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Development and Evaluation of a Multimodal Sensory Integrated Device for Autonomous Grocery Assistance for Visually Impaired Filipinos

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Abstract

Grocery shopping, a routine activity, becomes a significant challenge for individuals with visual impairments (PVIs) due to barriers in accessing product information such as nutritional facts, allergens, and expiration dates. This study introduces GaBuy, a multimodal sensory-integrated (MSID) assistive device designed to enhance the grocery shopping experience for PVIs by addressing key variables: independence, readability, convenience, accuracy, and efficiency. Initial surveys conducted with 35 visually impaired participants identified critical pain points, including difficulties in locating products, reading labels, and relying on external assistance. These insights guided the design and development of GaBuy, which integrates text-to-speech capabilities and streamlined product identification features. A simulation-based study compared participants' experiences between traditional grocery shopping methods (pre-treatment) and the use of GaBuy (post-treatment). Data analyzed using the Wilcoxon Signed-Rank Test revealed statistically significant improvements across all five key variables. Participants reported increased autonomy, reduced cognitive strain, and greater ease in acquiring essential product details, highlighting GaBuy's potential. This research bridges existing gaps in assistive technology by offering a user-centered solution that promotes inclusivity, independence, and accessibility for PVIs in grocery shopping environments. GaBuy sets a benchmark for future innovations, empowering PVIs to navigate daily tasks with confidence and dignity.

Keywords
Assistive Technology, Visual Impairment, Grocery Shopping, Low Vision, Design Thinking

1. Introduction

Vision is a crucial sense that allows an individual to perform essential activities pertinent to their survival, thus contributing to productivity and consequently affecting the global economy. However, in the data released by the World Health Organization (WHO) in 2023, it was revealed that at least 2.2 billion people have already acquired near or distant vision impairment, posing adverse effects both personally and economically. A Person with Visual Impairment (PVI) encounters challenges in basic tasks such as shopping, cooking, and the like (Jones et al. 2020). The Visually Impaired also find navigation inside indoor spaces such as buildings and public spaces complex due to unfamiliar features and challenging application of distance estimation. These instances force them to require assistance from persons without visual impairment (Jeamwatthanachai et al. 2019); however, many establishments do not allocate employees solely to assist PVIs due to perceived economic impracticality. In 2023, visual impairment has been reported to cause an immense annual global financial burden, amounting to an estimated global productivity loss of US$ 411 billion (WHO 2023).

The issues are particularly pronounced in the Philippines, as visual impairment is a significant health problem, especially for lower to middle-income earners. 1.98%, estimated at around 4 million, of Filipinos with eye problems remain undiagnosed due to socioeconomic problems in accessing eye care services. The availability of health resources is an obstacle to the eye care of many Filipinos because many community-based health centers lack the necessary equipment for eye examination, and regional hospitals have a scarcity of similar resources due to geological disparity because the majority of Ophthalmology practitioners and equipment are in the capital cities such as NCR. Philippines' plan of action for Senior Citizens providing community-based services faces challenges in implementation due to lack of technical assistance and wavering compliance of participating agencies; furthermore, these activities focus more on non-communicable diseases, giving little attention to ocular morbidities. Poor health literacy is also a significant contributor to a low understanding of the importance of eye services because many Filipinos believe that vision problems are a natural occurrence of aging. (Ho et al. 2022)This study is specifically aimed at PVIs falling within Categories 1 and 2. It excludes Blind PVIs, as their needs typically demand more specialized features that may not be necessary for the broader population of Persons with Disabilities (PWDs). This targeted approach ensures that the research focuses on addressing the specific challenges encountered by the most relevant demographic group, thereby enhancing the study's effectiveness and relevance to real-world situations.

1.1 Objectives

This study aims to develop and evaluate an accessible, user-friendly Multimodal Sensory Integrated Device (MSID) to address the challenges faced by PVIs, particularly adults with low vision in Categories 1 and 2 within NCR, during grocery shopping. The primary objective is to enhance independence, readability, convenience, accuracy, and efficiency by overcoming barriers such as inaccessible and illegible product descriptions, ultimately fostering a seamless and self-sufficient shopping experience.

