. As Treviranus argues, rather than designing for the statistical center and scaling through replication, inclusive design begins at the edges and scales through diversification. Rick's keyboard cannot be mass-produced, but the design approach documented here could be adapted for other individuals whose needs differ from his. Each edge user who participates in co-design stretches what keyboard design can accommodate. The system becomes more adaptive through accumulated diversity rather than through standardization.

This may have implications for how AT research is funded, evaluated, and disseminated, though exploring such implications is beyond the scope of this study. Funding structures that reward scalability through mass production may inadvertently disadvantage approaches designed for users with complex individual needs. Evaluation metrics focused on population-level outcomes may miss the significance of designs that work exceptionally well for individuals. Dissemination practices that prioritize generalizable findings may undervalue the detailed documentation of one-size-fits-one solutions.

6.5 Limitations

This study carries limitations that should inform interpretation of its findings and any broader applications. Acknowledging these constraints positions this work appropriately within the larger context of inclusive design and participatory research.

6.5.1 Single Participant

The most significant limitation is, in my assessment, the single-participant design. While the case study methodology (Yin, 2018) justifies in-depth engagement with individual cases, findings derived from one participant cannot be assumed to transfer to other individuals with cerebral palsy, other keyboard users, or other assistive technology contexts. Rick's embodied expertise, functional priorities, and spatial preferences reflect his specific motor capabilities, decades-long history with this particular keyboard, and personal values. Another individual with cerebral palsy might have entirely different priorities: perhaps valuing aesthetics highly, or requiring different spatial configurations, or possessing different technical capabilities for assembly and maintenance.

The single-participant limitation also means that the themes emerged from dialogue with one person. While thematic analysis does not require large sample sizes to identify meaningful patterns (Braun and Clarke, 2006), themes grounded in one participant's experience should be understood as documenting that individual's reality rather than claiming representativeness of broader populations.

6.5.2 Formal Data Collection Scope

The thematic analysis draws on transcribed data from three ninety-minute formal sessions. While the co-design partnership extended over ten months (with ongoing communication, prototype iterations, and informal consultation throughout), only the formal sessions were systematically recorded, transcribed, and subjected to thematic coding. This means that the analyzed data represents structured moments within a longer collaboration rather than the collaboration's full texture.

This limitation cuts two ways. On one hand, informal exchanges may have contained insights not captured in the formal data corpus. On the other hand, the extended relationship enabled depth that three isolated sessions could not achieve: by the third formal session, months of shared work had established mutual understanding that shaped what Rick chose to articulate and how I understood his statements.

The session structure was shaped by practical constraints (Rick's availability, scheduling logistics, and the timeline of a master's research project) rather than methodological determination of optimal duration. Future research might explore methods for systematically capturing data from the informal exchanges that often prove generative in extended co-design partnerships.

6.5.3 Researcher Positionality

My dual role as researcher and designer warrants explicit acknowledgment. I conducted the co-design sessions, performed the thematic analysis, and made the engineering decisions documented in Theme 4. While reflexive thematic analysis expects and accommodates researcher interpretation (Braun and Clarke, 2019), the lack of additional perspectives in the analysis process means that alternative interpretations of the data were not systematically explored.

My prior relationship with Rick and his family, having worked with his mother on accessibility projects before this research began, may have shaped the co-design dynamic in ways that are difficult to fully assess. This existing relationship likely facilitated trust and open dialogue; however, it may also have introduced assumptions or patterns of interaction that influenced the data.

6.5.4 Scope Limitations

This project focused on keyboard hardware design; software customization and broader computer access solutions were outside scope. Rick uses additional accessibility software (sticky keys, screen reader for some tasks) that interacts with keyboard input; however, this research did not systematically address software-hardware integration. A broader approach might have considered the keyboard as one component within a larger accessibility ecosystem.

The sustainability framework proposed in Theme 4, while addressing reproducibility and maintenance barriers, has not yet been tested through actual reproduction by others. The design package exists; whether it successfully enables independent fabrication remains to be demonstrated.

6.6 Recommendations

Building on the findings and acknowledging the limitations discussed above, this section offers recommendations for practitioners, researchers, and policy contexts.

