A study into the impact cross-device controllers may have on User Experience

The usability of cross-device controllers

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Abstract

Many digital platforms require a controlling device for people to interact with them. Examples include TVs with remotes, gaming consoles with controllers and computers with a keyboard. The systems are tightly coupled with their interfacing devices (controller). This coupling leads to unnecessary toxic electronic waste, increases the entry cost to use the digital platforms and often excludes people with niche accessibility needs. This research proposes the first step in assessing the feasibility of decoupling core platforms and controllers by investigating the impact that reusing controllers across different applications, for which they are not intentionally designed, would have on the User Experience. The mixed-method study uses McNamara and Kirakowski's 2006 theoretical framework of understanding Human-Computer Interaction (HCI) to assess research participants' experience of using three different controllers to interact with two digital products. The study found no significant degradation on the HCI when participants used different controllers. Instead, the results proved that non-conventional controllers enhanced some elements of the participants' experiences, such as effectiveness. The findings highlight the subjective nature of HCI and, by extension, the need for industry-wide standardisation of interfacing between controllers and platforms to drive innovation in the controller space, which will ultimately lead to better HCI.

1. Introduction and Background

The use of technology has become an integral aspect of our daily routine. Along with the main products and platforms, we often receive additional hardware peripheral devices to complement the main platform/product. Examples of these peripherals include the routers we get every time we switch Internet Service Providers (ISPs), earphones and chargers with new cell phones and tablets, and the controllers and remotes that accompany gaming consoles, drones, soundbars and other digital products we buy. While most of these devices serve similar purposes and may even look alike, each platform contributes to the growing collection of single-use controllers and peripherals we accumulate in our respective households that we can never use on anything else. This leads to three key concerns: the production of excessive e-waste, increased costs, and the marginalisation of people with disabilities in user experience. Decoupling interface devices from the core platform has the potential to reduce e-waste and create opportunities for the development of affordable accessibility-focused interfaces. The feasibility of such decoupling requires the understanding of how the HCI will be impacted when the core-platforms are engaged with using interfacing devices that are unconventional and were not originally designed with the platform. Thus, this study aims to understand this impact by measuring the HCI when digital systems are used with different interfacing devices.

Over the past decade, our reliance on electronic devices has experienced a significant surge. While the number of electronic devices being produced continues to increase, their lifespan is getting shorter [1]. In the year 2020 alone, the world generated approximately 50 million tons of electronic waste (e-waste), with an average annual growth of 2 million tons between 2010 and 2019 [1, 14]. This rise in e-waste has raised serious concerns, especially considering that electrical components often contain hazardous chemicals that can contaminate soil and water if not disposed of properly [1, 14].

According to the United Nations Institute for Training and Research (UNITAR)’s 2022 report on the Global Progress of e-waste legislation, Only 17.4% of e-waste is recycled responsibly, while the rest is illegally dumped, overwhelmingly in low- or middle-income countries [27]. This, according to the World Health Organisation's (WHO)’s “Children and digital dumpsites: e-waste exposure and child health” report, exposes children and adults who live and work near e-waste sites to over 1000 harmful substances, posing a great health risk [28]. Additionally, the prevalence of single-use controllers adds to the overall cost of purchasing these devices and platforms, making affordability a significant barrier for many individuals to use them and benefit from their value.

According to the World Health Organization (WHO), around 15% of the global population is estimated to have some form of disability [15]. Unfortunately, the standard controllers that typically come with electronic devices often do not consider the physical accessibility needs of individuals with disabilities. As a result, this exclusionary design approach has the potential to restrict access for millions of people worldwide.

1.1. Problem statement

The tight coupling of digital products and platforms to their interfacing devices (controllers) is problematic. It leads to increased e-waste, higher costs to purchase the products, stifles innovation and is exclusionary in nature.

1.2. Potential Solution

Currently, there are only a limited number of ways for controller devices to communicate with other hardware. USB is the most commonly used for wired connections, and Bluetooth has recently replaced infrared for wireless communication technology. The adoption of cross-device/platform reusable controllers is proposed as a potential solution to address the issues arising from single-use controllers. These controllers would continue to utilize standard communication methods but also work seamlessly with other platforms and products. The viability of this potential solution would require platform providers to adhere to industry-established standards to ensure seamless and engaging user interaction.

The software development field provides valuable insights into the potential structure of the architecture that could support this approach. The software development industry standards have shifted from building monolithic applications to constructing decoupled systems using approaches like the three-tiered architecture [9]. This architectural design separates the front-end, which handles the user interface, from the back-end where the application's core value resides, and the data layer, where data produced and required by the systems may reside in many forms.

This approach offers several benefits. It allows for the provision of multiple user interfaces that are developed using different technologies and by different teams and entities, all leveraging a single core business and logic layer. This empowers users of the solution to choose how they interact with the core service(s) provided by the system. Whether users prefer using a mobile or desktop device, or if they opt for an Android or iOS operating system, this architecture ensures that they have consistent access to the platform's core value while giving them the freedom to choose what interface best services their needs.

Similarly, by decoupling the interfacing or controller device from the core platform, users would gain the ability to make decisions on how they want to interact with the system while still accessing its core value. Some users might prefer tried and tested controller designs, while others might take pleasure in exploring new HCI possibilities. Overall, this approach grants users greater flexibility and empowers them to tailor their interaction experience with the system while benefiting from the platform's core functionality.

The diversity of accessibility needs globally is extensive [2]. Addressing accessibility needs involves intricate and tailored customizations, which can be challenging, considering that not all product designers have the required skills, resources, and funding to create controller interfaces that cater to everyone's needs. However, by separating the concerns of the controller device from the platform, the industry could enable users with physical accessibility needs to find controllers that best suit their individual needs. These individuals would then be able to use these controllers to interface with a wide range of platforms, offering them greater accessibility and flexibility while limiting the financial burden of commissioning the building of custom interfaces for the platforms they use.

1.3. Key Consideration

In order to facilitate industry-wide adoption of the approach to decouple the concerns of the controller and the platform, it is crucial to address a fundamental question: Will it work? This question can be broken down into two parts that consider the technical capabilities of our time and their impact on the people that have to use them.

The first aspect to consider is technological feasibility and asks:

> *Is it possible to create a controller that can be reused and re-purposed to interface with various devices and platforms?*

This question relates to understanding the technical requirements and limitations of such a setup and evaluating whether it is viable or not.

The second aspect deals with the impact on HCI and asks:

> *Will users still be able to enjoy the core value that platforms provide if they use a controller that was not explicitly designed for that platform?*

For instance, can a user play games, operate a drone or send messages if they use a different controller? Answering this question is critical to establishing the feasibility of this approach before significant investments are made in technological development.

Therefore, addressing both these aspects and the one around HCI, in particular, is essential to evaluate the feasibility of decoupling the controller and the platform's concerns while ensuring that the users can still meaningfully obtain the platform's core value. This study aims to address this question.

1.4. Research question

The purpose of the study is to assess the impact that using a digital product with controllers that were not initially explicitly designed for it has on the user's experience. This is done to add to a larger body of work aimed at reducing e-waste, the cost of technology and building an inclusive technology ecosystem driven by innovation.

The study attempts to answer the following research question:

How does the use of digital systems with interfacing devices that were not designed for them impact the Human-Computer Interaction?

This study, therefore, by extension, asks whether the potential degradation of the HCI is a barrier to the development of systems that are decoupled from their peripheral interfacing devices.

1.5. Significance of the study

Accessibility and Legislation

This research is being conducted during a period when there is a growing emphasis across the technology industry in general and the software development industry in particular, to prioritize accessibility for individuals who were previously excluded due to their accessibility needs. This effort is evident in the creation of dedicated accessibility gaming kits like the Microsoft Xbox Adaptive Controller [16], the SubPac M2X [13], and the QuadStick FPS Game Controller [11]. These kits cater to customers with specific physical disabilities and address a previously underserved market niche.

The priority is also evidenced by a growing number of legislative requirements to make digital systems accessible to everyone. Germany's Federal Parliament passed a bill on May 20, 2021, known as the Accessibility Act [29], which aims to ensure that digital systems are developed to cater to all of their users. This was done to implement the 2019 European Union's Directive on accessibility requirements for products and services [30].

Although the aforementioned peripherals fulfil a specific need, their compatibility is restricted to certain platforms. As a result, they only address the problem for a particular product and may not support the users' complete engagement with technology. The purpose of this research is to evaluate the potential impact of repurposing these controllers for other systems and applications that users may also need to use. By doing so, the research aims to understand how these controllers would affect HCI and whether they can effectively be used across a wider range of platforms and applications.

Cost of software development and Developer experience

The cost of software development is a major concern, prompting developers to seek ways to build applications once and deploy them across multiple platforms. One crucial aspect that developers need to consider is the controller used on each platform. They must determine the optimal button combinations for users to perform slightly advanced actions. However, this process becomes problematic in two ways.

Firstly, developers need to reconfigure the control scheme for each platform they intend to target, which increases development costs. This additional work creates overheads that impact both time and resources.

Secondly, it is impossible to make decisions that cater to the specific needs of every individual user. People have different hand sizes, cultural affordances, and varied experiences that affect their ability to perform certain movements and actions. Designing for an "average user" is often the default approach, which typically represents an able-bodied white male from a Western country. A demographic that is in the minority. This practice can be exclusionary as it fails to account for diverse user populations and their unique requirements.

By acknowledging these challenges and exploring alternative solutions to specific needs independently, developers can strive to create more inclusive and accessible designs that better accommodate the diverse needs of users from different backgrounds.

1.6. Definition of Terms

Term	Definition
HCI	Human-Computer Interaction
SMEQ	Subjective Mental Effort Questionnaire
CIT	Critical Incident Technique
Controller	A peripheral interfacing device, such as a remote or gaming controller
PS4	Sony PlayStation Controller
NASA-TLX	NASA Task Load Index
ASQ	After-Scenario Questionnaire
SUS	System Usability Scale
WHO	World Health Organisation
Study Participant	A person who volunteered to participate in the study. They must be above the age of 18.
Electrical and electronic waste (e-waste)	Any electrical or electronic equipment, which is waste, including all components, subassemblies and consumables which are part of the equipment at the time the equipment becomes waste
Disability	WHO defines disability as an umbrella term that encompasses impairments, activity limitations, and participation restrictions.
Accessibility	Refers to the design and implementation of products, services, and content in a way that ensures they can be used, understood, and enjoyed by people of all abilities, including those with disabilities.

1.7. Assumptions and Limitations

This study is conducted by a single researcher with time and resource constraints. As such, the number of participants studied is limited to 15 people. Furthermore, the systems that the participants engage with are set to facilitate a short enough playtime to limit the experiment to no more than an hour per participant.

This study is centred on the usability of digital products. While the development of the software follows industry standards which lead to overall better accessibility, this study does not claim to explicitly address accessibility considerations and needs.

2. Literature review and related works

This work builds on the knowledge provided by several research efforts undertaken over the past two decades. These efforts have focused on developing user-friendly and accessible technologies while also striving to create an environment that is comfortable and cost-effective for developers. The existing body of literature serves as the fundamental basis for this research.

2.1. Theoretical framework

The objective of this study is to utilize McNamara and Kirakowski's theoretical framework for understanding the interactions between computers and humans [3]. In their 2006 paper titled "Functionality, usability, and user experience: three areas of concern" [3], McNamara and Kirakowski propose three essential components to consider when evaluating technology usage. These components are the product itself, the interaction between the user and the product, and the user's experience while using the product. They categorize these components as "Functionality," "Usability," and "(User) Experience" [3]. By adopting this framework, this research aims to gain a comprehensive understanding of the impact and significance of these three elements in the context of technology and HCI.

The authors understand Functionality to be a technical aspect focused solely on the product and its features, performance, reliability, and durability. The primary goal of evaluating Functionality is to address questions related to what the product actually does.

In contrast, usability is described as the interaction between the user and the product. Since it involves user experience, the authors argue that it should be evaluated with real users. They recommend using established usability evaluation methods while ensuring their suitability for modern technologies. The authors propose defining usability as "the extent to which a product can be effectively, efficiently and satisfactorily used by specified users to achieve specified goals," as outlined in ISO 9241-11 [19].

Regarding User Experience, the authors acknowledge it as a relatively new field in HCI during their time, and they note the lack of well-developed assessment methods. They urge researchers to explore appropriate and relevant methods for assessing User Experience, considering the advancements in the field and the context of their own time. The aim of investigating User Experience is to explore users' personal experiences when using the product and to consider the broader relationship between the product and the user.

They strongly emphasize that the elements are not completely separate or independent from one another. As evidence, they refer to Tractinsky's study, which demonstrates that users' perception of a computerised system's beauty significantly influences their perception of its usability [18]. This example illustrates that a device's appearance can impact both usability and user experience.

