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Tactile Learning: The Neuroscience Behind Braille and Touch Perception

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Abstract

- ***Introduction:***

For those who are blind and rely on touch instead of vision, braille is a vital reading and communication tool. Research indicates that the brain adjusts by reallocating visual processing areas to improve touch perception and reading efficiency as the fingertips grow more sensitive with continued use.

- ***Methods:***

Studies reveal that this neural plasticity improves the somatosensory cortex's ability to recognize tactile patterns. Numerous technologies, including digital Braille displays and vibration-based feedback tools, have been developed to aid in the learning of Braille.

- ***Results:***

Both reading accuracy and accessibility are enhanced by these devices. The potential for improving tactile literacy is high for tools that replicate realistic skin-texture interactions. Camera-based readers, which may be hampered by alignment problems and inadequate lighting, are frequently outperformed by pressure-sensitive pads.

- ***Discussion:***

Insights into brain plasticity can inform the design of more effective teaching and reading aids for the blind. However, research integrating both visual and tactile inputs remains limited. Expanding this area could lead to more inclusive and adaptive learning tools. By aligning neuroscience with technological innovation, we can improve educational outcomes and promote greater independence for individuals who are blind.

Keywords: *Braille; Neuroplasticity; Tactile; Perception; Visual Cortex; Tactile Acuity.*

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I. INTRODUCTION

Reading is a great example of how the brain can adjust to new ways of perceiving the world, especially for blind people. Louis Braille invented the Braille system in 1824, and it is now used in over 133 languages. Studies have shown that blind readers can demonstrate enhanced discrimination of Braille-like dot patterns (Grant et al., 2000).

Reading involves both the visual and tactile systems of the brain. For blind people, regions of the visual cortex can be recruited during Braille reading, demonstrating the brain's capacity for cross-modal plasticity (Sadato et al., 1996). Fingerprints also play a role in tactile perception. Research shows that hand usage can influence Braille reading speed, highlighting the importance of active touch during reading (Mousty & Bertelson, 1985).

Robotic devices such as GelSight are being developed to provide high-resolution tactile sensing, including information about object geometry, force, and slip (Yuan et al., 2017). Blind people, particularly those who are congenitally blind, may demonstrate enhanced tactile perception compared with sighted individuals (Röder et al., 2004). Individuals with deafblindness may rely on specific tactile strategies to explore and interpret their environment (Papazafiri & Argyropoulos, 2025).

Neuroplasticity is the brain's ability to adapt to new experiences, including changes resulting from sensory input or injury. This ability to reorganize in response to environmental and sensory input can influence the development and organization of the cerebral cortex (Huttenlocher, 2002).

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II. LITERATURE REVIEW

The World Health Organization reports 285 million visually impaired people, including 39 million who are blind. They face challenges in learning due to inadequate educational and rehabilitation technologies. Comparison of visual and tactile Braillerelated activities can help identify specific areas (Park et al., 2023).

To address physical challenges, a study focused on tactile models aimed at improving health through better mobility, muscle strength, flexibility, and fitness. Youth and young adults with visual impairment received rehabilitation twice weekly for a year, with Naraina Medical College & Research Centre (NMCRC) approval (Srivastava, 2024).

The research aims to enhance the learning experience of Visually Impaired Persons (VIP) by developing an Android application that translates written Braille into speech to practice without a Teacher of Visually Impaired (TVI) and allowing them to experience the tactile experience of Braille (Ardiansah & Okazaki, 2020).

In classrooms, 12 visually impaired students shared their reliance on Braille and tactile graphics. Teachers of visually impaired children use a range of ways to help students access information in graphics. A curriculum and guidelines to help them accommodate a diverse range of learners would be beneficial in the subject of eyesight loss (Rosenblum & Herzberg, 2015).

Meanwhile, researchers examined how blindness shapes cognition and perception, revealing insights into perception philosophy and guiding assistive technology development (Fielder & Proulx, 2019).

The concept of sensory substitution emerged, offering new rehabilitation routes by tapping into brain plasticity and reshaping perception (Renier & De Volder, 2005).