For inclusive design practitioners, this project suggests prioritizing methods that enable participants to articulate embodied knowledge through extended dialogue, participatory design sessions, and collaborative meaning-making rather than brief consultation or observation-based research. Practitioners should also remain alert to individual variation; population-level research provides useful defaults but should not override individual preferences when direct engagement is possible.

For assistive technology developers, the sustainability framework offers a practical model: specify commercial components, design for zero-soldering assembly where feasible, and document designs thoroughly enough to enable reproduction.

For researchers, the voice distribution analysis demonstrated here might serve as a transparency tool in co-design research. Explicitly documenting whose contributions ground each finding may help readers assess participation quality and guards against tokenistic claims of co-design authority.

For policy contexts, this project highlights the ongoing challenge of custom assistive technology sustainability. Even well-designed, perfectly functional devices become disposable when the knowledge to maintain them is lost. Policies supporting AT provision might consider device acquisition alongside long-term maintenance documentation and knowledge transfer.

Chapter 7

Conclusion

This chapter returns to the research questions posed in the Introduction, reflecting on what the findings suggest for inclusive design practice more broadly.

7.1 Summary

This research began with a problem of device abandonment: Rick, an individual with cerebral palsy who had used a personalized accessible keyboard for decades, faced the loss of his remaining functional devices with no viable replacement options. The original King Keyboard, developed by Jutta Treviranus at the Inclusive Design Research Centre, had enabled decades of successful computer use, yet the manufacturer had ceased production and the expertise embedded in the original design was no longer available. Government assistive technology programs could not fund custom design, and no commercial alternative existed for a keyboard with Rick's specific layout and key-strike characteristics.

The research employed participatory co-design methodology, treating Rick as a design partner whose embodied expertise constitutes a form of knowledge that observation or interview alone cannot access. I chose this methodology because the research questions themselves demanded it: understanding embodied expertise requires genuine partnership, not extraction. Over three co-design sessions spanning ten months, the collaboration produced both a functional keyboard design tailored to Rick's specific needs and a reproducible design package intended to ensure long-term sustainability.

Reflexive thematic analysis of the co-design sessions revealed three themes emerging from Rick's contributions. The first theme, Embodied Expertise as Design Authority, documented how Rick's decades of keyboard use produced body-based knowledge, namely spatial memory anchored to the spacebar and precise self-awareness of motor patterns accumulated over years, that served as the irreplaceable foundation for design requirements. The second theme, Function as the Sovereign Design Value, revealed Rick's explicit prioritization of reliable key registration over aesthetic considerations, a finding that diverges from some patterns documented in assistive technology literature. The third theme, Spatial Optimization for Single-Hand Access, captured Rick's concrete design proposals: numbers consolidated on the left side, shift key relocated for comfortable access, and overall layout organized to eliminate cross-keyboard reaches that required whole-body repositioning. These participant-voiced themes are grounded primarily in Rick's direct statements (75-90% participant voice), establishing him as the authority on his own accessibility requirements.

A separate chapter documented the technical development journey through which Rick's requirements were translated into a manufacturable, sustainable design. This chronological narrative traced my learning of PCB design from scratch, the months-long struggle with the dual-footprint problem, and the eventual button switch breakthrough that enabled both sustainability and assembly accessibility. The technical framework I developed ensured the design could be reproduced and maintained without specialized expertise: zero-soldering assembly through factory-assembled switches, modular components, commercial parts, and detailed documentation.

Together, the participant expertise themes and the technical process documentation addressed the three research questions guiding the study. Rick's embodied expertise informed design requirements through a sophisticated spatial memory system and precise self-awareness of motor capabilities (RQ1). Design values and spatial preferences emerged through the co-design process, with function positioned as the sovereign priority and concrete layout proposals expressing Rick's embodied knowledge in actionable terms (RQ2). The sustainability framework demonstrated how assistive technology can be designed for long-term reproducibility through design package thinking and zero-soldering assembly using modular architecture (RQ3). The voice distribution across chapters, with Rick's statements grounding the participant expertise themes and my technical documentation grounding the process chapter, revealed participation dynamics that represent genuine co-design partnership where different forms of expertise operate in complementary domains.

7.2 Contributions

This research attempts to contribute to multiple domains: inclusive design scholarship, assistive technology development practice, and participatory research methodology. Whether these contributions prove valuable remains for readers and future researchers to assess, yet I believe the research offers something meaningful to each domain.