McNamara and Kirakowski also caution against adopting a standardised approach to measure these three elements, rejecting the idea of using a single method for all cases. They stress the importance of avoiding limitations to traditional usability evaluation methods, such as solely measuring completion time and the number of errors. Instead, they advocate for a more context-specific approach to evaluation [3].

McNamara and Kirakowski present a comprehensive framework for evaluating technology, which is a central focus of this study. Their framework identifies three key areas that need to be examined to assess the HCI for each control scheme. By comparing these three elements across various control schemes, this study aims to measure the overall impact of using cross-platform/device controllers on HCI.

Furthermore, the paper offers a general guideline that researchers should consider when measuring HCI. Understanding and implementing this guideline is crucial to the present study's objectives. It provides valuable insights into how the evaluation process should be carried out and what factors need to be taken into account to gain a deeper understanding of the impact of different control schemes on HCI.

2.2. Decoupled Systems

In order to conduct a suitable experiment, it is crucial to understand the implementation of a decoupled design pattern, which allows for the separation of the controller and platforms. In the second edition of his book "Cloud Computing [9]," Dan C. Marinescu provides insights into the history of computing and how the software engineering field has evolved to deliver solutions. In chapter one, Marinescu dissects the components of modern software solutions, offering a framework that can be adapted to the controller-platform context at hand.

To achieve this, Marinescu emphasizes the significance of providing "elastic services [9]" that are cost-effective. He highlights Cloud Technology as the core platform for delivering value in contemporary software solutions. In the undertaken study's context, this was the central platform used. The database was cloud-based, and the applications were hosted using a cloud service provider. Additionally, he positions the consuming front-end systems, which interact with the Cloud Services, in a similar peripheral/controller device position within the decoupled approach. This perspective facilitates understanding the interaction between controllers and platforms in the experiment.

The application of a decoupled design pattern is not only evident in the context discussed earlier but is also observed in other related fields, as exemplified in the article titled "A Three-Tier Architecture of Large-Scale Wireless Sensor Networks for Big Data Collection" by Abba Ari AA, Djedouboum AC, Gueroui AM, Thiare O, Mohamadou A, and Aliouat Z [7]. In their research, the authors explore the use of the three-tiered architectural pattern to create a mechanism for large-scale wireless big-data collection, particularly in the context of a smart city [7]. Their study showcases the potential of employing a decoupled approach in developing adaptable systems, aligning with the concept envisioned in this paper.

2.3. History of controller innovation

Prior to commencing the study, it was essential to gain a comprehensive understanding of the history and present status of controllers and their industry. This knowledge plays a vital role in shaping the research's focus and establishing design guidelines for the experiment. Although the study covers controllers beyond video game platforms, it is worth noting that a substantial body of academic work already exists on the evaluation and design of game controllers. This wealth of research serves as a robust starting point and offers valuable insights that can be adapted and applied to controllers in various domains beyond the realm of game development. Furthermore, interactions with games are among the most complex when compared to our daily use of technology.

The game controller domain has experienced significant evolution and progress over time. The integration and adoption of technologies like Virtual and Augmented Reality, Voice Recognition, and Motion Sensing have introduced intriguing aspects to consider when evaluating the feasibility of cross-platform controllers. These technologies have showcased both successful and unsuccessful implementations, offering valuable data points for analysis.

Voice control, in particular, serves as a noteworthy starting point for this evaluation, given its longevity. It stands out as one of the earliest non-standard methods developed to interact with computers. Interestingly, the concept of conversing with inanimate objects through voice predates the digital era, with several African cultures believing that gifted individuals could communicate with ancestors and spirits using non-living objects. This historical context adds a fascinating dimension to the study of voice control's evolution and potential impact on cross-platform controllers.

In their article titled "Word Play: A History of Voice Interaction in Digital Games [5]," Alison Cater and Gibbs highlight the intriguing historical background of speech recognition technology, which predates digital computers and is even present in children's toys. Despite this early existence, they note that speech recognition has not firmly established itself in modern control schemes. Instead, its usage has been sporadic, with varying influence on platforms and emerging technologies.

The authors delve deep into the history of voice control, shedding light on the industry's tendency to adopt a single-use approach to interaction design where non-standard controllers are concerned. They emphasize that hardware and software constraints have limited the design space for voice interaction, resulting in a cyclical pattern where voice interaction games rise in popularity with new game platforms, only to decline once their limitations become apparent [5].

These insights are highly relevant to the challenge at hand and align closely with the objectives of this study. They illustrate how innovative control schemes, like voice control in the case of the Singstar game [5], can introduce entirely new experiences. However, when closely tied to specific products and platforms, these novel experiences often lose traction once the initial excitement wears off.

By allowing users to choose how they interact with experiences and platforms, this study aims to address this issue and foster the wider adoption of non-standard controllers. Allowing users the freedom to creatively engage with technology can potentially lead to sustained and meaningful use of innovative control schemes, transcending the limitations posed by singular experiences and promoting broader acceptance.

An evaluation of the history of video game controllers reveals two prominent factors driving advancements in the field. The first factor is primarily economic, where companies employ gatekeeping strategies to direct users towards their broader suite of product offerings. This approach aims to create a sense of exclusivity and loyalty to the company's ecosystem.

2.4. Evaluating cross-platform designs

The second factor is an uncontrollable force that stems from the gaps in technology, accessibility, and novelty that arise due to the gatekeeping practices in the industry. Since platform developers cannot cater to every individual's unique needs, smaller and niche devices emerge to fill these gaps. This phenomenon underscores the limitations of the coupled model, as it restricts innovation and fails to address the diverse requirements of users.

In contrast, the decoupled approach holds significant potential for creating a more expansive and specialised industry that can offer accessible solutions. By allowing users the flexibility to choose from a variety of controllers and platforms, a more diverse range of devices can be developed to cater to individual preferences and needs. This approach fosters innovation, facilitates the emergence of specialised solutions, and addresses the shortcomings of the coupled model, ultimately leading to a more inclusive and user-centric gaming experience.

The paper titled "Video Game Controllers", authored by Heatherly and Howard [8], presents a comprehensive history of controller developments and their psychological impact on users. On the other hand, Rieger and Majchrzak's work, "Towards the definitive evaluation framework for cross-platform app development approaches [12]," offers a methodological approach to assess cross-platform application development frameworks with a strong theoretical foundation. In their paper, Rieger and Majchrzak strive to create a future-proof, adaptive evaluation framework for cross-platform app technology [12], which could be valuable for evaluating tools in this study.

The authors propose that the evaluation of cross-platform approaches can be accomplished by considering four key elements:

- Infrastructure: This element focuses on what the framework provides, including its ability to deliver functionality across multiple platforms.
- Development: This aspect pertains to issues related to support and tooling, which are crucial factors influencing a developer's ability to effectively accomplish their tasks using the framework.
- App: The authors assess whether there is evidence of successfully developed cross-platform apps that meet the specific requirements at hand.
- Usage: This element is concerned with the user experience of the app, examining how well it performs and meets the needs of end-users.

By considering these four elements, the evaluation framework proposed by Rieger and Majchrzak [12] aims to provide a robust and adaptable approach to assess cross-platform app technologies, which is applied in this study to evaluate the tools under examination.

The authors present their framework as a "future-proof, long-lived, adaptive evaluation framework for cross-platform app technology [12]," expressing confidence in setting a standard for future evaluation endeavours. According to their argument, any cross-application technology can be thoroughly and fairly evaluated using this comprehensive framework. This framework serves as a solid foundation for evaluating cross-platform frameworks and tooling, thereby providing a means to assess the tools proposed for use in this research.

However, in my opinion, two essential factors related to cross-platform technology evaluation are not explicitly addressed in this framework. The first factor is Developer Experience (DX), which refers to capturing how developers perceive and feel about their activities within their working environments [20]. Considering DX is crucial as it helps understand the ease of use, satisfaction, and overall effectiveness of the tools from a developer's perspective.

The second factor is the integration of cross-platform technology into existing workflows and the availability of relevant skill sets. Evaluating how well a tool fits into existing development practices and how easily developers can leverage their existing skill sets to work with the technology is vital for practical adoption and implementation.

In summary, while the proposed framework offers a strong basis for evaluating cross-platform frameworks and tooling, incorporating Developer Experience and considering the integration into existing workflows and skillsets would enhance the completeness and practical applicability of the evaluation process for the proposed study's tooling.

When assessing "development," the authors of the framework primarily concentrate on technical aspects like rapid development, preparation time, scalability, and methodologies [12], but they overlook the significance of the developer experience. As noted by Fagerholm and Munch in their conference paper titled "Developer Experience: Concept and Definition," presented at the International Conference on Software and System Process in 2012, they highlight that software development environments are intricate social systems. They stress the growing importance of complex factors such as trust, confidence, communication, and identification with goals [20].

Therefore, neglecting to consider the Developer Experience in the evaluation process can have significant consequences. Software development is not solely about technicalities; it involves the people who work in these environments. The well-being and motivation of developers play a crucial role in the success of a project. If a tool is chosen without considering how it will impact the developers using it, it may lead to potential issues, including reduced productivity, dissatisfaction, and inefficiency.

Incorporating the developer experience aspect in the evaluation is essential for creating a supportive and engaging working environment. It allows for a holistic understanding of how the tool will be received and utilised by the development team. By recognizing the social dynamics and human factors within software development, the evaluation process can lead to better-informed decisions and ultimately contribute to more successful and productive outcomes.

The authors of the framework position it within the context of building enterprise systems, but they overlook the reality that many enterprises have large, stagnant legacy systems that everything else must integrate with. This integration process can significantly impact the time-to-market and the overall development process. Therefore, it becomes crucial to consider factors like integration with existing workflows and tooling, as well as the developer experience, including the available developer skills, when selecting the technology to use.

In the context of this study, the tools are chosen based on all four elements proposed by Rieger and Majchrzak. However, additional considerations are taken into account, such as the developer's expertise in web development technologies, technical interests, background in game development, and leveraging their software development industry experience. These technical decisions are further elaborated in the "Research Design" section found later in this report.

By factoring in these additional considerations, the study aims to ensure that the selected tools align well with the existing expertise and skill sets of the developer, promoting a smoother integration process and enhancing the overall development experience. The goal is to optimize the choice of technology based not only on technical criteria but also on the practicalities of the development environment and the capabilities of the researcher.

2.5. Case study design and development

In the paper titled "Beyond the Gamepad: HCI and Game Controller Design and Evaluation [4]," Brown, Kehoe, Pitt, and Kirakowski describe how they applied McNamara and Kirakowski's framework to assess data obtained from a research experiment involving a driving game. The experiment involved the use of both a steering wheel and a keyboard-and-mouse controller [3, 4].

In this particular case study, Brown et al. sought to explore the disparities in HCI resulting from using different control methods, namely, a keyboard, gamepad, and steering wheel, to play a racing game. The researchers assessed these control methods based on functionality, usability, and user experience [4]. The study's participants were instructed to play the racing game with each of the three controllers while maintaining the same game settings, and their interactions were closely observed. The dependent variables measured were the three aspects of technology interaction as defined by McNamara and Kirakowski [3], and the results obtained from each controller were subsequently compared.

Brown et al.'s study [4] presents a well-structured approach to employing McNamara and Kirakowski's framework for gaining a deeper understanding of HCI. Their methodology involves a combination of in-game statistics, subjective data collection through the use of the Subjective Mental Effort Questionnaire (SMEQ), and reflective techniques like the Critical Incident Technique (CIT). This comprehensive approach serves as a strong foundation for the current study.

However, the study acknowledges a potential limitation related to participants becoming more familiar with the game as they try different controllers, which could influence the findings [4]. To address this issue, the researchers randomised the order in which the controllers were tested. Ensuring a fair distribution of the order of testing was also a critical consideration in this study, helping to mitigate any potential biases and ensure a reliable evaluation.

The success of this case study relies on the development and utilization of custom applications and controllers. It is worth noting that there are nearly 9000 programming languages known to exist worldwide. The TIOBE Programming Languages Index, which applies stringent criteria and even excludes markup languages like HTML, identifies approximately 274 distinct programming languages currently in widespread use [21]. With such a vast array of tools and languages available, the selection of appropriate technology and tooling for the experiment's development phase becomes a critical and complex decision.

Given the abundance of choices, it is essential to carefully consider the technological requirements and objectives of the study. The right technology and tooling must align with the specific goals of the experiment, the skills and expertise of the developer, and the overall feasibility of implementation. A thorough evaluation of the available options and their suitability for the study's unique requirements is crucial in ensuring the successful execution of the research. The aim is to make well-informed decisions that optimize the development process and facilitate the achievement of the study's objectives effectively.

In addition to the technical implementation challenges, it is essential to ensure that the experiments with which the controllers will be used are built in a user-friendly manner, adhering to the best available design guidelines. This involves understanding how users interact with systems and finding the most effective ways to design and build for a diverse audience. Critical evaluation of the design approach is necessary to ensure that the tools are accessible and usable for as wide a range of users as possible.