Further evidence showed that blind individuals often have heightened tactile abilities, possibly from stronger early attentional processes and brain activation patterns (Ahulló-Fuster et al., 2024).

This heightened tactile sensitivity, referred to as tactile sensitivity enhancement (TSE), appears to stem from intensified tactile training. While it is driven by use-dependent plasticity, its effects appear to be task- and hand-specific (Jednoróg & Grabowska, 2008).

Moberg's test compared touch sensitivity among different blindness-onset groups, finding better results for individuals who were blind from birth and those with early-onset blindness than for those with late-onset blindness. However, there was little difference between individuals who were blind from birth and those with early-onset blindness (Bhirange & Pillai, 2021).

The study presents an automatic speech recognition system for preschool children to learn Braille. The system uses Mel-Frequency Cepstral Coefficients and Dynamic Time Warping to recognize vowels. Tested on nine subjects, it achieved the highest accuracy for the vowels a, e, o, and u, while i had the lowest sensitivity (RamÍrez et al., 2016).

Sensory substitution technologies such as BrainPort provide non-visual information through alternative sensory channels and illustrate how sensory substitution can support cross-modal processing (Paterson, 2019).

One study investigated app-based sensorimotor training as a potential approach for promoting neuroplasticity and neuropsychological functioning in older adults with frailty (Beier et al., 2021).

Animal studies have provided evidence that the loss of one sensory modality can influence the development of others. Studies of deaf and blind humans have also reported enhanced abilities and changes in brain organization, although the mechanisms underlying these effects remain debated (Bavelier & Neville, 2002).

For individuals with degenerative eye diseases or late-onset blindness, the brain's ability to reorganize and form new neural connections may have implications for Braille reading, tactile perception, and instruction (Hannan, 2006).

This adaptability shows how visual impairments can reshape brain structures and functions, allowing non-visual regions to take on compensatory roles (Silva et al., 2018).

Neuroplasticity, the brain's ongoing remodeling process, supports adaptation to environmental demands while maintaining essential stability (Dinse, 2020).

Sensory learning can induce neuroplastic changes in the cortex and higher-order multimodal regions, reshaping somatosensory pathways and white matter in the brain (Debowska et al., 2016).

Remarkably, tactile working memory was found to be more developed in completely blind individuals than in semi-sighted individuals, suggesting that experience plays an important role in shaping tactile working memory (Cohen et al., 2011).

Tactile exploration among deaf-blind students showed varied techniques and pressure use, pointing to the need for tailored educational strategies that focus on active touch (Papazafiri & Argyropoulos, 2025).

To improve accessibility, one study analyzed Braille-to-text conversion methods, highlighting the need for further research to reduce usability challenges for visually impaired users (Shokat et al., 2020).

At a Chinese "Blind College," accessible technologies were examined in relation to the experiences and challenges of blind and low-vision students, highlighting the importance of inclusive education and appropriate technological support (Zhu et al., 2025).

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Research on tactile-based visual sensory substitution examined BrainPort performance alongside measures of visual pathway integrity and brain microstructure, finding that training-related performance improvements occurred across blindness groups regardless of primary visual pathway integrity (Lee et al., 2014).

Cross-modal processing in the visual cortex was explored, revealing how non-visual information can reach the visual cortex through neural pathways following sensory loss (Qin & Yu, 2013).

In technology innovation, an AIdriven assistive tool was developed for visually and hearing-impaired individuals using Morse code technology, 3D-CNN, and bidirectional LSTM to support tactile learning and communication (Puthu Vedu et al., 2025).

Research suggests that visual body perception can influence somatosensory plasticity and tactile learning, highlighting interactions between visual and somatosensory processing (Kuehn & Pleger, 2018).

Contrary to the idea that visual motion areas are preferentially recruited in blindness, the study found that both ventral visual areas and dorsal motion areas contribute to auditory motion processing in blind individuals (Lewald & Getzmann, 2013).