For inclusive design scholarship, the project provides detailed documentation of how embodied expertise may operate as a design resource. Hamraie (2017) developed the concept of "access-knowledge" to describe expertise that emerges from lived experience navigating accessibility challenges. Rick's articulation of his spacebar-centered spatial memory system, a form of body-based knowledge that emerged through sustained co-design dialogue, provides what I hope is useful empirical grounding for this concept. The finding that Rick's priorities diverge from documented patterns in assistive technology aesthetics literature demonstrates the importance of individual engagement over population-level assumptions. Aggregate research provides useful defaults; nevertheless, this case suggests that genuine co-design must remain open to individual variation.

For assistive technology development practice, the sustainability framework offers what may be a useful model for addressing device abandonment. Rather than delivering a singular artifact that becomes irreplaceable when its creator is unavailable, this project produces a design package: specifications, component lists, assembly instructions, and firmware code that enable reproduction without the original designer's involvement. The zero-soldering assembly principle, achieved through factory-soldered button switches, reduces maintenance barriers by eliminating the technical skill requirements that render many custom assistive technologies inaccessible to users and their support networks.

For participatory research methodology, the voice distribution analysis demonstrates what I found to be a useful tool for assessing participation quality in co-design contexts. Whether this approach transfers to other settings is a question future research might explore. Explicitly tracking whose contributions ground each theme provides transparency regarding how design authority was exercised. The distribution observed here, participant-primary on requirements and researcher-primary on implementation with mutual validation throughout, represents one model of authentic co-design partnership where different forms of expertise operate in complementary rather than competing domains.

7.3 Future Work

Several directions for future work emerge from this research, ranging from immediate next steps to longer-term questions.

The most immediate priority involves completing the final prototype and conducting iterative testing with Rick. While the current design has been validated through firmware testing and component verification, extended daily use will likely reveal refinements needed for optimal performance. The co-design methodology employed throughout this project will continue into this testing phase, with Rick's feedback guiding any necessary modifications.

A second priority involves testing the reproducibility of the design package. I have argued that the sustainability framework enables reproduction without specialized expertise, yet this claim has not been empirically validated. Future work should include reproduction attempts by individuals unfamiliar with the original design process to assess whether the documentation achieves its intended purpose.

Longer-term research might explore how the sustainability framework developed here could apply to other forms of personalized assistive technology. The principles of zero-soldering assembly and modular design package thinking are not specific to keyboards; they might inform the development of other custom devices that currently suffer from the same sustainability vulnerabilities.

The divergence between Rick's aesthetic priorities and patterns documented in AT literature suggests another research direction: investigating individual variation in AT value hierarchies. A comparative study examining function-versus-aesthetics priorities across multiple AT users might reveal whether Rick's preferences represent an outlier case, a subpopulation with similar values, or evidence that the existing literature has overemphasized aesthetic concerns.

Finally, this project highlights policy implications regarding assistive technology sustainability that warrant further investigation. Current funding structures emphasize device acquisition rather than long-term maintenance or knowledge transfer. Research examining how policy frameworks might better support sustainable AT provision (including documentation requirements and maintenance funding, as well as open-source design repositories) could translate the principles developed in this single-case study into systemic recommendations.

7.3.1 Closing Reflection

This MRP began with a crisis of device abandonment and concludes with what I hope are the outlines of a sustainable solution. Rick approached the IDRC seeking help after an extended period without functional equipment; the co-design process documented here produced both a keyboard tailored to his specific needs and a framework intended to ensure that keyboard can be reproduced and maintained over time.

A contribution that may prove useful is methodological rather than technical. This research suggests that long-term assistive technology users possess forms of expertise, embodied and spatial, accumulated over decades, that conventional design research methods struggle to access. Rick's knowledge of his own accessibility requirements, held in muscle memory and manifested in precise spatial preferences, would likely not have emerged through observation or brief consultation alone. It emerged through sustained co-design dialogue that treated his expertise as authoritative. In this sense, the keyboard that results from this process represents, I hope, what can happen when embodied expertise is genuinely centered in design.

Bibliography

Baum, F., MacDougall, C., and Smith, D. (2006). Participatory action research. *Journal of Epidemiology and Community Health*, 60(10):854–857.