Drawing from the works of scholars who have focused on developing design guidelines provides a valuable starting point. These guidelines offer insights and principles that inform the design decisions for the experiments. By following well-established design guidelines and considering user feedback and preferences, the study creates experiments that are intuitive, efficient, and enjoyable for participants.

A user-centric design approach is key to promoting engagement and obtaining meaningful results. It ensures that the controllers and applications are well-received by users, leading to a positive user experience and increasing the likelihood of successful adoption and participation in the study. Ultimately, careful attention to design considerations contributed to the overall success and impact of the research.

According to the Merriam-Webster dictionary, a heuristic is defined as "an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods [22]." In the context of cognitive psychology, it refers to "mental shortcuts that allow people to solve problems and make judgments quickly and efficiently [23]," as explained by psychologist, author, and educational consultant Kendra Cherry.

Narrowing down the focus to the application of heuristics in developing design principles, Heather Desurvire, Martin Caplan, and Jozsef Toth, in their article titled "Using Heuristics to Evaluate the Playability of Games [6]," consider heuristics as "design guidelines that serve as a useful evaluation tool for both product designers and usability professionals [6]." They present a framework known as the "Heuristics of Evaluating Playability (HEP)", which comprises a list of criteria that designers and developers can use to assess the usability of their product.

By utilizing heuristics, designers and developers can expedite the evaluation process and identify potential issues and improvements in their product's playability more efficiently. The HEP framework offers a structured and practical approach to evaluating the usability of digital systems, providing valuable insights for refining the design and enhancing the overall user experience.

Desurvire, Caplan, and Toth's work focuses on games, and they present a heuristic framework that examines four key areas of game development [6]. These areas are:

1. Gameplay: This category includes elements such as minimizing player fatigue by introducing varied activities and ensuring the replayability of games.
2. Game Story: In this category, the focus is on elements that make the game's story clear and comprehensible to the player.
3. Mechanics: This category delves into the mechanics of the game, considering how the game operates and functions.
4. Usability: The final category concerns the user's experience when engaging with the game, focusing on how easy and efficient it is to interact with the game.

Within each category, they provide a list of heuristics that they believe should be used to assess the playability of a game, particularly during the early stages of the game development lifecycle. They suggest incorporating this heuristic evaluation in addition to playtesting.

In their methodology, Desurvire et al. detail a process where a sample of testers is monitored and evaluated during a two-hour one-on-one session. Participants are asked to verbalize their thoughts while engaging with the game prototype, and evaluators ask questions during the session to gather valuable insights and observations [6].

By using this approach, Desurvire and her colleagues aim to gain a comprehensive understanding of the game's playability and identify potential areas for improvement during the development process. The combination of heuristic evaluation and playtesting provides a well-rounded approach to enhance the overall gaming experience and optimize the game's design. This process is resource intensive, and since this study is undertaken by a single researcher, the process involving play-testing is not undertaken, despite the framework being used to evaluate the tools developed for this study.

HEP consistently identified more issues compared to traditional user testing across all four categories (gameplay, game story, mechanics, and usability). One possible reason for this discrepancy could be the psychological environment created during the one-on-one sessions, where participants are prompted to reflect and provide feedback, potentially leading them to be more critical of the prototype. While this evaluation method is valuable for uncovering finer issues, it might not fully address the technical components of usability, which are crucial to the core focus of this study. The authors themselves acknowledge that the HEP method is better suited for experiences with story play, and it might not perfectly align with this study's specific requirements.

Nevertheless, the heuristics outlined in the HEP framework play a critical role in ensuring the usability of the study's prototype, as the gameplay, mechanics, and usability heuristics can guide the development of a well-built and playable game. This is of utmost importance since the study relies on custom-built games, and any design flaws or usability issues in the game could impact the accuracy and validity of the study's findings.

By incorporating the relevant heuristics into the game development process, the study aims to create a high-quality and user-friendly game that aligns with the research objectives. Paying close attention to usability is essential to achieving reliable and meaningful results when using the McNamara and Kirakowski framework [3] to evaluate cross-platform controllers. A well-designed and playable prototype will be crucial for obtaining accurate insights and ensuring the study's success.

Jakob Nielsen, a renowned usability expert, developed a framework titled "10 Usability Heuristics for User Interface Design" [10], which presents a valuable set of guidelines for designing interactions in user interfaces. While the HEP framework offers a solid foundation for evaluation and includes heuristics for designing games, its focus on games with stories makes it less suitable for the proposed study compared to Nielsen's heuristics, which are aimed at general user interface design - a core focus of this research.

Nielsen's list of heuristics is specifically designed to ensure user-friendly and intuitive interactions in various user interfaces. The first set of heuristics, including "Match between system and the real world" and "Consistency and standards," emphasize the importance of designing interfaces that align with users' mental models and cultural affordances. By making the system behave in a predictable and familiar manner, users can quickly learn how to use the product, which builds trust in the system.

The second set of heuristics, such as "User control and freedom" and "Error prevention," focuses on creating a safe space for users to explore the system or product. Providing the ability to undo actions and preventing errors allows users to experiment without fear of irreversible consequences. Additionally, offering clear error messages and guidance helps users recognize, diagnose, and recover from errors efficiently.

The last two heuristics, "Flexibility and efficiency of use" and "Help and documentation," cater to users of all experience levels. Designers should incorporate shortcuts and efficient features for experienced users while ensuring that beginners are not overwhelmed. Offering help and accessible documentation further supports users in understanding and engaging with the system or product effectively.

These guidelines provided by Nielsen are applicable to designers in all fields and will be closely followed to ensure that the products developed for this study are user-friendly and provide a seamless user experience. By adhering to these heuristics, the study aims to create interfaces that are intuitive, efficient, and supportive of users across different levels of expertise.

The literature review conducted for this research offers a comprehensive and diverse guide to developing digital products with a strong emphasis on user-centric design. The reviewed works provide valuable insights and principles that ensure ease of use and place the user at the forefront of all design considerations. By drawing from these sources, the research gains a solid foundation for designing and evaluating the experiment before it is utilised in the study. Moreover, the literature review equips the study with essential tools to assess the data that will arise from user interactions with the experience.

Additionally, examining similar studies in the literature review offers valuable lessons that help mitigate potential data pollution and, consequently, safeguard the integrity of the study's findings. The cited works form the backbone of the study, providing the necessary knowledge and guidelines for conducting a robust and successful research project. By incorporating the insights from these sources, the study ensures that the development of digital products and the evaluation of user experiences are conducted in a well-informed and effective manner.

3. Methodology

3.1. Introduction

This research project expands on Brown’s experiment[4], where the impact of the use of multiple controllers to interact with the same digital system is evaluated. The evaluation is done by comparing quantitative and qualitative data collected during participants’ interaction with a digital system in an attempt to answer the research question:

How does the use of digital systems with interfacing devices that were not designed for them impact the Human-Computer Interaction?

This section will detail the case study design, considerations as well as the hardware and software tools used to conduct the case study. This section will then detail how the different datasets are collected.

3.2. Case study Design

In this research experiment, users are given two unrelated systems to engage with. Both systems are 2-dimensional (2D) browser-based games. The first is a web-based remake of Atari Inc’s 1979 hit classic game: *Asteroids*. The second is a custom platformer game called *Bemilanche*. The participants are requested to play each game using three(3) different controllers, namely: a gamepad, a keyboard and a customisable controller developed for this study whose layout is chosen by each participant when they engage with each game. The participants are asked to fill in questionnaires after engaging with the systems.

As part of the experiment, quantitative data is collected by the operational software which is developed by the researcher. This data includes the time taken for a user to provide the first input, the time taken to complete the task on each controller, the participant’s score and the number of unique detectable inputs of each controller. Qualitative data is collected by means of questionnaires to evaluate subjective aspects concerned with the participant’s experience.

3.3. Ethical Considerations

As the study revolves around individuals, the involvement of human participants plays a pivotal role. The research is conducted with a firm commitment to unwavering ethical considerations. One of the key considerations was the protection of participants’ private information.

The study does not rely on any personal identifying information, and as such, no identifying information is captured at any point. However, the participants must be afforded the right to request the data obtained through their participation and the right to request such data to be excluded from the study's findings within a reasonable time. Furthermore, the data points need to be grouped so that a holistic understanding of each participant's experience and the factors that contribute to it can be reached.

In order to strike a balance between privacy (not capturing identifying data) and having the ability to group data points, a random pseudo-name is generated for each participant at the beginning of their participation. They are then advised to store the pseudonym securely by whatever means they choose. They provide this pseudo-name when filling in questionnaires, and should they require their data or seek to have their data excluded, they will need to furnish the researcher with the pseudo-name. It is also used to group data collected through the different aspects of the case study.

3.4. Software

Solution Design & Architecture

The study requires a customised configuration of a number of technical elements to facilitate the interaction. This includes hardware configuration, 3D printing of some elements, Software custom Development and use of online freemium services. Figure 1 below provides a consolidated view of both the software and hardware elements and how they interact with each other.

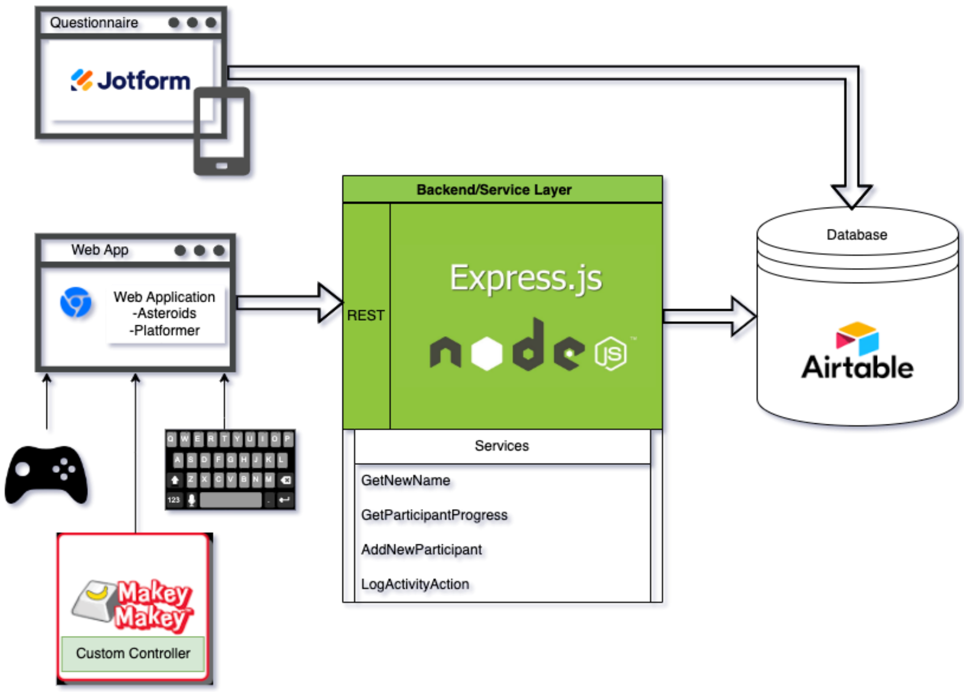

Fig. 1: Architectural Diagram of technical setup for the study

Applications Development

The front-end software aspect is separated into three major concerns

1. *Asteroid* Game
2. *Bemilanche* Game
3. Overarching main application to manage all interactions

Main application

An overarching web application has been developed by the researcher. The web application manages the interaction as a whole. It presents the participants with information about the study, its purpose, how to contact the researcher and instructions on what to do. It also houses the other two games and tracks the interactions that the participant has with both games. It sends the data to a secure cloud-based database through a custom-built back-end solution.

The application generates a pseudonym on load and remembers. Should a participant reload the application for whatever reason, it will ask them to confirm whether they are the same participant it has in memory or not and allows them the opportunity to generate a new name and start a new session. Figure 2 below is a screenshot of the main page which initiates the experiment.