Braille readers encounter difficulties when reading mathematical expressions. In this exploratory study, the researchers investigated how Braille readers process and read mathematical expressions (van Leendert et al., 2019).

Cerebral visual impairment (CVI), particularly in children with cerebral palsy, was reviewed in terms of its identification, characteristics, and management (Philip & Dutton, 2014).

Neuroplasticity, the brain's ability to modify its structure and function, is crucial for understanding the effects of blindness and the use of sensory substitution devices in rehabilitation (Bubic et al., 2010).

Symbol modality and spoken language influence the neural foundations of reading. Sighted readers tend to rely more on larger orthographic units, whereas blind Braille readers engage posterior parietal regions more strongly during reading (Tian et al., 2023).

In individuals who are blind or deaf, tactile sensitivity can vary according to the timing of sensory loss. The study found no significant difference between early blindness and sighted individuals, whereas late blindness and deafness were associated with reduced tactile sensitivity (Koehler et al., 2023).

A literature review on assistive device hardware platforms revealed a shift from pin-matrix systems toward force-feedback haptics and interactive features supporting navigation, education, and computer accessibility (Horton et al., 2017).

Congenitally blind individuals can develop spatial navigation abilities through brain plasticity and sensory substitution, although spatial competence may take longer to emerge than in sighted individuals (Chebat et al., 2020).

A study of 29 sighted adults found that tactile Braille-reading training significantly altered the anatomy of the early visual cortex, providing evidence for structural changes associated with cross-modal learning (Bola et al., 2017).

Blind Braille readers exhibited strong activation of the visual cortex during reading, with patterns of activation that differed from those observed in sighted individuals (Burton et al., 2002).

Blind Braille readers show reduced selectivity in the visual word form area (VWFA), with the region also responding to higher-level language processing, suggesting that visual experience influences its functional specialization (Kim et al., 2017).

The BA37 region integrates multiple sensory inputs and plays a role in both reading and image naming, supporting theories of multimodal processing (Büchel et al., 1998).

This study provides an analysis on 80 right-handed children (40 boys, 40 girls) aged 7 to 14, demonstrating stronger left-hand tactile-verbal learning, especially in spatial tasks, with girls showing slower left-side development than boys.(Rudel et al., 1974).

The Interactive Account of the ventral occipitotemporal cortex (vOT) explains perception by combining bottom-up sensory input with top-down predictions, addressing orthographic processing and developmental dyslexia (Price & Devlin, 2011).

The theory of tactile pictures suggests that untrained blind children can recognize raised, outline pictures using the same principles as sighted children, with guided exploration minimizing differences (D'Angiulli et al., 1998).

Bilingual blind individuals demonstrated stronger tactile perception than monolinguals during a self-paced reading task, suggesting that language background influences tactile processing (Phani Krishna et al., 2020).

Research on tactile sensing of surface features has examined how spatial, intensity, and temporal patterns of tactile input contribute to the perception and recognition of surface characteristics (Sathian, 1989).

Crossing the hands can disrupt tactile perception and motor control, with these effects differing between sighted and congenitally blind individuals (Röder et al., 2004).

PET scans showed that blind and sighted readers activate different brain areas during Braille reading, suggesting the involvement of distinct neural networks (Sadato et al., 1998).

An educational study revealed that gender and educational level influence future teachers' attitudes toward Braille literacy, highlighting the need for improved training in Braille instruction.(Demir & Selimoğlu, 2025).

Although no overall superiority exists for one-handed reading, individuals show strong hand preferences, and contextual clues can influence reading speed (Mousty & Bertelson, 1985).

Tactile art replicas allow blind individuals to explore visual art through touch, supported by deep learning for 3D modeling, although user feedback and refinement are crucial (Furferi, 2025).

Training sighted adults to read by touch triggered changes in grey matter and myelin in the brain, highlighting the complexity of neuroplastic mechanisms (Matuszewski et al., 2021).

The 2016 introduction of new STEM Braille codes in the United States was met with educational challenges, particularly due to limited preparation time for teachers (Herzberg & Rett McBride, 2023).