Birt, L., Scott, S., Cavers, D., Campbell, C., and Walter, F. (2016). Member checking: A tool to enhance trustworthiness or merely a nod to validation? *Qualitative Health Research*, 26(13):1802–1811.

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2):77–101.

Braun, V. and Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*, 11(4):589–597.

Buehler, E., Branham, S., Ali, A., Chang, J. J., Hofmann, M. K., Hurst, A., and Kane, S. K. (2015). Sharing is caring: Assistive technology designs on thingiverse. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pages 525–534, New York, NY. ACM.

Clarke, R. E., Briggs, J., Armstrong, A., MacDonald, A., Vines, J., Flynn, E., and Salt, K. (2021). Socio-materiality of trust: Co-design with a resource limited community organisation. *CoDesign*, 17(3):258–277.

Desmond, D., Layton, N., Bentley, J., Boot, F. H., Borg, J., Dhungana, B. M., Gallagher, P., Gitlow, L., Gowran, R. J., Groce, N., Mavrou, K., Mackeogh, T., McDonald, R., Pettersson, C., and Scherer, M. J. (2018). Assistive technology and people: A position paper from the first global research, innovation and education on assistive technology (great) summit. *Disability and Rehabilitation: Assistive Technology*, 13(5):437–444.

Geertz, C. (1973). *The Interpretation of Cultures*. Basic Books, New York, NY.

Hamraie, A. (2017). *Building Access: Universal Design and the Politics of Disability*. University of Minnesota Press, Minneapolis, MN.

Hendren, S. (2020). *What Can a Body Do? How We Meet the Built World*. Riverhead Books, New York, NY.

Munteanu, C., Molyneaux, H., Moncur, W., Romero, M., O'Donnell, S., and Vines, J. (2015). Situational ethics: Re-thinking approaches to formal ethics requirements for human-computer interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, pages 105–114, New York, NY. ACM.

Okun, M. S. et al. (2024). Device abandonment: Key factors and the need for industry- and government-level solutions. *Frontiers in Human Neuroscience*, 18:Article 1377020.

Östlund, B. and Frennert, S. (2021). How have user representations been sustained and recreated in the design of technologies between 1960 and 2020? In Peine, A., Marshall, B. L., Martin, W., and Neven, L., editors, *Socio-Gerontechnology*, pages 228–240. Routledge, London.

Profita, H. P., Stangl, A., Matuszewska, L., Sky, S., and Kane, S. K. (2016). Nothing to hide: Aesthetic customization of hearing aids and cochlear implants in an online community. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '16)*, pages 219–227, New York, NY. ACM.

Sarmiento-Pelayo, M. P. (2015). Co-design: A central approach to the inclusion of people with disabilities. *Revista de la Facultad de Medicina*, 63(Sup. 1):S149–S154.

Treviranus, J. (1994). Mastering alternative computer access: The role of understanding, trust, and automaticity. *Assistive Technology*, 6(1):26–41. An early framework for understanding skill acquisition in alternative computer access.

Treviranus, J. (2018a). Let's not spend public funds to perpetuate digital disparity. Medium. Inclusive Design Research Centre, OCAD University.

Treviranus, J. (2018b). The three dimensions of inclusive design: Part one. Medium. Inclusive Design Research Centre, OCAD University.

Treviranus, J. (2018c). The three dimensions of inclusive design: Part three. Medium. Inclusive Design Research Centre, OCAD University.

Treviranus, J. (2018d). The three dimensions of inclusive design: Part two. Medium. Inclusive Design Research Centre, OCAD University.

Waycott, J., Davis, H., Thieme, A., Branham, S., Vines, J., and Munteanu, C. (2015). Ethical encounters in hci: Research in sensitive settings. In *CHI'15 Extended Abstracts on Human Factors in Computing Systems*, pages 2369–2372, New York, NY. ACM.

Williams, M. A., Buehler, E., Hurst, A., and Kane, S. K. (2015). What not to wearable: Using participatory workshops to explore wearable device form factors for blind users. In *Proceedings of the 12th Web for All Conference (W4A '15)*, pages 1–4, New York, NY. ACM.

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods*. SAGE Publications, Thousand Oaks, CA, 6th edition.