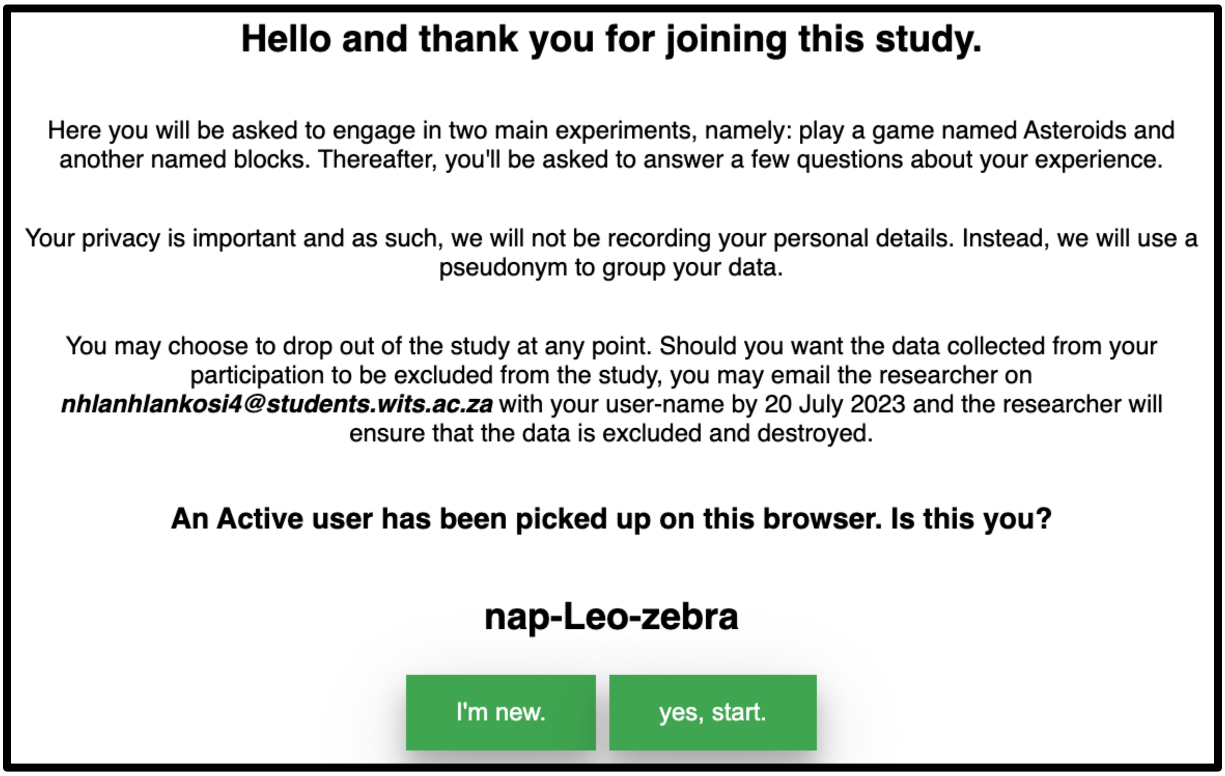

Fig. 2; Screenshot of main landing page

The web application is built using HTML, CSS and JavaScript and no other front-end framework. It requests a new pseudonym from the NodeJS service when loaded and stores it using the browser's local storage. When reloaded, it checks the local storage for an existing user and presents it to the user. If it cannot find one, it assumes this is a new user and requests a new name from the server.

The app exposes key functionality that is reused by the games to randomise the order in which the controllers are used for each game, record the scores and send them as a single payload to the NodeJS layer upon completion of each game with each controller.

3.4.1.Asteroid: The classic Shoot 'em up Game

Asteroids, the classic arcade video game introduced by Atari, Inc. in November 1979, has solidified its position as a pioneering and enduring masterpiece within the realm of electronic gaming. Developed by Lyle Rains and Ed Logg, this space-themed multidirectional shooter game pushed the technological boundaries of its time and profoundly impacted the gaming industry [31].

Set against the backdrop of outer space, *Asteroids* tasked players with piloting a triangular spaceship amidst a chaotic field of asteroids and enemy saucers. With its innovative use of vector-based graphics, the game delivered a distinctive visual experience that set it apart from its contemporaries. Players have to deftly navigate their spacecraft, employing precise rotation, thrust, and firing mechanisms to obliterate asteroids while evading collisions and fending off adversaries.

The allure of *Asteroids* lay in its simple yet captivating gameplay. It enticed players with the challenge of surviving increasingly intense waves of obstacles and foes while striving for high scores. The game's mechanics require a blend of strategic planning and quick reflexes, making it a timeless source of excitement for both novice and experienced gamers alike.

What makes *Asteroids* particularly compelling for testing controllers is its intricate balance between precision and speed. The fluid movement, rapid adjustments, and split-second decision-making necessary to excel in the game provide an ideal testing ground for evaluating the performance of different controllers and the arising User Experience. The dynamic challenges presented by *Asteroids* mirror real-world gaming scenarios, which are among the most complex scenarios in which we use controlling devices. This enables researchers to assess how well controllers adapt to the nuanced demands of fast-paced, multidirectional gameplay.

Incorporating *Asteroids* into controller testing offers a unique opportunity to gauge how effectively controllers translate player input into on-screen actions and how the users experience them under pressure. The game's enduring appeal and status as a quintessential arcade classic further enhance its suitability for such evaluations.

While the original version of the game was released in an arcade cabinet, the version used for this study is a modern JavaScript reboot of the classic game. Figure 3 below is an image combining two screenshots. The first is of the main menu and illustrates the randomisation of what controller should be used by the participant, and the second is a screenshot of in-game play. Both images show the integration of the customised pseudonym and show that the system is timing the player and recording their score.

Fig. 3: Screenshot of main menu and gameplay

The study is concerned with controllers and their impact on User Experience and not necessarily the process of building software. As such, the researchers use open-source and freely available software where possible. This version of *Asteroids* is developed by GitHub user Phil Spilsbury and hosted on his GitHub profile[32]. Spilsbury released the software under the GNU General Public License, which permits the use of the software for any purpose. The licence also grants permission to change and share the software either in its original or changed form for any purpose[33].

3.4.2. Bemilanche: The platformer game

Bemilanche is a game where you need to escape death by wall-jumping on falling blocks. Points are earned by how high you go on the screen before being crushed, touching a “death” block or drowning.

Bemilanche is a browser-based game which makes it possible to integrate into the greater custom-built web application that records scores and user interaction. The game is much simpler than *Asteroids*, as it only has three inputs, namely: left and right movement and jumping. It's slower-paced, allowing for a balance in stress and pressure for the participants.

The game is about timing the jumps correctly, increasing the need for participants to have reliable input mechanisms. This positions the game as a good experiment for this study. The image in Figure 4 below is a screenshot of the in-game play and illustrates the recording of the score.

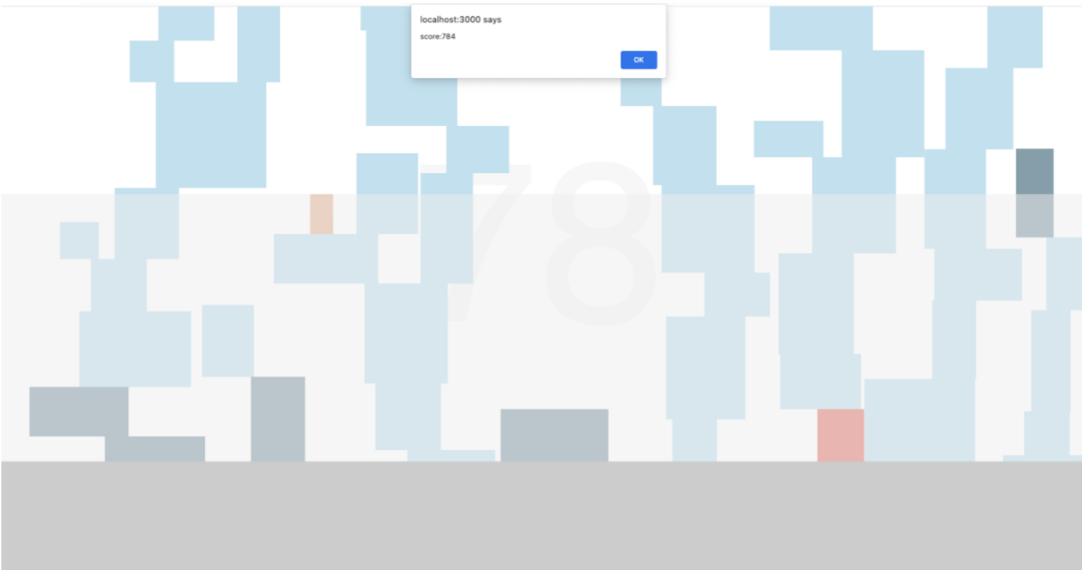

Fig. 4: An in-game screenshot of Bemilanche.

External Software and Services

Airtable

The secure storage of data is crucial for this study. As such, Airtable is used as the study's core database, securely storing the data collected and limiting access only to the researcher. Airtable is a cloud-based collaboration platform that combines the flexibility of a spreadsheet with the functionalities of a database. It allows users to create, organize, and manage various types of information in a visually intuitive and customizable interface [38]. Airtable is designed to streamline data management, collaboration, and workflow automation, making it a versatile tool for a wide range of projects and studies. It has a free tier which provides all the features needed for this study.
Airtable supports integration with other tools and platforms, allowing researchers to import and export data, automate tasks, and connect with other applications used in the study. Since this study makes use of a custom build web application, Airtable's API plays a key role in the researcher's ability to automate the storage of the data collected. Airtable employs industry-standard security measures to protect data, ensuring the confidentiality and privacy of participants' information.

JotForm

JotForm, a versatile online form builder, was chosen for the study to streamline data collection and participant engagement. Its user-friendly interface enables easy form creation, customization, and deployment. JotForm's adaptable design allows researchers to gather specific information while offering various question types, validation options, and branding possibilities.

The platform supports real-time collaboration, facilitates data organization, and ensures secure data handling. JotForm's accessibility and integration capabilities make it an ideal tool for efficient and effective data collection in the study. JotForm's free tier has all the features necessary to collect the data required for this study.

In this study, JotForm was used to consolidate the different questionnaires aimed at attaining the different insights required into a single, coherent form that minimises duplication, is quick to fill in and can be accessed through any device with an internet connection. Jotform also has built-in integration with Airtable. This makes it simple to store all the data in one location once the study has been completed.

3.5. Hardware

The post-experiment questionnaires can be filled in on any device, including the participant's own smartphones. The physical experiment is conducted on a single laptop provided by the researcher. This is to ensure consistency in the performance of the application and affords the researcher the opportunity to ensure that the data is collected consistently. In addition to the laptop required, there are three controllers required, namely: gamepad, keyboard, and custom controller. All three devices connect to the laptop through a USB connection.

Gamepad: PS4 Controller

The Sony PlayStation 4 (PS4) controller, a pivotal component of Sony's gaming ecosystem, emerged as a significant milestone in the evolution of gaming controllers, seamlessly blending innovation and user-centric design [34].

Debuting in November 2013 alongside the PS4 console, the PS4 controller, also known as the DualShock 4, marked a departure from its predecessors while retaining familiar elements. Boasting a refined ergonomic design, the controller introduced a touchpad at its centre, offering a novel input method that added versatility to gameplay mechanics. This touch-sensitive interface enabled developers to incorporate new interactive features like controller-based sound and DualShock feedback capabilities, and gestures through the built-in accelerometer into their games, enhancing the overall player experience.

The DualShock 4's improved analogue sticks and triggers, coupled with its responsive buttons, translated player input with precision, contributing to a heightened sense of control. Furthermore, the built-in speaker and headphone jack facilitated immersive audio experiences that drew players deeper into the virtual worlds of their favourite games.

The PS4 controller's combination of innovation, ergonomic design, and multifunctional capabilities positions it as an ideal candidate for testing various controllers. Its responsiveness, touch-sensitive interface, and diverse input options provide a robust platform to evaluate how controllers perform across different game genres and interactive contexts.

The PS4 controller is designed for use with a PS4 console. The researcher has leveraged the browser's Gamepad API [35], a standardised interface for accessing gamepad devices, to seamlessly connect the DualShock 4 controller to the study's web-based application and games. The researcher is able to use the PS4 controller to interface with all the elements of the study using the API. Figure 5 below is an image of the PS4 controller.

Fig. 5: Sony PlayStation 4 (PS4) Controller

Keyboard

The experiment is conducted using a laptop with an integrated keyboard. Using this keyboard would limit participants' freedom to position the keyboard as they wish in terms of distance from the screen and rotation. As such, a wired keyboard was used.

The keyboard used in this study is the Logitech K120 Plug-and-Play USB Keyboard. It has deep profile keys and a USB cable length of 150cm [37], affording the participants enough flexibility to position the keyboard comfortably while maintaining the reliability of a wired connection. An image of the keyboard is shown in Figure 6.

Source: logitech.com

Fig. 6: Logitech K120 USB Keyboard

Custom Controller (Powered by Makey Makey)

Custom controllers built with the Makey Makey kit offer a creative and interactive approach to user input and engagement, merging the digital world with the physical through inventive and accessible design.

Makey Makey, an invention kit developed by Jay Silver and Eric Rosenbaum, allows individuals to transform everyday objects into interactive touchpads [36]. The kit utilizes the principles of capacitive touch to convert various conductive materials into buttons or keys, effectively turning anything conductive into a user-input device. This opens up a world of possibilities for creating custom controllers that respond to touch, thereby enabling unique and personalised interactions.

The process of building custom controllers with Makey Makey begins by connecting the kit's main board to a computer via USB. Users then attach conductive materials, such as fruits, vegetables, graphite, or even human bodies, to the Makey Makey board's inputs. When these materials are touched or interacted with, they complete a circuit, triggering actions within software applications or games.