Specifically, the study seeks to:

1. **Identify Challenges:** Analyze the specific difficulties PVIs encounter in accessing product information while shopping.
2. **Determine Essential Features:** Define key functionalities for an MSID, including accessibility tools and support for health-conscious decisions.
3. **Leverage Technology:** Integrate innovative solutions that provide instant and detailed product information, such as nutritional data, while addressing barriers like inaccessible packaging designs.
4. **Enhance User Experience:** Design and test an intuitive and reliable MSID tailored to the needs of PVI shoppers.
5. **Promote Independence:** Develop a solution that empowers PVIs to shop confidently and autonomously in physical grocery environments.

2. Literature Review

The framework of this study is grounded in Input-Process-Output (IPO), which utilizes existing literature to address challenges (input) and solutions (output) related to accessibility, cognitive load, and technological interventions. Various studies highlight the difficulties individuals with visual impairments face in daily tasks, particularly shopping and navigation. Studies by Marmamula et al. (2020) and Tshuma et al. (2022) emphasize the psychological stress on PVIs doing daily tasks, resulting in higher depression levels and lowering their self-esteem. Angioletti et al. (2023)

and Balconi (2022) discuss the cognitive and orientation difficulties encountered while shopping, leading to stress and disorientation. Additionally, Redd et al. (2022) and Madake (2023) emphasize logistical barriers such as cost, distance, and provider shortages.

Studies emphasizing the technological interventions to address these issues, like George (2022) and Musale et al. (2019), introduce QR codes and barcode scanning as potential accessibility solutions. Subekti et al. (2021) and P. Miralles et al. (2023) examine the role of ATMs with audio guidance, tactile buttons, and smartphone-based solutions such as speech-to-text (STT) and text-to-speech (TTS) technologies. Additionally, AI-driven innovations like virtual shopping assistants (Villegas-Ch 2023) and wearable devices (Hung et al. 2019) offer enhanced user experiences. Deshmukh et al. (2022) and Mikotzidis et al. (2020) further contribute by integrating computer vision and object detection systems for improved accessibility.

Despite various interventions, significant research gaps and challenges remain. People with visual impairments struggle to locate products, read descriptions, and access accurate information. Additional barriers include low technological literacy hindering the use of assistive tools, the psychological impact of shopping difficulties, and the limited availability of assistive technologies tailored for local grocery stores.Moreover, existing literature on health-related injuries caused by visual impairment acknowledged that there is a high prevalence of obesity and undernutrition reported in people with visual impairment (VI) who have reported multi-factorial obstacles that prevent them from achieving a healthy diet, such as having restricted shopping and cooking abilities. A study by Jones et al. (2020) highlights how numerous elderly individuals in the UK who are diagnosed with VI are malnourished.