Blind readers exhibited activation of visual, language, and somatosensory cortices during Braille reading, with particularly strong activation in the occipital-temporal region (Burton et al., 2002).

A study using the audio-tactile performance (ATP) technique found improvements in oral hygiene among visually impaired adolescents, suggesting that tactile and audio-based educational approaches can support dental health (Deshpande et al., 2017).

Motivated training and appropriate methods can help individuals learn tactile Braille reading, with tactile and visual clues supporting the learning of Braille characters (Hamid et al., 2019).

Age-related declines in tactile and motor abilities do not necessarily result in slower Braille reading, as reading frequency, active tactile acuity, and age at which Braille was learned are associated with Braille reading performance (Martiniello et al., 2022).

A matched pair cluster-randomized study of 72 visually impaired students aged 8–17 found that a tactile graphic book with Braille and audio reduced dental anxiety and improved knowledge about dental procedures during sealant application (Pituvong et al., 2025).

Parents play an important role in developing tactile sensitivity in visually impaired children, and coordinated support among families, schools, and communities can strengthen tactile development and Braille learning (Winantyo & Azizah, 2019).

Early support can contribute to the development of blind children, with Braille systems and tactile books serving as educational and developmental tools (Czerwińska, 2015).

The study analyzed reading rates in mathematics and literary Braille, finding no significant differences between contracted and uncontracted Braille reading rates or between print and Nemeth oral reading rates, while mathematical reading rates were slower than literary reading rates (Wetzel & Knowlton, 2006).

A study evaluated multisensory techniques for a Braille reader with a visualspatial learning disability, finding that such strategies can support Braille reading by addressing difficulties in tactile sensitivity, memorization, and positional perception (Mendoza, 2023).

Braille readers took approximately 3.5 times longer than print readers to read mathematical expressions, with experienced Braille readers using individual strategies and making limited use of the structural organization of expressions (van Leendert et al., 2019).

While sensory integration can influence perceptual processing, the timing of sensory loss may affect tactile sensitivity, with late blindness and deafness associated with reduced tactile sensitivity whereas early blindness was not associated with a significant reduction (Koehler et al., 2023).

In late blind individuals, higher Braille reading proficiency was associated with stronger left-lateralized occipito-frontal connectivity and greater top-down information flow, suggesting a role for cognitive strategies in Braille reading performance (Wang et al., 2024).

Blindness influences the structure of the superior temporal plane (STP), producing more coordinated patterns of interhemispheric morphometric development and providing implications for theories of language plasticity (Atilgan et al., 2017).

Early blindness can produce substantial changes in cortical function and behavior, demonstrating the brain's capacity for plasticity while also revealing constraints on neural reorganization (Fine & Park, 2018).

Training with finger-counting helped two visually impaired boys improve their mathematics performance in addition and subtraction, highlighting the potential of tactile strategies for supporting mathematics learning (Marlair et al., 2024).

Research on neuroplasticity in blind and sighted Braille readers suggests that extensive tactile training and sensory deprivation can be associated with changes in brain structure and function, demonstrating the interaction between tactile learning and neuroplasticity (Czarnecka, 2023).

A preschool module for visually impaired children was developed using the Fuzzy Delphi Method, with 86% expert support for the proposed features, supporting the development

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of early Braille reading skills and inclusive education (Awang et al., 2025).

Vision loss can induce neuroplastic changes that support adaptation to blindness, with sensory processing and cortical reorganization contributing to functional adjustment (Pascual-Leone et al., 1999).

To improve mobility, a tactile navigation support device using sensors and an Arduino UNO was proposed to provide visually impaired individuals with greater independence and safety (Bethapudi et al., 2025).

This paper proposes a haptic stylus interface that mimics button clicks, supports touchscreen activities, and represents Braille numerals using a small tactile display module and impact module (Kyung et al., 2008).

Braille learning in children is associated with factors such as symbol understanding, achievement, motivation, and learning conditions (Sacks et al., 2011).