One of the most exciting aspects of using Makey Makey for custom controllers is the limitless creativity it allows. Users can design controllers that mimic traditional gamepads or invent entirely new forms of interaction. For instance, a user might create a controller using a banana and a few pieces of wire, turning the banana into a "button" that triggers actions within a game. This playful and exploratory approach to controller design encourages a unique user experience and fosters a sense of innovation and experimentation.

In this study, the Makey Makey circuit board is used to facilitate the creation of customisable controllers. The circuit board triggers keyboard events that are handled by the game. The wires are then connected to each touch-based controller the participants wish to use. For instance, if a participant wishes to touch a different banana for each action required, each banana would be connected to the relevant keyboard event trigger. When a player touches one of the bananas while touching the wire connected to the ground pin, the relevant keyboard event will be triggered. Figure 7 below shows an example of the configuration with multiple bananas.

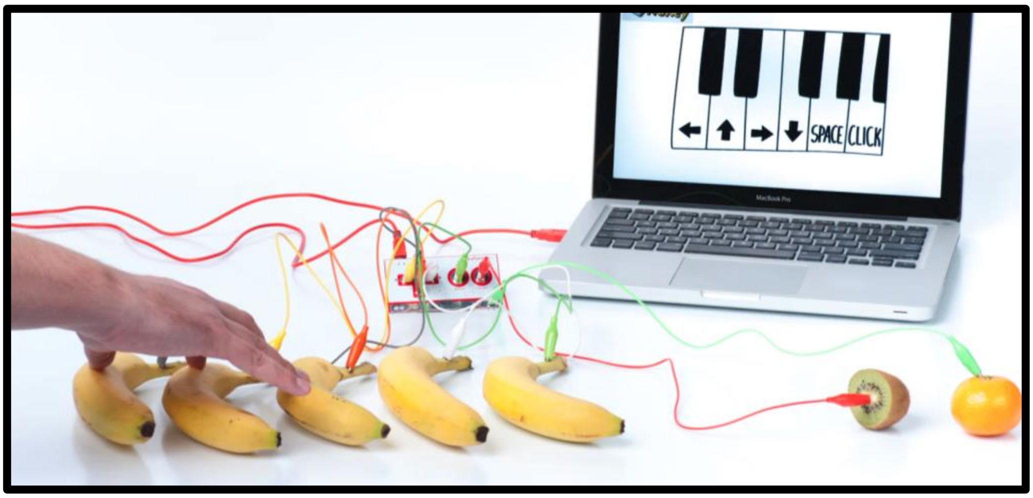

Fig. 7: Example configuration of Makey Makey

3.6. Study Methodology: Mixed Methods

In order to assess the impact of using different controllers on HCI, it is necessary to collect data pertaining to functionality, usability, and user experience, as stipulated by the framework presented by McNamara & Kirakowski [3].

These three domains entail distinct kinds of data. Functionality is concerned with quantitative data, encompassing aspects such as the controller's capacity to deliver all necessary unique inputs and the speed of communication with the platform to deliver the triggers. User experience focuses on individuals' personal encounters and relies on qualitative data, including users' emotions and perceptions. Usability is evaluated using both qualitative and quantitative data, as it comprises subcategories such as efficiency - quantitatively gauged through factors like time taken to complete tasks with each controller - along with effectiveness and satisfaction, both of which are appraised using qualitative data linked to users' sentiments about their experiences.

Given that the assessment framework hinges upon the evaluation of elements necessitating the amalgamation of both qualitative and quantitative data, this study necessitates the adoption of a Mixed Methodology approach.

In their paper titled "Mixed methods research: Expanding the evidence base," Allison Shorten and Joanna Smith define mixed methods study to be a "research approach whereby researchers collect and analyse both quantitative and qualitative data within the same study [24].” This approach holds significant potential as it capitalizes on the advantages of both qualitative and quantitative assessment techniques. The different adaptations of this method primarily revolve around the assessment of data and the interpretation of outcomes. In specific instances, as outlined by Shorten and her colleagues, one type of data is employed to corroborate the findings obtained through the primary data collection [24]. This approach requires the clear identification of the core data type of the methodology.

U. O¨stlund et al. argue that to get the best value out of a mixed-method study, the quantitative and qualitative findings should be integrated if possible [25]. This undertaken study takes on an integrated approach where the quantitative and qualitative data are used to measure different elements and have the same weight when evaluated. This mixed methods approach, where the quantitative and qualitative data is collected to measure different elements of a theoretical framework, can be described as being “complimentary”, as explained by Chen in their 2006 paper titled “A Theory-Driven Evaluation Perspective on Mixed Methods Research.” [26].

3.7. Study Setting

The study is conducted in an identical setting for all participants. A large classroom-type setting was secured and used. The room had desks with adjustable heights and enough room for all participants to choose a comfortable stance and position when engaging with the system. Only one participant was allowed to engage with the system at a time.

Each participant received an information sheet detailing the study and their rights (Appendix A), a demonstration of how the games function, a consent form to read and sign (Appendix B), and a walkthrough of the setup they were presented with. The setup includes a laptop, a USB keyboard, A PS4 controller connected by USB to the laptop and a Makey Makey case with leads connected to the necessary ports. Figure 8 below is an image of what the setup looks like.

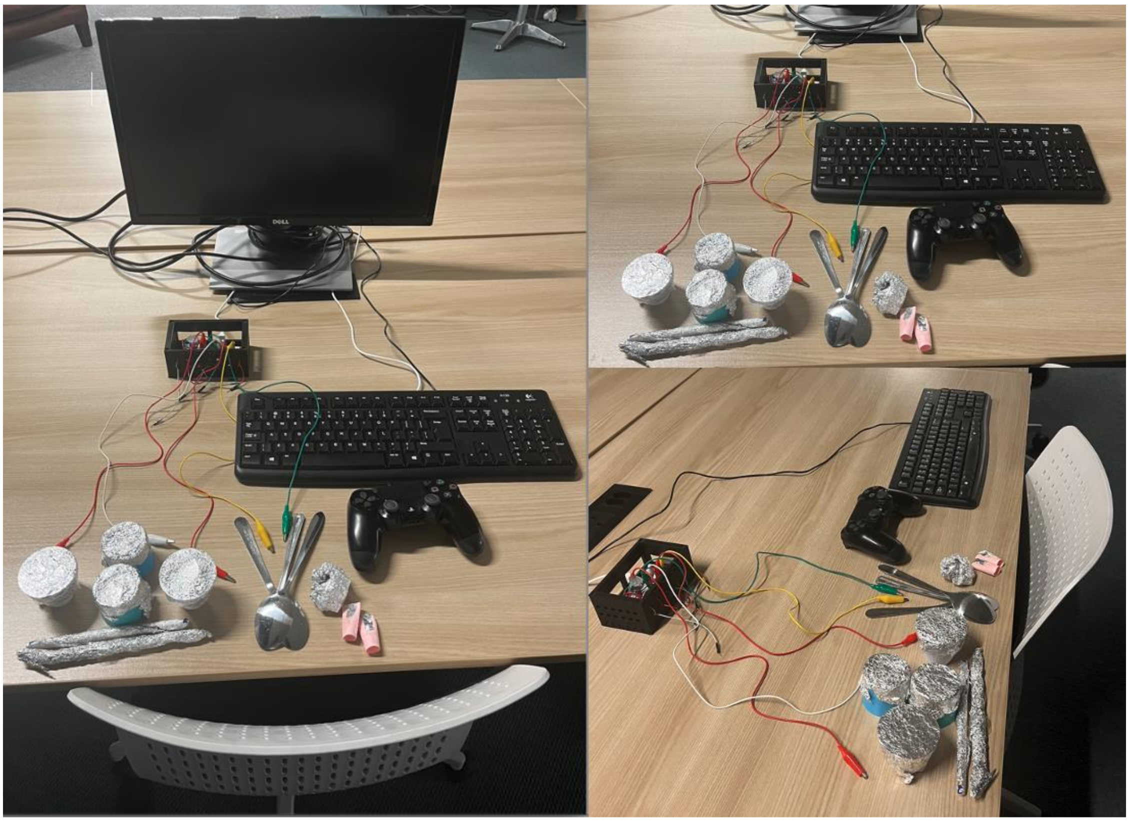

Fig. 8: Hardware Setup

The participant is greeted by a welcome message on the study's web app (shown in Fig. 2), through which they get guidance for each step of the study. The software randomly decides the order in which the controllers should be used and the order in which the games should be played.

When the participant has to use a custom controller, they advise the researcher of their desired control scheme, and the researcher configures it using household items. Figures 9 & 10 below show two such examples.

Fig 9: Foot pedal with foil and teaspoon

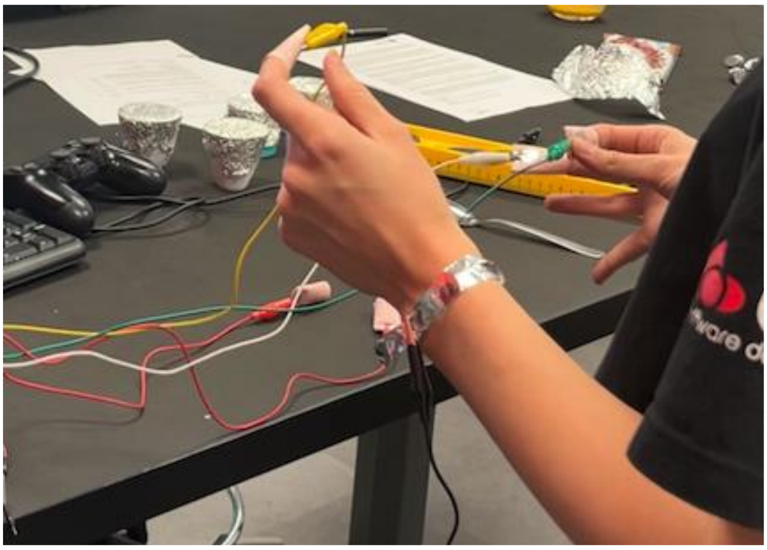

Fig 10 – Finger snaps controller

In Figure 9, the participant wished to have a foot pedal to trigger the jump function for the platformer and to accelerate the spaceship. A foot pedal was constructed by wrapping conductive tin foil around the participant's shoe and placing a teaspoon under the ball of the participant's foot. The teaspoon was connected to the up-arrow key on the Makey Makey, and the foil made contact with the participant. When the participant stepped on the spoon, it triggered the jump on the platformer and the accelerator on the Asteroids game.

In Figure 10 above, the participant wished to "snap" different fingers to interact with the games. Fingertip covers were built with paper-based sticky notes to insulate each finger from the others. A wire with foil on the tip (for increased surface contact area) was connected between each tip and the corresponding pins on the circuit board. A foil bracelet with a wire connecting it to the ground pin was wrapped around their wrists. This allowed them to trigger the different keyboard events each time one of her exposed fingers touched the insulated ones. Other custom controllers included 3D-printed Bongo drums, fruits and drinking water with a straw.

Once the interaction was completed, each participant was asked to fill in the form. A QR code was generated for the form, and the participants were encouraged to fill in the form on their own devices, removing the time pressure and reiterating that they have the agency to withdraw their participation at any point of their choosing. Appendix C is a pdf export of the form.

3.8. Participants

The participants were recruited from the researcher's place of employment. At the time of this study, the researcher is employed on a full-time basis as a Software Engineer in a bespoke software development firm. The company has over a thousand (1000) employees, most of whom are based in the same office as the researcher in Johannesburg, South Africa.

The company has an established email-based channel where employees are permitted to reach out to all of their colleagues for non-work-related matters such as participation in academic studies. The researcher sought explicit consent from the company's senior leadership to recruit participants and use the research lab to conduct the study. Appendix D is a copy of the letter permitting the researcher to recruit their colleagues and make use of the office space. The participants were recruited by means of email in which the Participation Information Sheet, available as Appendix A, was also attached. A total of 15 participants were recruited for the case study.

3.9. Data Collection and Analysis

This is a Mixed Methods study which requires the collection of both quantitative and qualitative data.

Qualitative data is collected by means of a questionnaire. The questionnaire is a combination of established questionnaires that need to be answered for each controller used on each digital product. Instead of asking the participants to fill in the same questionnaires six times, they were consolidated into a user-friendly form using JotForm.

Quantitative data around the characteristics of the instruments used, such as each controller's number of unique inputs, is collected by means of inspecting data specification sheets that come with prebuilt solutions and hardware. Custom and emergent quantitative data that is generated through the interaction is collected through the custom-built software. It tracks all the user's inputs and stores them in the Airtable database.

The study requires the collection of data to measure the three primary elements of McNamara and Kirakowski's theoretical framework of understanding interactions between computers and humans [3]. The elements are Functionality, Usability, and (User) Experience.

Functionality

In this experiment, functionality is evaluated by comparing the quantitative data in terms of the range of outputs produced by each controller with the possible inputs recognised by the application. For instance, when using the drone, this criteria would ask the question: if the drone has x possible inputs, how many of those inputs is each controller able to cater for and with what level of accuracy? This data is collected by analysing the specifications of the software and hardware products used in the study.