2.1 Conceptual Framework

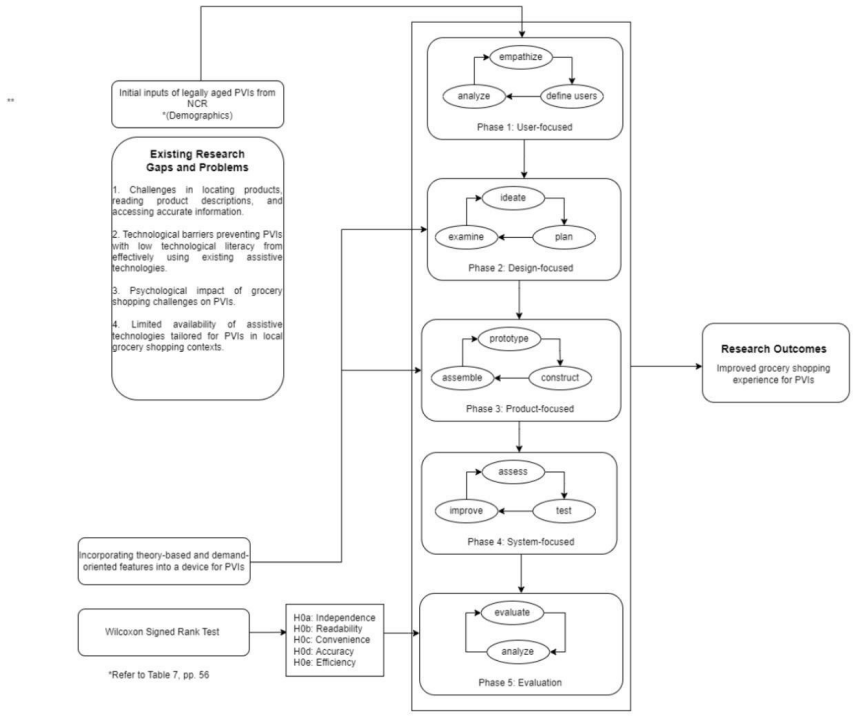

Figure 1. Conceptual Framework

Figure 1 shows the conceptual paradigm of the study. The framework for the Input-Process-Output (IPO) model is structured to develop a user-centered assistive technology for visually impaired individuals during grocery shopping. The **input** stage incorporates research gaps, pre-survey insights from legally aged visually impaired individuals in NCR, and statistical tools like the Wilcoxon signed-rank test to measure improvements in accessibility, readability, and convenience.

The **process** follows a five-phase design thinking approach:

1. **The User-focused research** understands the challenges faced by visually impaired individuals,
2. **The Design-Focused Ideation** builds a design that incorporates different research theories and demand-oriented features for PVIs,
3. **The Prototype development** constructs an assistive device,
4. **The System-focused testing** refines functionality and
5. **The Evaluation stage assesses** the effectiveness of the prototype developed using the independent variables.

This study considered five independent variables during the evaluation phase of the prototype developed: **independence, readability, convenience, accuracy, and efficiency**. These factors ensure that the design developed directly addresses and benefits people with visual impairment during grocery shopping. The **output** reflects the study's key findings, showing that the assistive device significantly enhances the grocery shopping experience for PVIs, as indicated by the Wilcoxon Sign-Rank Test.

2.2 Comparative Analysis

This section compares GaBuy with existing assistive technologies, evaluating key aspects such as features, strengths, and limitations. By analyzing these aspects, we highlight GaBuy's unique contributions in providing an intuitive, efficient, and user-friendly shopping assistant tailored to the needs of visually impaired consumers.

Table 1. Comparative analysis of Gabuy and existing assistive technologies

Assistive Technology	Key Features	Strengths	Limitations
GaBuy (2024)	GaBuy is a compact, handheld device for visually impaired users, featuring barcode scanning for quick product identification. It has a button-based interface, a screen for product details, and a text-to-speech function that announces key information like name, expiry, price, and nutrition, ensuring accessibility and independence in shopping.	GaBuy introduces an original design unique to the Philippines that caters to persons with visual impairments (PVIs). Its user-friendly and intuitive interface ensures accessibility across all age groups, making grocery shopping more accessible and efficient for its target users.	GaBuy's database requires continuous updates to maintain accuracy and relevance. Due to budget constraints, only a prototype has been developed, limiting large-scale production. Product testing remains limited, and more extensive simulations are needed to refine its functionality.
EyeBill-PH Alon et al. (2020)	EyeBill-PH is a portable assistive device that helps visually impaired users identify Philippine paper currency. Using a Raspberry Pi 4 and Pi Camera, it detects bills and announces their denomination via text-to-speech. Its user-friendly design promotes ease of use and financial independence.	EyeBill-PH specializes in Philippine currency with an 86.3% accuracy rate in detecting and announcing denominations. Its quick audio feedback helps visually impaired users manage money independently. A simple design enhances accessibility and usability.	EyeBill-PH is designed exclusively for currency recognition but requires good lighting for accuracy and may struggle with worn or folded bills. Hardware costs could also limit widespread adoption.
AiSee Boldu et al.	AiSee combines a micro-camera and cloud-based AI for object	AiSee aids visually impaired individuals in grocery	AiSee requires a stable internet connection, may

