Hemispheric Variances in Information Processing: Exploring the Impact of Handedness on the Brain

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Handedness is characterized by the tendency to prefer and utilize one hand over the other for all hand-related activities. The majority of the world is right-hand dominant and only a small portion constitutes the population that prefers their left-hand or ambidexterity. This unequal distribution of handedness originates through a combination of different factors such as evolution, brain asymmetries, social conformity, and genetic components. One fundamental aspect of handedness lies in differences spanning the two brain hemispheres. Lateralization of the brain involves each hemisphere being specialized for different cognitive responses. Distinctions observed specifically in the motor regions of both hemispheres account for most of the differences caused by handedness. This paper focuses on the origins and determinants of handedness, and how they impact motor and cognitive functions in individuals. It delves into the role of brain lateralization, and the implications of differences in brain processing based on hand preference. The paper also examines the latest research findings and their potential impact on our understanding of cognitive and neurological variations associated with handedness. This study is crucial to understanding human diversity because this research underscores the handedness aspect of human behavior, which gives insight into how different individuals carry out daily tasks and the variability in brain processing, functionality, and organization.

Introduction

Handedness is the tendency to prefer and be more skilled at using one hand over the other for certain tasks and motor activities. Hand preference is binary, but it is not split evenly among the population. Throughout evolution, hand preference has been predominantly the right hand. Even today, a majority of individuals are right-hand dominant[1]. Generally, the minority of individuals who do not predominantly use their right hands are likely to possess a higher preference for both hands compared to strict right-handers[2]. Origins of handedness have been explored and many theories have been proposed, including certain genes, evolutionary implications, cultural factors, and the lateralization of the brain. Brain lateralization is significantly associated with handedness, shaping the consequences and further differences arising from it. Brain lateralization involves understanding the difference in functions performed by the two brain hemispheres, especially the differences in motor control and coordination mechanisms that play a major role in establishing handedness. Our brain is lateralized by its specialized use of its right and left hemispheres. Differences vary slightly among individuals, but for most, the dominant hemisphere is considered to be the left hemisphere which largely incorporates speech and language functionality and primarily controls the contralateral motor signals. Other specializations within the hemispheres involve spatial recognition, face recognition, and other structural differences. For right-handers engaged in dominant hand activities, the left hemisphere is the primary receiver of information even though both hemispheres play a significant role in other major functions. This specialization is pronounced in language processing and fine motor control for the dominant right hand. On the contrary, the left hemisphere manages language-related functions and precise motor coordination. Individuals who are not right-hand dominant, such as left-handed or ambidextrous individuals, exhibit an opposite hemispheric dominance pattern, with the right hemisphere having a more prominent role in activities involving their dominant hand[1]. This study aims to clarify the specific origins of handedness by evaluating and presenting the different theories that contribute to it. Additionally, it aims to bring the different research about variations in cognitive and motor neural functions together. This identifies the inconsistencies and creates a more cohesive understanding of the implications of handedness in the brain.

Results

Handedness

The origin of handedness is based on multiple theories such as early tool use, the fighting hypothesis, and socio-cultural conformities that portray how the human population evolved to be a right-hand majority community. The development of handedness begins in the embryonic stage and is mainly influenced by genetics.

The prevalence of right-handedness is still debated among researchers, and many conclusions have culminated in the current scientific understanding of it. A combination of different theories involving evolutionary advantages, genetic anomalies, and problems during embryonic development account for the determination of handedness. Studies have found that this variation of handedness is unique to the human species and the prevalence of right-hand preference has not been significantly observed in other primates. However, larger trends involving brain asymmetries and lateralization have been observed in other species that date back to our early ancestors. These trends include the lateralization of language and hand gestures in the left hemispheres even in our early ancestors and monkeys[3].

Besides lateralization, the evolution of early tool usage is also a major factor in the origins of handedness[4]. Early humans began constructing tools suited for the right hand and being right-handed significantly helped with their survival. As tools became more prevalent in societies, right-handed individuals were more skilled at using most tools made to suit the right hand. This survival ability made right-handedness advantageous, contributing to the majority prevalence of right-hand preference through natural selection[5]. The "Modified Fighting Hypothesis" suggests that right-handedness prevailed due to an advantage people had when they fought. It is found that the left side of your body tends to be more vulnerable due to the location of vital organs such as the heart and aorta on that side. Attacking with a weapon exposes the left thorax of one's body due to the necessary combat position when attacking with the left hand, making it more susceptible to damage during fights. Right-handed attacks are safer because the left side of the body is better shielded in that attack position. Since fighting is an important human adaptation, right-handed individuals may have been more successful in combat situations and more likely to survive and pass on their genes. This selection pressure propagated the right-handedness trait and it evolved to be in the majority[6]. Left-handedness was not eliminated although it had a disadvantage in fighting because left-handers were found to have more even laterality which enabled them to persist as the minority. Left-handers might have embraced this reduced lateralization to gain versatility and adaptability and acquire a higher fitness advantage[6]. The hypothesis was strengthened by data that demonstrated that a high number of left-handers, around 28-35% prefer using their right arm to throw and only around 1.6% prefer using their left hand. The throwing arm is likely used for fighting, conveying left-handers' flexibility and adaptability advantage that would have helped them persist[7].