Usability

The usability evaluation can be split into three parts: Efficiency, Effectiveness and Satisfaction.

Efficiency is assessed based on the cognitive effort required to operate the different controllers, and this qualitative data is collected through two questionnaires. As part of the JotForm questionnaire, the participants are asked the succinct single-question self-report Subjective Mental Effort Questionnaire (SMEQ), which gauges the perceived task difficulty on a sliding scale. Additionally, NASA's task load index (NASA-TLX), consisting of five questions, aims to provide insights into the efficiency of the controller by capturing qualitative aspects such as cognitive, physical, and temporal demands. Appendix F is a copy of the NASA-TLX, and Appendix E is an example of the SMEQ.

The **effectiveness** of the controller is measured by how well the participant completes the task. This quantitative data is recorded by the software that facilitates the interaction between the controllers and games. The data encompasses quantitative factors such as task completion speed, the number of failures during the process, and the participant's score when using the specific controller.

The user's **satisfaction** with the experiment as a whole will be determined through the After-Scenario Questionnaire (ASQ), attached as Appendix G, which has three questions aimed at ascertaining how satisfied the user is with a task. The questionnaire gets the qualitative data by asking the user to determine, on a scale, where they agree with the statements that they are satisfied with the ease of the task, the time taken to complete it, and the available support information.

Experience

Qualitative data describing the user's experience will be collected using the System Usability Scale (SUS), which aims to provide an overall usability assessment measurement. The 10- question SUS – A copy of which can be found in Appendix H - is favoured in this instance over the Critical Incidents Technique (CIT) – a method in which participants are asked, often in an interview setting, to recall and describe critical moments in their experience. While CIT would help point out issues with designs more accurately, it relies on memory; therefore, some details might be lost as users are more likely to recall out-of-norm incidents. The CIT can also be stressful and time-consuming for the participant. The SUS is thus favoured in order to limit the number of questions the user has to answer and the cognitive load required of the user. This is important since, as the iConnect consortium found in their study on the effects of questionnaire length [17], shortening a relatively lengthy questionnaire increases the responses to a survey significantly.

3.10. Methodology Conclusion

The research study is conducted with the highest regard for the protection of private personal information. The methodology followed allows for the researchers to avoid collecting any personal identifying information while still maintaining the ability to group data around a participant and exclude a participant's data upon request.

A combination of open-source, free and custom software is used to build the research's software platform. It is complemented by a PS4 controller, a keyboard and a Makey Makey to assess the interaction between a participant and the games as per McNamara and Kirakowski's theoretical framework of understanding interactions between computers and humans.

The Mixed Methods study collects both quantitative and qualitative data in the form of a questionnaire built and hosted on JotForm - the cloud-based form-building service - and data collected by the system that has been developed by the researcher. All data is stored securely using the free tier of Airtable. The form which collects the qualitative data related to the participant's demographic and experience is available at https://www.jotform.com/231627376223051.

The source code, along with a sample of the experiments are housed on a public GitHub repository available at https://github.com/LuckyNkosi/ma-experiements.

4. Results

The case study is designed to collect data in different forms. The analysis of such data is aimed at measuring the HCI when each digital product is used with different interfacing device. This section details how each of the components proposed by McNamara et al to measure HCI are used in this study. Each subsection focuses on an aspect of the framework, namely functionality, usability, and experience, detailing how each of them are measured.

4.1. Functionality

Functionality pertains to the technology-driven aspect of interaction. The pivotal concern lies in assessing whether the controller has the necessary capabilities to facilitate the user's engagement in the game. This part of interaction depends much on where or who is using it. There are two things to think about. First, can the controller do all the game actions? Second, how the controller does these actions is also important.

4.2 Input requirements

4.2.1 Possible Inputs

Assessing if the interfacing device can provide all the required inputs is contextual, as it's not simply about the number of direct inputs a controller has. It also requires the consideration of the combinational use of the inputs. A PS4 Controller has two analogue sticks, the L2 and R2 analogue shoulder buttons. The analogue inputs are capable of producing 255 unique inputs. It has buttons which are either pressed or not (two states) in the form of a D-pad (four directional buttons), the binary L1 and R1 shoulder buttons, the Triangle, Circle, X, Square buttons, share, and options buttons. It also has a touchpad capable of detecting various touch gestures. To calculate the total number of unique inputs, we multiply the possibilities for each input together.

*65,536 (analog sticks) * 16 (D-pad) * 16 (shoulder buttons) *
16 (triangle, circle, X, square buttons) * 2 (options button) * 2 (share button) =* ***268,435,456***.

Similar calculations can be done for the keyboard, which has 149 buttons in total and the Makey Makey board, which has a total of 18 direct input pins resulting in a total of *1,230,259,200* and *262,144* possible inputs, respectively.

In the context of this study, each game requires a different number of unique inputs. The Asteroids game requires inputs to accelerate, rotate left and right, shoot at enemies and hyperspace jump. The platformer game requires inputs to jump and move along the horizontal axis. Both games need basic navigational inputs to start the game, which can be the same as in-game controls. This brings the total required unique inputs to 5 and 3, respectively. Table I below shows the contrast between possible inputs and the required inputs for each game, where the "admin" label refers to the inputs required to start the game, such as navigating a menu or activating the "start game" button.

	PS4	**Keyboard**	**Makey Makey**	**Asteroids Requirement**	**Bemilanche Requirement**
Total Unique Inputs Possible	268,435,456	1,230,259,200	262,144	5 in-game 3 admin	3 in-game 1 admin

Table I: Unique inputs possible with controllers and required inputs for each game.

Considering Table I above, we can deduce that all three controllers are able to provide the functionality required to engage meaningfully with both systems.

4.2.2 Quality of input

The question of functionality also requires us to explore how well the input is supported. The Asteroids game's rotation and acceleration controls offer an opportunity for a much more nuanced analysis of how well the actions are supported by the controllers. The platformer's jump functionality offers a similar opportunity as all these functionalities support both analogue and digital inputs.

Digital inputs are triggered either through a keyboard key press or a button on a game controller. These inputs are then interpreted by the game, which adjusts an analogue value based on how long the digital input is active. For instance, activating the digital input for acceleration leads to a rise in vehicle speed determined by how long the input remains active within the limits set by the game's physics engine.

As shown in Table II below, the PS4 analogue inputs offer a distinct advantage when it comes to input for controls, just as turning and acceleration compared to the Makey Makey and the keyboard. This enhanced level of control is attributed to having a higher resolution which allows for fine-grain control over how much to turn or accelerate.

Control Parameters	**PS4 Controller (Turning Left/Right)**	**Keyboard (Left/Right)**	**Makey Makey**
Approx. Unique Possible Positions	180	2 (binary)	2 (binary)
Analog Counts	256 (8-bit)	N/A (not applicable)	N/A (not applicable)
Dead Zone	Yes (Center)	No	No
Approx. Angular Resolution	Approx. 1.4	N/A (not applicable)	N/A (not applicable)

Table II: Accuracy of controllers

The angular resolution of an analogue stick is determined by the number of unique positions it can detect as it's moved - measured in degrees per step. For the PS4 controller's analogue stick, we can assume it can detect 256 unique positions along the turning axis. Since a stick can be moved 360^{O} around the center, we can assume it moves 180^{O} for each direction and only half of the steps used to measure for the specific direction and therefore resulting in:

$$\textit{Angular Resolution} = 180 \textit{ degrees} / 128 \textit{ steps} \approx 1.40 \textit{ degrees per step}$$

This means that every 1.4-degree turn of the analogue stick can provide a unique input to the game about how much to turn the spaceship. A similar control can be afforded to the jump control of the platformer, allowing greater control of how high to jump.

It is important to note that while in this study, no participant requested an analogue input for acceleration, turning or jumping when configuring their custom controller made from household items, it is possible to build one using common household items. This would provide for greater input control. Figure 11 below shows an example of how one could be built as guided by Makey Makey producers [39].

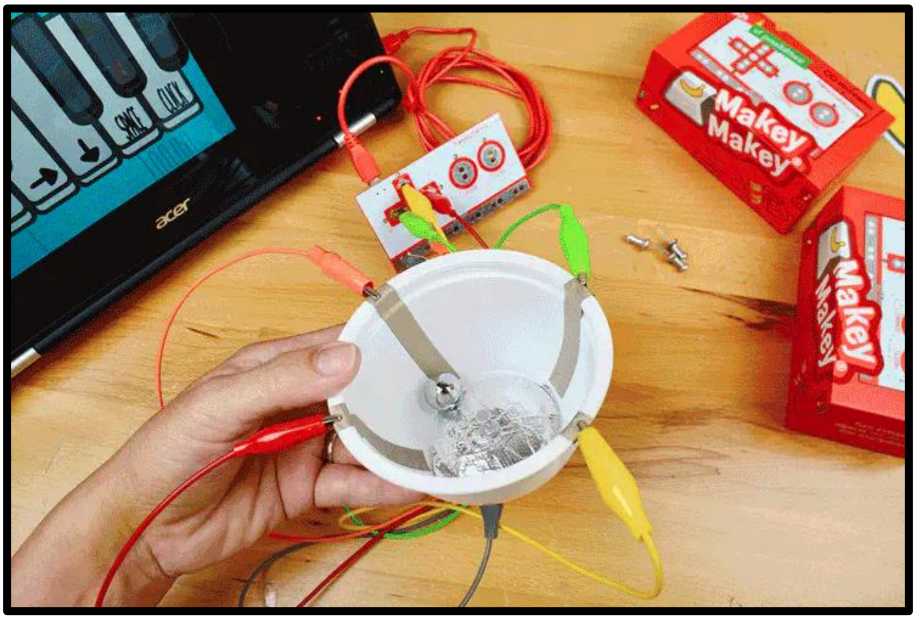

Fig. 11: Example analogue controller for Makey Makey

As seen in the image in Figure 11 above, the resolution would be reliant on how many inputs can be connected to the bowl. In the most extreme case, where all 18 direct input pins of the Makey Makey are connected to only one side of the cup, the approximate angular resolution would be ***≈ 10 degrees per step,*** which means that a 10-degree change in the rotation would result in a unique input detection by the digital system, making the PS4 analogue controller **7.14** times more accurate in terms of turning angle and acceleration amount.

Table III below shows a comparison considering a custom-built analogue input controller for the Makey Makey:

Control Parameters	**PS4 Controller (Turning Left/Right)**	**Keyboard (Left/Right)**	**Makey Makey**	**MakeyMakey (with Custom Analog)**
Approx. Unique Possible Positions	180	2 (binary)	2 (binary)	180
Analog Counts	256 (8-bit)	N/A (not applicable)	N/A (not applicable)	18
Dead Zone	Yes (Center)	No	No	Yes (center)
Approx. Angular Resolution	Approx. 1.4	N/A (not applicable)	N/A (not applicable)	Approx. 10

Table III: Accuracy of controllers, including a custom analogue controller.

This data clearly indicates that within the scope of this experiment and considering functionality in terms of the framework, the PS4 controller emerges as the superior control method. It boasts the broadest scope of motion and heightened sensitivity. In contrast, the keyboard lags behind both the MakeyMakey in terms of functionality, as it solely accommodates binary input for both steering and acceleration.

4.3 Usability

The usability evaluation is measured in three sub-components: Efficiency, Effectiveness and Satisfaction.

4.3.1 Efficiency

The efficiency component of usability is determined by evaluating the mental exertion required when using the different controllers. This qualitative information is gathered through two questionnaires. The questionnaires are the Subjective Mental Effort Questionnaire (SMEQ), consisting of a single inquiry regarding the perceived difficulty of the task, presented on a sliding scale and the five questions of NASA's task load index (NASA-TLX), designed to capture insights into the controller's efficiency by gathering qualitative details on mental, physical, and temporal demands experienced by the participants. Example copies of the NASA-TLX and SMEQ are provided in Appendix F and E, respectively.

While the SMEQ is simple to analyse because it has a single question, analysis of the NASA-TLX can be complex. The NASA-TLX employs a multidimensional approach to evaluating Mental Workload (MWL) along six distinct dimensions: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (OP), Effort (EF), and Frustration Level (FR). When using the TLX, participants are often required to provide two pieces of information. The first is the actual score, and the second is the weight. The weights represent the subjective importance of each dimension as a source of MWL in the task of interest [40]. Weights are determined through a pair-wise comparison of the dimensions. There is a total of 15 pairs, and they are included in NASA's Task Load Index guide, available as Appendix X. For each pair, participants indicate which dimension they perceive to have a greater impact on their workload [40]. This helps establish the relative importance of each dimension compared to the others.