(2020)	recognition, with bone conduction headphones for non-intrusive feedback. It was refined through user research and testing.	shopping with AI-driven object recognition and bone conduction headphones for clear, non-obtrusive feedback, continuously refined to meet user needs.	experience latency in low-connectivity areas, and is primarily for grocery shopping. It has limited uses, requires frequent recharging, and may need an adaptation period.
MobiEye Mao et al. (2019)	MobiEye is a shopping aid for visually impaired users that uses real-time video analysis. It features speech targeting, walking guidance, and picking-up modules to help locate products, navigate, and assist in picking them up.	MobiEye improved the pick-up success rate by 13% and reduced pick-up time by 12 seconds. For smaller items, it achieved 98.5% accuracy, a 50% improvement in pick-up, and 75% less communication overhead compared to other systems.	MobiEye relies on real-time video streaming, which can be affected by poor lighting, crowded areas, and obstructions. These factors may lead to item misidentification and unoptimized walking guidance.
e-Vision Migkotzidis et al. (2023)	E-Vision uses AI-powered computer vision to recognize grocery items and provide real-time information through smart glasses or mobile integration, offering a hands-free shopping experience. It enhances independence with advanced image recognition and personalized assistance.	E-Vision is an AI-powered system that assists visually impaired individuals in daily activities like shopping and navigation. Using Wi-Fi-enabled camera glasses and a smartphone app, it provides real-time visual data through earphones, promoting autonomy and social inclusion.	E-Vision requires high-quality cameras, stable internet, and a compatible smartphone or wearable device, limiting accessibility for some users. Setup and calibration may also be complex, requiring technical familiarity.

3. Methods

This study employed a mixed-method approach, integrating literature review, surveys, and prototype testing. The Design Thinking framework involved five stages: empathizing with users, defining challenges, ideating solutions, prototyping, and testing. The study focused on key independent variables—Independence, Readability, Convenience, Accuracy, and Efficiency—identified through preliminary surveys and literature analysis. Participants were selected based on criteria ensuring their legal age, residence in NCR, and medically diagnosed visual impairments impacting grocery shopping. Thirty-five (35) respondents, determined through the G*Power software, participated in providing insights into usability and accessibility challenges. A Wilcoxon Signed-Rank Test was conducted to compare pre and post-treatment survey results, ensuring statistical reliability in evaluating the developed MSID's (GaBuy) effectiveness. Prototyping involved iterative improvements based on user feedback, refining text-to-speech accuracy, barcode scanning reliability, and overall usability. The final prototype was assessed in controlled simulations replicating real-world grocery shopping scenarios. The study also addressed ethical considerations, ensuring informed consent and data confidentiality.

4. Data Collection

The same individuals who participated in the preliminary survey were also involved in the main survey, conducted both before and after using GaBuy. Initially, participants completed a pre-treatment survey to assess their experience in locating specific product information without assistance. They were then introduced to GaBuy and tasked with performing the same activity, after which they completed a post-treatment survey. A 4-point Likert scale was employed to measure responses across the identified variables in both pre-treatment and post-treatment surveys. Participants rated their level of agreement with various statements, ranging from "strongly disagree" to "strongly agree." The collected data were then summarized using medians to represent the key independent variables.