As cultures and religions emerged worldwide, conformity to right-handedness was imposed upon many children. Since right-handedness has always been the majority and complying with the majority is considered virtuous, cultures have adopted this pattern and historically condemned left-handers, forcing children to convert the hand that they write with and considering the left hand to be "impure". This doesn't necessarily change handedness but motivates left-handers to be more ambidextrous. These biases are still followed in some cultures around the world, possibly further minimizing the already established minority of pure left-handedness through this type of artificial selection[8].

Other determinants of an individual's handedness include genetic components and parental factors. An example of heredity and genes contributing to handedness is that left-handers tend to have left-handed mothers. The handedness correlation seen in twins also indicates a hereditary and genetic component[9]. Epigenetic factors, which are environmental factors affecting one's genes, can also promote handedness. In addition, certain genes whose implications have not fully been understood have been found to trigger handedness. A study on population and lateralization conducted by Dr. Marian Annett from the University of Leicester looked further into this. She proposed the Right Shift Theory which suggests that a gene is involved in enabling the transfer or shift of manual and language functions to the right hemisphere, leading to left-handedness. Specifically, a gene called the RS+ gene is postulated to induce a left hemisphere specialization in language and motor control by weakening the right hemisphere. Other variations of this gene are linked to creating a more unbiased distribution of functions in both hemispheres, possibly catering to left-handedness10. The RS genetic model was further supported by Dr. Annett's study on handedness in twins. The model predicted that twins would have a higher frequency of left-handers because the RS+ gene is not strongly expressed in twins. The low expression level would induce left-handedness. In her 1994 survey with 30,000 participants, she found that singleborns had a 7.1% incidence of left-handedness while twins had a high incidence of 11.7% and these results aligned with her theory[10]. Other genetic components are also said to be associated with handedness which suggests more of a polygenic etiology rather than a single gene playing a role in determining handedness[11].

The development of handedness starts in the womb. A developing fetus more often sucks on its right thumb and turns its head towards the right, showing early signs of handedness development. Left-handedness is said to develop in utero and is sometimes due to developmental disturbances during the intrauterine phase that cause the transfer of motor functions to the right hemisphere, corresponding to possible left-handedness or ambidexterity[12]. Other factors implicating the normal intrauterine process in multiple ways have also been shown to affect brain development in ways that correspond to left-handedness. Some of these developmental differences include hormonal levels, perinatal stress, and immature birth[12]. Premature children with a low birth weight have shown a statistically significant number of left-handers. Genetic defects are more prone to result in a left-handed individual because it has been found that people with developmental complications and certain genetic problems are more likely left-handed. Once handedness is decided in the womb, its further implications and developments in the individual depend on environmental, social, and cultural pressures[12].

Brain Lateralization

Lateralization of the brain can vary based on handedness, and specific research and theories assert that it causes differences in brain asymmetries and hemispheric dominance for motor and cognitive tasks.

The lateralization of the brain is due to structural asymmetries that cause one hemisphere in the brain to be slightly more dominant. Asymmetries refer to the differences between the brain hemispheres based on their function, structure, anatomy, and cortices. Larger asymmetries are seen in right-handers who have differences in the distribution and structure of veins and arteries between the two hemispheres of the brain, as well as larger left-hemisphere brain regions[13]. In contrast, individuals who are not right-handed have more evenly split control across hemispheres but with a possible higher dominance in the right hemisphere. Strong right-handedness is found to be associated with higher brain asymmetry compared to left-handedness which encompasses a variety of possible asymmetries. These asymmetries mostly involve functional asymmetries such as language control and certain structural differences in the cerebral cortex. Specifically, left-handers show reduced leftward surface area asymmetry in the anterior insular cortex and parts of the occipital lobe. These specific asymmetries suggest a different neural network distribution for functions related to the articulation of preferred hand and motor imagery[14]. It is found that, overall, left-handers demonstrate less pronounced asymmetry of the brain structure and function but tend to have higher variability in their differences of functional and structural lateralization[13]. An experiment by Helmuth Steinmetz in 1996 included the resampling of structural brain image data to map asymmetries in the cerebral cortex of 28,802 right-handers and 3,062 left-handers. The experiment showed that the cerebral cortex is more left-lateralized in right-handers and the cerebral cortex of left-handers is generally less lateralized[14]. It was also shown from a connectivity network analysis that interhemispheric connection is more prevalent and pronounced in left-handers, suggesting a better overall bihemispheric coordination[15].