Chang et al. [42], among others, have written extensively about the shortcomings of different weighting calculations and one of the proposed solutions is to ignore them altogether. This method is known as Raw-TLX [41] and only uses the arithmetic mean of dimensions' scores to determine the overall Task Load Index, which is an efficiency score in this study. Virtanen et al., in their paper titled "Weight Watchers: NASA TLX weights revisited," caution that "While Raw-TLX is an effective and straightforward version of the original NASA-TLX, its use is justified only when the importance of the dimensions is a priori known to be approximately equal in a task of interest [41]." Since the concern of this study is the overall experience, with no favour or specific concern of one element of user interaction over another, it's justified to use the RAW-TLX analysis of the data and treat all components of the task load as equal parts.

Table IV below presents the efficiency scores for each of the controllers considering both the SMEQ and NASA TLX. Both questionnaires measure difficulty out of 6 (negative phrasing) instead of ease, and therefore, the lower the score, the better the controller performed.

	SMEQ		NASA-TLX		
	Bemilanche	Asteroids	Bemilanche	Asteroids	Efficiency Score
Gamepad	2,29	3,14	1,98	2,12	2,38
Keyboard	2,57	3,14	2,14	2,79	2,66
Custom	5,14	5,86	4,64	5,00	5,16

Table IV: Efficiency as SMEQ and NASA-TLX mean.

The combination of two questionnaires in a mixed-method study may be used to either corroborate or highlight nuances in the primary data. The table above shows that in terms of the SMEQ and TLX, both configurations and analysis would lead to the same conclusion: that the Gamepad and Keyboard performed similarly with the keyboard in the lead in terms of efficiency, while the custom controller was found to be significantly less efficient.

4.3.2 Effectiveness

The evaluation of the controllers' efficacy hinges on the user's task completion proficiency. This quantitative information is recorded through the software that orchestrates the interaction between the controllers and the games. Both games were score-based instead of objective or destination-focused. The participants were given three lives in each game, and their scores were calculated.

The mean scores on each game for each controller are calculated and shown in Table V below. The results show an inconsistency in controller performance for each game. We were able to simply use the arithmetic mean in the previous analysis to determine an overall result for efficiency because our subject was the controller and the user's experience of them. In this case, the arithmetic mean would not suffice since the two games have fundamentally different scoring systems and scales. Furthermore, the scores are more susceptible to influence by external factors such as luck. In the Asteroids game, this could translate to an enemy saucer spawning right next to the participant's ship. In the platformer game, the blocks are generated randomly along the horizontal axis, which could lead to the player being locked in with no way of jumping out of a corner. In order to attain a meaningful view of the controllers' performance across the entire experiment in terms of scores, the arithmetic means of each controller's scores for each game can be normalised and compared. A Z-normalisation can be employed to transform the data into a comparable form.

Z-normalization is a statistical technique used to transform data into a standard normal distribution. In Z-normalization, each data point is transformed by subtracting the mean of the data and then dividing by the standard deviation. The resulting transformed values, known as Z-scores, have a mean of 0 and a standard deviation of 1. This transformation effectively allows for the analysis of the averages. This transformation enables direct comparisons between variables with different units and ranges. This normalisation technique is favoured over the summation of the two scores because it can mitigate the impact of outliers [43] on the results, which is significant when summation is used. The formula for the normalisation applied to each controller's mean is shown below.

$$z = \frac{(x - \mu)}{\sigma} = \frac{(value - mean)}{standard\ deviation}$$

Table IV Below shows the mean scores for each controller on each game, the z-normalised mean, and the resultant effectiveness score, which is calculated by averaging the normalised means.

	Mean Scores		Z-Normal		
	Bemilanche	Asteroids	Bemilanche	Asteroids	Effectiveness Score
Gamepad	816,00	6494,44	-1,25	1,00	-0,12
Keyboard	1331,00	5387,78	0,05	0,36	0,21
Custom	1784,00	2388,89	1,20	-1,37	-0,08
Calculated Controls for normalisation					
Mean	1310,33	4757,04			
Std Dev	395,45445	1734,40923			

Table V: Effective score across both games

As shown in Table V above, the custom controller performed the best in the platformer game while it did the poorest in the Asteroids game. The gamepad performed poorly in the platformer but produced the highest mean score in the Asteroids game, while the keyboard was in second place for both games. In terms of overall effectiveness, the keyboard performed the best, as shown by the mean normalised score understood to be effectiveness. The custom controller came in second, and the gamepad performed the poorest by the same measure.

4.3.3 Satisfaction

The user's satisfaction is determined through the After Scenario Questionnaire (ASQ), which has three questions aimed at ascertaining how satisfied the user is with a task. The questionnaire gets the qualitative data by asking the user to determine, on a scale, to what extent they agree with the statements that they are satisfied with the ease of the task, the time taken to understand and learn it, and the available support information.

	Satisfaction with:				
	ease of using the controller	time to learn controls	available information	Mean	ASQ Score (%)
Gamepad	4,86	4,86	5,00	4,91	82%
Keyboard	4,00	4,43	5,00	4,48	75%
Custom	2,71	3,14	5,29	3,71	62%

Table VI: ASQ Scores for user satisfaction

Table VI above shows that while participants felt that the custom controller had enough information for them to use it, they found it more challenging to learn the controls and use it, thereby making it score the poorest of all three. The gamepad scored higher than the keyboard due to participants finding it easier to use and requiring less time to learn. The keyboard lags closely behind the gamepad, with participants finding it slightly less easy to learn and use.

4.3.4 Overall Usability

Usability is considered in terms of three components, efficiency, effectiveness, and satisfaction. Table VII below shows the ranking of the controllers in terms of each category. Table VII shows that overall, each controller performed differently in each category when compared to the others. The keyboard proved to be the most efficient and effective, while the gamepad provided the most satisfaction to participants.

Rank	Usability		
	Efficiency	Effectiveness	Satisfaction
1	Keyboard	Keyboard	Gamepad
2	Gamepad	Custom	Keyboard
3	Custom	Gamepad	Custom

Table VII: Usability rankings of each controller

The measure of usability is complex as it relies on three elements which themselves have a multitude of data points. The efficiency measure is reliant on fourteen questions that combine two questionnaires (SMEQ and TLX). This is significantly large when compared to the six questions of the SUS and the ASQ, with three questions. The difference in scores attained by participants is also distributed, with some participants scoring on the extreme ends of the spectrum. The differences might be due to statistical chance or point to the differences in the controllers having a much more significant impact on one element over another. A series of one-way ANOVAs were used to determine if the differences in the mean of the usability components have statistical significance.

ANOVA, or Analysis of Variance, is a statistical method used to compare arithmetic means among three or more groups to determine if there are significant differences between them. It assesses whether the variation in the data is due to differences between group means or simply due to random chance.

In simpler terms, ANOVA helps us understand whether the differences observed in data are likely caused by real factors (like controllers) or if they could have occurred by random fluctuations. It does this by analysing the variance, or differences, between group means and within each group. If the variance between group means is significantly larger than the variance within each group, it suggests that there are meaningful differences among the groups. The results of the ANOVA for the usability components are presented in Table X below.

ANOVA	Efficiency	Effectiveness	Satisfaction
F-value	0.2218	0.9454	0.3967
Degrees of Freedom	2	2	2
P	0.8015	0.8171	0.008183
Statistical significance in variation	Insignificant	Insignificant	Significant

Table X: ANOVA Results for Usability

Since this is an exploratory study, as with Brown et al. [4], all three ANOVAs were calculated with a significance level (alpha) of 0.05. This is a commonly used level and sets the acceptable chance for a Type I (false positive – that variation is insignificant) error at 5%. The results in Table X above show that the statistical variation is only significant in the satisfaction element of usability. This means that there's a chance that the difference in controllers affected people much more significantly in this category than in efficiency and effectiveness.

4.4 Experience

Qualitative insights into the user's experience are gained through an adaptation of the System Usability Scale (SUS) questionnaire. The questionnaire has ten questions, some of which would not have relevance to the context of this study as they were concerned with finding integration pitfalls of a specific system. The version used has seven questions aimed at getting insights about the user's experience with using the controllers.

The original SUS mixes phrasing in terms of the polarity of their phrasing and inverts scales for some questions. For instance, one statement states, "I found the system unnecessarily complex", while the next says "… I would like to use it frequently." This means that the results cannot be simply averaged. The answers to two of the questions need to be inverted. For instance, a rating of 5/6 for finding the controller unnecessarily complex maps to 1/6 in the positive lens. This transformation was done for two question negatively phrased questions.

	I'd use frequently	unnecessary complexity	easy to use by others	quick to learn by others	felt confident	amount to learn	fun	SUS Score
Gamepad	5,57	3,86	5,57	5,57	5,43	4,71	4,86	5,08
Keyboard	5,43	4,00	5,71	4,86	5,29	4,00	4,71	4,86
Custom	2,29	1,71	2,43	2,29	2,43	1,71	5,14	2,57

Table VII: SUS Results

Table VIII above show the SUS results for each controller. The gamepad emerged as providing the best overall experience of all three controllers. The custom controller proved to be the most fun to engage with but proved to be overly complex when compared to the rest. It also scored poorly in terms of the amount to learn, and it was found to be the least likely to be used by other people as well.

4.5 Findings Conclusion

All three controller devices studied were able to aid the study participants in engaging with the core platform and systems. The controllers varied in performance in terms of different elements of McNamara and Kirakowski's framework ranging from functionality to sub-components of usability and overall experience. The lack of an outright dominator in all respects highlights the subjective nature of HCI. Despite the participants using the custom controller for the first and therefore not possessing the cultural affordances developed through years of experience with the controller and keyboard, all participants were still able to use it to complete their tasks. This, and the HCI being about the subjective experience of a participant - a key component of which is fun, further points out that it is possible to reuse controllers across devices that they were not meant for without significantly degrading the quality of the HCI.

The custom controller scored highest in several sub-components of one of the games, such as effectiveness and fun. This further highlights the potential space for non-conventional controllers in games and digital product interfaces in general, especially with further research and development that would couple these custom controllers with ergonomic design principles which was beyond the scope of this study.

In terms of the research question at hand, which asks, "How does the use of digital systems with interfacing devices that were not designed for them impact the Human-Computer Interaction?" the data collected shows no overall significant impact on the overall HCI but highlights subjective nuanced differences in the functionality, usability and experience which are largely based on the participant's experience and affordances.

5. Discussion

This research aimed to explore the first step in assessing the feasibility of cross-platform controllers by studying their potential impact on HCI. These would be reusable controllers that are decoupled from the core platform, device, and application. The decoupling would be aimed at allowing users to use a controller device of their choice to interact with most digital products with ease. The shift to decouple core platforms and their interfacing devices would be done to reduce e-waste, decrease the cost of entry to digital products and services, address accessibility needs and create space for an industry of niche controllers to emerge.

The exploration of cross-platform controllers' potential impact on the HCI is done by studying the interaction of 15 study participants with two digital products in terms of McNamara and Kirakowski's theoretical framework of understanding interactions between computers and humans [3]. The framework has three primary elements: Functionality, Usability – which is split into efficiency, effectiveness, and satisfaction, and User Experience.

The study builds on Brown's experiment [4] and tasks participants to play two games with varying input requirements, motor skills, cognitive loads, and urgency. The games used are a remake of Asteroids and a basic Platformer game named Bemilanche. The mixed method study makes use of both quantitative and qualitative data. The former was captured by means of multiple questionnaires, while the latter was captured through custom software developed by the researcher. The data was analysed using established statistical analysis methods, and the findings are summarised below.

5.1. Overall Findings

Table IX below is a summary of the findings detailed in the results section, highlighting the performance of each control scheme against each other and ranking them in the first, second, and third positions per element.

Rank	Functionality	Usability			Experience
		Efficiency	Effectiveness	Satisfaction	
1	Gamepad	Keyboard	Keyboard	Gamepad	Gamepad
2	Custom	Gamepad	Custom	Keyboard	Keyboard
3	Keyboard	Custom	Gamepad	Custom	Custom

Table IX: Consolidated findings of controller performance

Table IX above shows that despite the core platform being a laptop, there was no outright dominance of the keyboard (which is literally coupled with the core product) over the other controls. It also shows that despite the applications used for the experiment being games, the gamepad also failed to outperform the other controllers in all categories. These findings highlight the potential for decoupling controllers from their platforms by showing that the HCI is subjective and that users have different preferences that impact their interactions with computers in different ways.

It is important to note that despite the participants having no prior experience with the custom controller and it being built from repurposed common household products that provided no feedback, auditory, haptic or otherwise, it performed significantly well in several aspects. The custom controller had the highest mean score for the platformer game and produced the highest single score of 3500 points for the same game. While it scored significantly lower for overall experience, it proved to be the most fun controller to use. This points to defamiliarisation playing role in evoking curiosity, surprise, and reflection in players, fostering a more immersive and intellectually stimulating experience which highlights the potential for a niche controller industry.

The results for the keyboard proved it to be a strong choice in terms of efficiency and effectiveness and lagged only slightly behind the others in categories where it did not lead. The gamepad proved to dominate in terms of functionality and user experience.