To ensure the reliability of the statistical analysis, assumptions for Non-Parametric Tests and the Wilcoxon Signed-Rank Test were evaluated. This was achieved through the Normality Test and Statistical Test of Skewness, which confirmed the suitability of the test for analyzing differences between pre-treatment and post-treatment survey results. Once these assumptions were validated, the Wilcoxon Signed-Rank Test was applied to determine whether significant differences existed between the two datasets. The interpretation of results was conducted using Descriptive Statistics and Ranks provided by SPSS, ensuring a comprehensive analysis of the impact of GaBuy on the participants' grocery shopping experience. Consequently, the study's main survey was utilized to quantify user perceptions, focusing on:

- Independence: Ability to shop without external assistance.
- Readability: Ease of accessing product information.
- Convenience: Overall user-friendliness of GaBuy.
- Accuracy: Reliability of barcode scanning and text-to-speech functionality.
- Efficiency**:** Reduction in time taken to complete shopping tasks.

Observational data were recorded to supplement survey responses, capturing real-time usability challenges and behavioral changes. Ethical considerations included informed consent, ensuring participants understood the study's purpose, and confidentiality measures to protect their data.

5. Results and Discussion

5.1 Numerical Results

In this study, the Wilcoxon Signed Rank Test was applied to evaluate whether the use of GaBuy significantly improved the experience of PVIs in locating and accessing specific product information. The results, summarized in the table below, demonstrate the statistical outcomes of the Wilcoxon Signed Rank Test.

Table 2. Summary of the Wilcoxon Signed Rank Test

Hypothesis	Asymp. Sig. (2-tailed)	Interpretation
H0a: There is no significant difference in the independence of visually impaired individuals (PVIs) when identifying product details between using GaBuy and traditional methods. **H1a:** There is a significant difference in the independence of visually impaired individuals (PVIs) when identifying product details between using GaBuy and traditional methods.	0.000	Significant
H0b: There is no significant difference in the readability of product information, such as allergens and ingredients, between using GaBuy and traditional methods. **H1b:** There is a significant difference in the readability of product information, such as allergens and ingredients, between using GaBuy and traditional methods.	0.000	Significant
H0c: There is no significant difference in the ease of locating product information on packaging between using GaBuy and traditional methods. **H1c:** There is a significant difference in the ease of locating product information on packaging between using GaBuy and traditional methods.	0.000	Significant
H0d: There is no significant difference in the accuracy of the product details gathered by visually impaired individuals (PVIs) when using GaBuy compared to traditional methods.	0.000	Significant

H1d: There is a significant difference in the accuracy of the product details gathered by visually impaired individuals (PVIs) between using GaBuy and traditional methods.		
H0e: There is no significant difference in the efficiency of locating product details (such as allergens, price, ingredients, etc.) between using GaBuy and traditional methods. **H1e:** There is a significant difference in the efficiency of locating product details (such as allergens, price, ingredients, etc.) between using GaBuy and traditional methods.	0.000	Significant

Since all null hypotheses (H0) were rejected and their corresponding alternative hypotheses (H1) were accepted, the findings suggest that GaBuy significantly improves the shopping experience for PVIs. Specifically, it enhances independence, readability of product information (such as allergens and ingredients), ease of locating product details, accuracy of gathered information, and overall efficiency.

The analysis is further supported by the Ranks Table, which identifies whether the differences in the scores were positive or negative, and the Descriptive Statistics, which provide a detailed overview of the data distribution.

Table 3. Summary of the Ranks Table

Independent Variable	Negative Ranks	Positive Ranks	Ties
Independence	0	29	6
Readability	0	35	0
Convenience	0	32	3
Accuracy	0	32	3
Efficiency	0	32	3

The results indicate that GaBuy significantly outperforms traditional methods in all measured aspects, as evidenced by the absence of negative ranks, overwhelmingly high positive ranks, and only a few ties.

5.2 Graphical Results

5.2.1 Comparative Analysis of Gabuy's Impact: Pre and Post-Intervention Across All Independent Variables

Figure 2. Comparison of pre and post-intervention results for Gabuy across independent variables

Figure 2 presents the mean scores from the Likert scale in the pre-and post-surveys, with each segment corresponding to a different independent variable and including three related questions. The mean scores for each segment were compared before and after the Gabuy intervention, showing significant improvements with scores ranging from 1.60 to 2.00. Efficiency showed the greatest improvement (2.00), followed by Convenience (1.83), indicating better usability. Independence (1.60), Readability (1.80), and Accuracy (1.74) also improved, reflecting gains in autonomy, clarity, and precision. These results suggest the intervention positively impacted key user experience metrics.