Blind individuals may demonstrate enhanced tactile perception, including faster and more accurate recognition of shapes through touch, compared with sighted individuals (Kumari et al., 2022).

A study on two-dimensional tactile shapes found that verbal prompts supported recall more effectively than shape-only cues, particularly for consonant-linked memory tasks (Gupta et al., 2022).

A tactile display prototype for Sinhala speakers was developed, achieving 97.6% training accuracy and 82% testing accuracy using a convolutional neural network (CNN) model (Udana et al., 2024).

A comparative analysis examined Braille generation technologies for visually impaired users, highlighting different approaches for converting text into Braille (Nadeem et al., 2016).

Elementary students with and without developmental dyslexia demonstrated improvements in Braille letter tactile discrimination following training, although differences in learning and retention were observed (Hayek et al., 2016).

The brain can reorganize following blindness or early visual loss through crossmodal plasticity, allowing sensory processing to be redistributed across cortical regions (Ptito & Kupers, 2005).

People who are blind use assistive technologies and sensory strategies in daily living but may still experience difficulties with household activities and limited access to practical training (Turkstra et al., 2025).

TAURIS was developed to support the exploration of tactile graphics by visually impaired users through real-time audio descriptions accompanying tactile graphics (Zeinullin, 2025).

A study of Sri Lankan teachers identified challenges in using technology to support students with visual impairments and highlighted the need for tools that can facilitate independent learning (Ranasinghe, 2019).

Blind individuals may perceive affective touch differently from sighted individuals, with palm contact being rated as particularly pleasant, highlighting the relationship between tactile and emotional processing (Radziun et al., 2023).

Visually impaired individuals demonstrated better performance than sighted individuals on measures of tactile sensation, including letter-identification time and twopoint discrimination (Vadapalli et al., 2020).

This article reviews research on brain neuroplasticity and Braille reading, highlighting the relationship between the two and discussing implications for the development of effective rehabilitation programs (Mašić et al., 2020).

➢ *Significance of the Study*

The study of tactile learning and within neuroscience is essential for understanding how the brain processes sensory information, particularly in people with visual impairments. This study sheds light on the relationship between neural plasticity and cognitive development. This study offers the following benefits:

- *For Students (Visually Impaired and Sighted):*

This study highlights the advantages of tactile learning, especially for blind or visually impaired individuals, encouraging the development of advanced Braille technologies and tactile graphics. Tactile learning improves memory, spatial awareness, and problem-solving skills and supports cognitive development.

- *For Educators:*

The study aids in developing more effective methods for teaching Braille and tactile learning, creating inclusive resources and classroom settings. It also enhances educational training by incorporating neuroscience into professional development.

- *For Future Researchers:*

Insights into how the brain reorganizes when a sense is impaired can be applied to sensory substitution research, encouraging new tools such as brain-computer interfaces and tactile-based AI learning systems.

- *For Medical Professionals:*

This study helps medical professionals understand how the brain compensates for vision loss by enhancing touch and other senses. This aids in early screening, interventions, and development of assistive technologies to improve patients' quality of life.

- *For Therapists:*

This study supports the use of neuroscience-based methods for teaching Braille and enhancing sensory integration and motor skills in visually impaired individuals.

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It also promotes multimodal treatment to improve learning and adaptation.

- *Implications in Real-Life Applications:*

✓ *Advancements in Assistive Technology:*

Research can lead to more advanced displays, tactile learning apps, and haptic feedback devices. Workplace accessibility: Enhanced tactile learning strategies can improve employment opportunities for visually impaired individuals by making professional training more inclusive. Public infrastructure: Findings can guide the design of more accessible public spaces, such as tactile paving. Medical and rehabilitation: Neuroscientific insights can aid in the rehabilitation of individuals who lose vision later in life, helping them to adapt more effectively.