5.2. Conclusions

In contribution to a drive aimed at decoupling interfacing devices and their core platform, this study set out to explore a feasibility component by assessing the impact that using a digital product with controllers that were not explicitly designed for it has on the HCI and thus attempts to answer the research question:

How does the use of digital systems with interfacing devices that were not designed for them impact the Human-Computer Interaction?

The study found that the use of digital systems with interfacing devices that were not designed for them had no severe impact on the quality of HCI.

This study, therefore, also concludes that the potential degradation of the HCI is not a barrier to the development of systems that are decoupled from their peripheral interfacing devices.

5.3. Discussion

5.3.1. Game Choices and Pivots

The execution of this case study required the researcher to pivot from the proposal. The proposed study was meant to make use of a drone and the Asteroids game. The study is aimed at digital systems in general and not just video games. Most of the systems we engage with, such as communications applications (chat, social media) and entertainment units (TVs, sound systems), have simple input requirements. The study required systems with slightly complex interface requirements to truly explore the complexities involved in interfacing with technology. The drone offered enough complexity while also being a physical object that exists in space.

The drone that was to be used is the Parrot Mambo Mini Fly Drone. The drone is 5.2 x 5.2 x 1.6 inches big and fits in the palm of an average-sized hand, which makes it safe to fly indoors. A single Mambo Mini Fly drone had already been secured for the study. It was chosen for its size and the researcher's experience with writing custom software for the drone, allowing it to be controlled with a controller of choice, including the custom controllers built with the Makey Makey. The task was to fly the drone through an obstacle course that required the participant to make the drone action all its movements (take-off, roll, pitch, yaw, flip, and land). The experiment was also developed to provide a different means of calculating effectiveness by looking at how long it would take participants to complete the course and how many times the drone would have crashed.

The first two study participants that engaged with the experiment crashed the drone multiple times and could not get past the first obstacle. They were incredibly frustrated and began to doubt their own ability to understand the controls. The drone in question also has collision avoidance technology on board. If it detects an object too close to it, it will increase its altitude to try and go over the object. This caused further confusion for the participants as they witnessed movements that they did not initiate. This severely impacted their trust and confidence in the systems they were engaging with. Considering all the above factors, the researcher pivoted the study and used the platformer instead.

The platformer limited the experiment to digital games, which narrows the scope of the study. However, it also brought about essential balance to the study. The drone and the Asteroid game are both third-person view navigation-based systems. This means that participants who tend to struggle with such experiences could have skewed the data significantly. Asteroids is a fast-paced game with multiple elements to be weary of, and gameplay is about brute force and destruction. Bemilanche offered a counter experience and allowed for much calmer gaming. It centred precision and timing over rush and panic.

5.3.2. Measurements

Losing the drone as part of the experiment meant the loss of data dimensions, such as time to completion of objective-based tasks and the number of crashes/failures. While these dimensions would have brought about interesting insights, particularly with the demographics of the participants, having a common measure of effectiveness (game score) simplified the calculations for that element of usability.

5.3.3. Findings

The participants' experience with playing video games has the potential to impact subjective elements of the framework such as satisfaction with using the controller and their efficiency with it. To measure the correlation of these variables, participants were asked to describe their gaming experience as either regular, occasional or having no gaming experience, in addition to the established questionnaires and their results are plotted below.

Figure 12 below is an image of a graph that shows the average score for satisfaction plotted against the study participants' gaming experience.

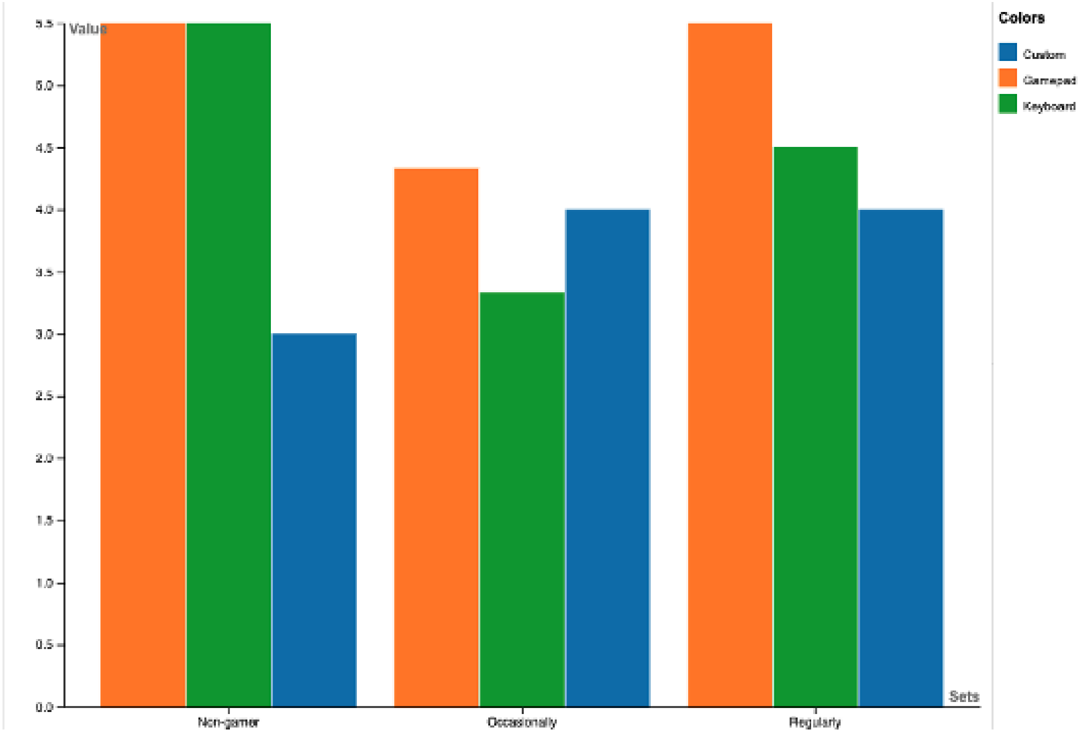

Fig. 12: Gaming Experience vs Mean Satisfaction

The results in Figure 12 may shed light on the potential reason for the significant variance seen in Table X. The graph shows that participants with no gaming experience scored the custom controller significantly lower than the established gamepad and keyboard for satisfaction. The reasons for this may vary. One potential reason might be that the games demanded significant effort from the participants, that the controller became a hindrance to completing the tasks well.

This hypothesis is supported by the graph in Fig 13 below. The graph plots the correlation of gaming experience to efficiency (how hard it was to use each controller). The results show that non-gamers found the custom controller harder to use than participants with more gaming experience.

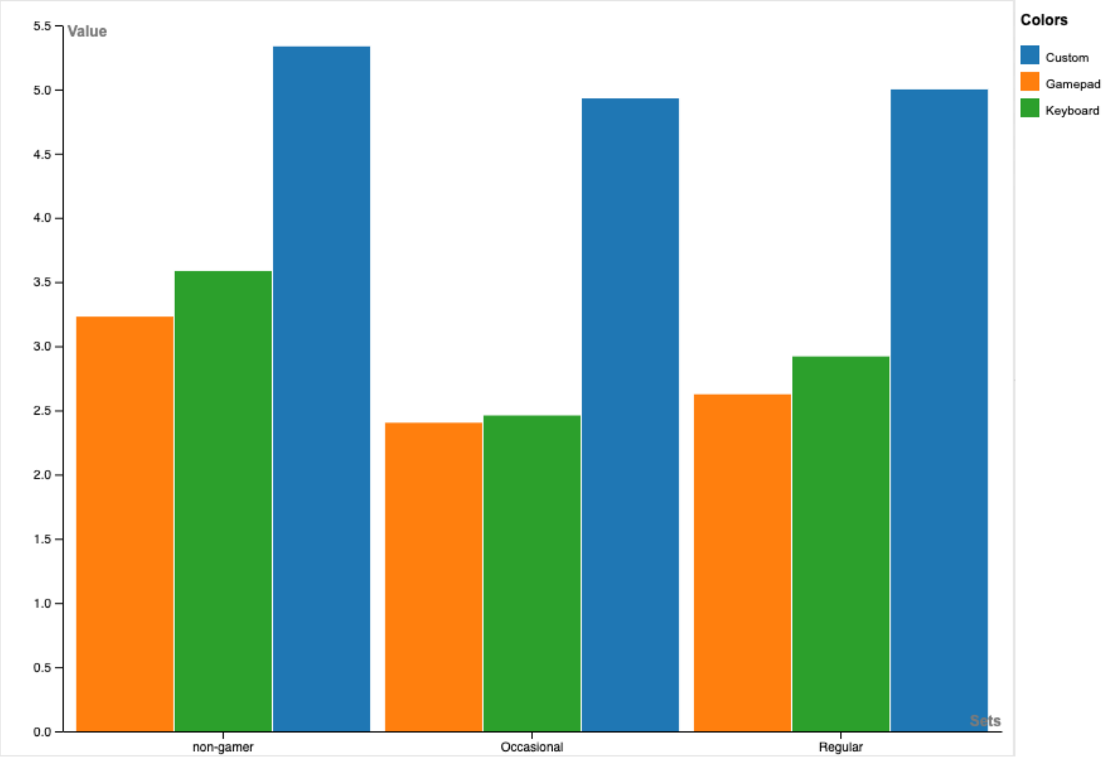

Fig. 13: Gaming experience vs efficiency

5.4. Future Research

This case study was constrained to exploring digital products running in a web browser. The tasks were limited to video games that were deliberately chosen for their relatively short playtime. Future research should explore the impact of HCI over continued long-term use to investigate how the HCI changes over time. Future research should also expand the research beyond games and the web medium. It should include interactions with everyday utility digital products to reach a wider understanding of the impact. The data suggests that decoupling controller devices from their platform without degrading the HCI is possible. While this study deliberately excludes accessibility considerations, the results prove to cross-platform custom controllers being viable, thus enabling individuals with unique accessibility needs to have bespoke controllers that they can use with varied platforms. This would lead to improved user experience for them with a reduced cost barrier to technology. This would ultimately lead to reduced e-waste as people will likely gravitate to their niche preferred devices and not need to purchase new ones with each platform. These are is an important aspect of research. Future research should take a close analysis accessibility, costs, and e-waste.

The study did not consider what makes the controllers different from each other beyond their functionality. Future studies should seek to understand the nuances in the differences between the controllers to understand how the choice of controllers may impact the HCI and, therefore, the results of such a study.

Economics plays a significant role in the research and development of technology. The economic viability of such controllers needs to be studied further in terms of the impact that decoupling controllers from their platforms might have on the current hardware industry and the potential it has for creating a new niche industry.

Finally, future research should seek to propose a standard that would enable the easy interfacing and configuration of controllers with as wide a variety of digital platforms and products.

6. Conclusion

This study proposed that the first step towards decoupling core platforms and their peripheral interfacing devices (controllers) is research into the impact this would have on the HCI. A case study was developed and undertaken by extending the Brown et al. [4] experiment. Study participants were given two digital products to engage with using three different controllers: a gamepad (PS4 controller), a standard keyboard, and a custom controller built with the Makey Makey kit. The interactions were recorded and analysed in terms of McNamara and Kirakowski's theoretical framework for understanding the interactions between computers and humans [3]. The framework considers the interaction in terms of three primary elements: Functionality, Usability (separated into efficiency, effectiveness, and satisfaction), and User Experience.

This mixed methods study made use of both qualitative and quantitative data to study different elements of the interaction. The quantitative data was collected through custom-built software that facilitated the interaction. The qualitative data was collected by means of established questionnaires combined into a post-experiment survey. The SMEQ and NASA-TLX were used complementarily to measure efficiency. The ASQ was used to measure satisfaction, and the user experience was measured with the SUS.

The study set out to determine if there was a significant degradation of the HCI when digital products were used with controllers that were not specifically designed for them. The findings showed that despite the platform used being a computer, the keyboard did not prove to be the best interfacing device in all respect. The gamepad (PS4) also did not dominate throughout, despite the two digital products being video games. The custom controller performed better than the other two in some categories, including effectiveness in one of the games, despite being poorly built with common household products and providing no feedback to users.

The data collected in this this study highlighted the subjective nature of Human Computer-Computer Interactions. It brought to the fore that people have different needs and preferences in interfacing devices, and therefore, no single device can address everyone's needs. Based on the findings, this study, therefore, concluded that the use of digital systems with controller devices that were not specifically designed for them has no significant negative impact on the HCI. By extension, this research also concluded that the use of cross-platform controllers would not degrade the user's experience and that, conversely, it will enhance some aspects of the interaction for users with specific niche needs, limitations, and interests.

This research study was conducted with 15 study participants and only used video games with a short playtime. Further studies would need to have a larger pool of participants, engaging with a more diverse range of products and over a longer period to understand the interaction over time as participants get used to the platforms, products, and controllers.

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