5.2.2 Micro-indicators of all Independent Variables Between Pre-Treatment and Post-Treatment Survey Responses

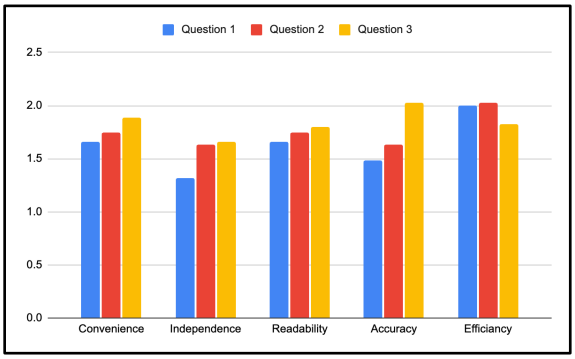

Figure 3. Mean differences in all independent variables between pre-treatment and post-treatment survey responses

This study analyzed all the independent variables using micro-indicators to analyze each question and gain a deeper understanding. This approach assessed how specific aspects of the user experience were influenced by GaBuy.

Figure 3 presents the micro-indicators for all independent variables, highlighting the specific questions where GaBuy had the most impact. For Convenience, Question 3, which measures the effort needed to identify product details, showed the highest improvement with a mean difference of 1.886. In Independence, Question 3, assessing users' ability to comprehend product details without assistance, had the greatest increase with a mean difference of 1.657. Readability also saw its most notable improvement in Question 3, with a mean difference of 1.800, indicating that GaBuy significantly enhanced the clarity and legibility of product information. For Accuracy, Question 3, which evaluates the need for repeated verification of product details, showed the highest improvement with a mean difference of 2.029. Lastly, for Efficiency, Question 2, measuring the time required to review product labels, recorded the most significant progress with a mean difference of 2.029, reflecting a faster and more streamlined shopping experience.

5.3 Proposed Improvements

To further enhance GaBuy's real-world applicability, the study recommends conducting simulations in actual grocery store environments using real product databases. This approach would enable a more accurate assessment of how visually impaired individuals shop for groceries, providing researchers with valuable insights into usability and accessibility. A key aspect of this improvement involves selecting a grocery store with a comprehensive product database, including stock-keeping unit (SKU), price, expiration date, allergens, and other critical product details. This would facilitate direct integration with GaBuy, allowing users to scan a wider range of items beyond a limited selection. Furthermore, the prototype's size and wiring inconsistencies have been identified as barriers to usability, making it less accessible for individuals with limited dexterity or grip strength; enhancing the wiring design will lead to a more user-friendly and efficient product. Additionally, future research should explore broader challenges faced by visually impaired individuals, particularly in navigation. Indoor navigation, such as moving through shopping centers, buildings, and public areas, remains a significant obstacle for PVIs due to unfamiliar routes, obstacles, and difficulty judging distances. Addressing these challenges in future iterations of GaBuy could enhance user independence and confidence, making it a more comprehensive solution.

5.4 Validation

Before analyzing the data, key assumptions for non-parametric tests and the Wilcoxon signed-rank test were verified to ensure statistical validity and accurate assessment of pre-treatment and post-treatment data. Non-parametric test assumptions include Independent Observations, Ordinal-Level Data, and Non-Normal Data, while Wilcoxon signed-rank test assumptions include Matched Pairs, Ordinal-Level Data, and Symmetric Distribution of Differences. The assumptions of Independent Observations and Matched Pairs were met, as the dataset consists of two distinct points—before and after using GaBuy—while responses were collected from the same participants under different conditions. Ordinal-Level Data was satisfied, as responses were recorded using a 4-point Likert scale, which maintains a meaningful order without assuming equal intervals.