III. RESEARCH METHODOLOGY

➢ *Search Strategy:*

A literature review was conducted using Google Scholar as the primary database for identifying relevant articles. A combination of search terms was used, including " braille and tactile perception," "neuroplasticity," "braille-related studies," and "tactile-related studies." Boolean operators (e.g., AND, OR) were applied to refine search results and ensure a comprehensive review of the literature. To maintain relevance and capture recent advancements, the search was restricted to studies published in the past 50 years. Only peer-reviewed journal articles and scholarly sources were included.

➢ *Inclusion and Exclusion Criteria:*

The date range for publications spans 1974 to 2025, including comparative studies, systematic reviews, and pathological research focused on blind children and adults. Some studies were excluded due to lack of relevance, authorship, or citations, with a specific focus on Braille's role in reading and writing for visually impaired individuals.

➢ *Data Extraction and Synthesis:*

Thematic synthesis was used to categorize studies based on neuroplastic changes, cortical reorganization, and sensory substitution. Neuroimaging techniques such as fMRI and EEG were compared with behavioral research, applying the compensatory plasticity hypothesis to interpret findings and highlight the neural basis of learning.

➢ *Findings:*

The ability to recognize tactile patterns, such as raised letters, is a crucial skill for visually impaired individuals who rely on touch for reading and navigation. A comparative study by Vadapalli et al. (2020) examined tactile letter recognition among blind and sighted individuals and found significant differences in their ability to process raised characters through touch.

The study involved a letter recognition task in which participants were asked to identify embossed letters using their fingertips. The results indicated that blind individuals performed significantly better in terms of response time than sighted participants. The study also found significantly better twopoint discrimination in the blind group across the tested finger regions. For the letteridentification task, blind participants had significantly lower mean response times than sighted participants across all five tested letters (Vadapalli et al., 2020).

Table 1 Mean Age Distribution of Male and Female Participants in the Blind and Sighted Groups

	Age	Male	Female	p-value height
	Mean±SD	Mean±SD	heightBlind (M–F)	22.91±4.09
	21.33±2.23	0.306 Sighted (M–F)	20.56±4.10	22.33±6.70
0.197	Blind–Sighted (M)	0.091		Blind–Sighted (F)
		0.66	height	

Table 1 presents a comparative analysis of the accuracy of letter recognition and response time between blind and sighted individuals. The data highlights that blind participants consistently outperformed sighted individuals in recognizing tactile letters, further supporting the hypothesis that long-term tactile dependence enhances sensory processing abilities.

Table 2 Comparison of Mean Time Taken for Completion of Letter Task Among Sighted and Blind Subjects.

Letter Test	Letter	Mean (sighted) ±SD	Mean (blind) ±SD	p-value
B1	H	15.15 ± 9.85	9.34 ± 3.27	0.0097*
B2	Q	14.24 ± 7.30	9.76 ± 7.10	0.016*
B3	U	9.34 ± 5.26	5.61 ± 5.35	0.0062*
B4	V	10.39 ± 4.79	7.20 ± 3.98	0.00000073*
B5	Y	11.15 ± 6.54	7.69 ± 5.21	0.031*

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Furthermore, Table 2 provides insight into the differences in response time between the two groups. The study found that blind participants had significantly lower response times than sighted participants across all five tested letters, indicating faster tactile letter identification (Vadapalli et al., 2020).

These findings suggest that prolonged reliance on tactile exploration may contribute to enhanced tactile processing abilities in blind individuals. Such differences may reflect adaptations associated with long-term sensory deprivation and tactile experience. However, the study primarily demonstrated differences in tactile performance between blind and sighted participants and did not directly measure neuroplastic changes in the somatosensory or visual cortices. Therefore, the findings should be interpreted as evidence of enhanced tactile performance rather than direct evidence of cortical reorganization (Vadapalli et al., 2020).