A Test of Normality was conducted to determine whether the data met the conditions for the Wilcoxon signed-rank test. According to Laerd Statistics (n.d.), this test is a non-parametric alternative to the dependent t-test, making it suitable when normality cannot be assumed. It is often used to analyze changes over time or across conditions. The table below presents the normality test results for the "before" and "after" variables using the Kolmogorov-Smirnov and Shapiro-Wilk tests.

Table 4. SPSS results for tests of normality for each data set

Independent Variables	Kolmogorov-Smirnov	Shapiro-Wilk
Before_Independence	0.000	0.000
After_Independence	0.000	0.000
Before_Readability	0.000	0.000
After_Reaability	0.000	0.000
Before_Convenience	0.000	0.000
After_Convenience	0.000	0.000
Before_Accuracy	0.000	0.000
After_Accuracy	0.000	0.000
Before_Efficiency	0.000	0.000
After_Efficiency	0.000	0.000

The Shapiro-Wilk test was used to determine the result since it is more sensitive to small sample sizes. The test yielded significance values (p-values) of 0.000 for all variables. As these values are less than the standard alpha level of 0.05, the null hypothesis of normality is rejected, indicating that the data deviate significantly from a normal distribution.

The Statistical Test of Skewness was utilized to measure the symmetric distribution of differences. If the distribution is symmetrical, it indicates a balanced spread of differences. In such cases, the Wilcoxon signed-rank test can be appropriately applied to analyze the study data (Laerd Statistics, n.d.). According to Ramachandran and Tsokos (2020), skewness is the mathematical measurement of symmetry.

Table 5. Summarized SPSS Results for Skewness

Independent Variables	Skewness Statistic
Convenience	0.544
Independence	0.115
Readability	-0.265
Accuracy	0.039
Efficiency	-0.590

This study uses SPSS to calculate the skewness between differences in pre-treatment and post-treatment data. Hair et al. (2022) state that a skewness statistic between -1 and 1 follows a symmetric or normal distribution. Based on the table below provided by SPSS, the Skewness Statistics between the differences of pre-treatment and post-treatment data indicate a symmetric distribution.

6. Conclusion

This study successfully addressed its objectives by developing and evaluating GaBuy, an MSID that transforms the grocery shopping experience for PVIs. The study identified key challenges through extensive research and testing,

including difficulties in accessing product information, reliance on external assistance, and inefficiencies in product identification. In response, an innovative solution was developed by integrating text-to-speech technology, product identification features, and an intuitive interface tailored to the needs of PVIs. The device's effectiveness was then evaluated using a simulation-based study and a rigorous simulation-based evaluation. The Wilcoxon Signed-Rank Test confirmed statistical improvements with p-values equal to 0.00 across five key variables: independence, allowing PVIs to shop with minimal assistance; readability, enhancing access to product information; convenience, making the shopping process smoother and less stressful; accuracy, ensuring precise product identification; and efficiency, reducing the time required for shopping.

Beyond addressing grocery shopping challenges, this study contributes to the landscape of assistive technology, inclusive design, and human-centered innovation. Unlike existing solutions focusing solely on navigation or object recognition, GaBuy pioneers a holistic, multi-sensory approach for a more comprehensive assistive tool. Furthermore, this study sets a benchmark for future innovations, demonstrating the potential of user-driven assistive devices and paving the way for further advancements in accessibility solutions. The findings also emphasize promoting inclusive retail practices, ergonomic design, accessibility-focused store environments, and adaptive technologies tailored for PVIs.

In conclusion, this research underscores the value of cross-disciplinary collaboration, combining industrial engineering, human factors, and technology to meet the needs of PVIs. Through data-driven design and iterative prototyping, the study demonstrates the potential of user-driven assistive technology in enhancing accessibility. Validating the effectiveness of GaBuy offers valuable insights for the future of inclusive retail environments and assistive device development. Ultimately, this research calls for continued innovation and advocacy, ensuring that accessibility remains a fundamental right.

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