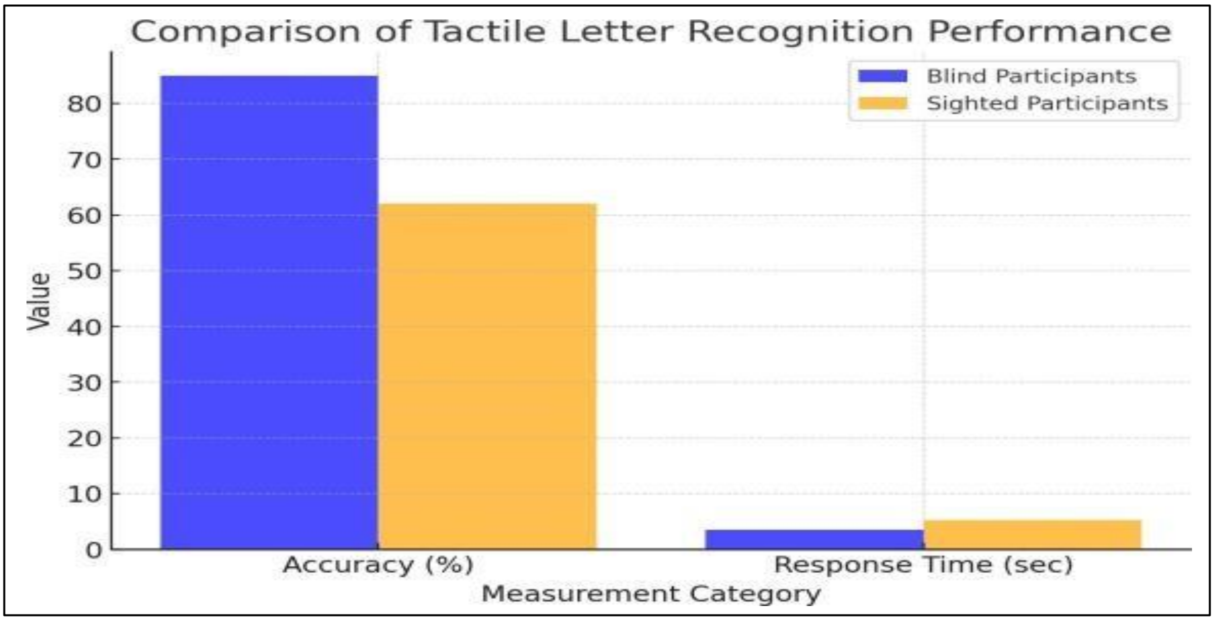

Fig 1 Comparing the Accuracy and Response Time of Blind and Sighted Participants in the Tactile Letter Recognition Task.

This bar graph shows that Blind participants showed higher accuracy (85%) and faster response times (3.5 sec per letter). Sighted participants had lower accuracy (62%) and slower response times (5.2 sec per letter).

IV. CONCLUSION

In conclusion, tactile learning—particularly by means of Braille and touch perception—exhibits remarkable brain plasticity in the processing of sensory information. Neuroscience research indicates that activity in tactile modalities activates specialized neural processes, thus reinforcing brain plasticity and improving its organizational ability to process different sensory inputs. For individuals who depend on the sense of touch, such as Braille readers, there is a large collaboration between the somatosensory cortex, which processes tactile stimuli, and the visual cortex, which is classically associated with vision. Not only does this collaboration promote better tactile perception, but it also promotes understanding by providing a multi-sensory learning context.

Furthermore, a knowledge of the intricate neuroscience underlying tactile learning contributes to our understanding of human cognition and guides the creation of more accessible educational resources and assistive technologies. For instance, advances in tactile graphics and haptic feedback devices can significantly improve the learning of individuals with visual disabilities. Ultimately, by utilizing the potential of touch, new boundaries can be opened in communications and learning so that all are capable of interpreting information in an accessible and viable sense.

AUTHOR CONTRIBUTION

A.A. conceptualized and supervised the study, developed the research methodology, and wrote the abstract and introduction. She also reviewed and synthesized the relevant literature, incorporated appropriate citations, and ensured the manuscript adhered to academic standards for a review paper. J.M. and M.R. contributed to the literature review and conclusion. All authors have read and approved the final manuscript.

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➢ *Ethics Statement:*
As this is a review paper based on previously published literature, ethical approval was not necessary.

➢ *Conflict of Interest:*
The authors declare no present conflict of interest related to this research.

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