Another theory suggests the brain is lateralized differently for specific manual functions based on handedness. The Dynamic Dominance model conveys that the left hemisphere is efficient at processes that predict environmental and body dynamics which refers to the change in the external environment that could affect manual tasks. The right hemisphere tends to focus on minimizing errors and allowing accurate and stable positioning during unexpected mechanical conditions. The main hypothesis suggests that the left hemisphere is lateralized for motor behavior in familiar environmental conditions and the right hemisphere specializes in environments that are new and unexpected for impedance control. This difference in motor control of different hemispheres can explain specific lateralization differences based on handedness. Right-handers who tend to predominantly use the left hemisphere for motor control perform better motor functions and movement dynamics in familiar and consistent situations. Specializing in impedance control, left-handers, whose motor control is dominated by the right hemisphere, excel in adapting to unpredictable and diverse environments, demonstrating proficiency in rapid adjustments[16].

Cognitive and Behavioral Distinctions/Specializations

The two hemispheres in the brain work in coordination and contain almost identical regions in each hemisphere except for a few specialized exceptions. Major cortical regions of the brain include the frontal lobe and the parietal lobe which are involved in motor control, language, and sensory processing and usually have functional asymmetries pertaining to speech and motor control.

Speech

In most people, the left hemisphere controls language and speech. This distinction is seen in a majority of people regardless of their hand preference and it is one of the key differences observed between the left and right hemispheres. It has been theorized that there is a genetic link between speech and gesture evolution, explaining why both functions are left-hemispheric in the majority of people. The Broca's area is a part of the brain located in the left frontal lobe. This part is associated with language production and is enlarged in the left hemisphere while in monkeys the Broca's area is bilateral and related to manual actions and vocalization. This difference suggests an early connection between language and hand gestures. The removal of manual gestures as a necessary component of language in humans, along with the continued dominance of the left hemisphere for language processing, may have contributed to the legacy of right-handedness we see today[3].

The Right Shift Theory also involves speech functions and right-handedness evolving in the left hemisphere attributed to a single RS+ gene which is associated with coding necessary information to induce a left-hemispheric advantage. Another study by Stefan Knecht and colleagues in 2000, theorized that the evolution of handedness created the basis for the development of speech and other motor functions in the hemispheres. Overall, individuals who are not right-hand dominant have also been found to have their speech functions located more often in both hemispheres or the right hemisphere as compared to strict right-handers. Regardless, the majority of people still have speech control localized in their left hemispheres[17].

Motor Functions

Motor functions have also been found to be lateralized or more specialized for different aspects of motor functions and processing based on handedness. The key findings for differences in motor function include variation in types of hand movements and patterns, tactile memory, hand reaction time, and spatial relations.

The Dynamics Dominance Model discussed previously in the brain lateralization section also conveys that the left hemisphere is specialized for controlled, predictable movements while the right hemisphere is more specialized for unpredictable movement and impedance control.

Another significant difference found between the two hands was through haptic memory, which refers to the ability to recall information based on the tactile sensations associated with the shape, texture, and physical properties of an object. In a 1998 study, Arlette Streri and colleagues demonstrated the difference in haptic habituation and memory between the right and left hands in 96 2-month-old infants. Haptic habituation refers to the process by which the subjects get accustomed to the tactile sensation of a certain object in their hand. Results showed that when infants were habituated to certain objects, they retained the object shape information better in their left hand. The results also revealed a noticeable sex difference. Specifically, females were able to recognize the object after interference only in the left hand conveying that the left hand appeared to relate to information processing speed. In addition, females took longer to habituate with their left hand compared to their right hand[18].

The effect of hand preference in other motor functions, including controlled movement tasks, is based on the degree instead of the direction of handedness. Strongly lateralized individuals (strictly left- or right-handed individuals) perform precise and controlled movements faster than ambilateral individuals. A 1975 study by Kenneth Flowers on controlled movement concluded that, for ballistic movements, which involve planned rapid movements hard to control after initiation, there was no difference in speed between subjects. However, ambilateral subjects made fewer errors. For controlled movement functions, ambilateral subjects were found to have two non-preferred hands and might rely on ballistic movements more than strongly lateralized individuals. There is also a theory suggesting that both hands are equipotential for controlled movements, with better performance observed in the dominant hand. The dexterity difference between the dominant and non-dominant hand is argued to come from the feedback and sensory control of movements instead of the physical motor functions. Feedback control corresponds to relaying information to modify movements and sensory control refers to the overall utilization of sensory information to control motor actions. Together, these processes cause the differences in the performance of controlled versus ballistic movements[19].

Lateralization patterns involving motor functions for spatial relations also differ for people based on handedness. An experiment by Bruno Laeng and Michael Peters in 2000 was conducted with 66 participants to find a correlation between hemispheres and spatial and categorical judgments based on response times. Results indicated specialization in the left hemisphere for categorical spatial relations responses and the right hemisphere for processing coordinate spatial relations. While this pattern was observed in right-handers, it was not widely seen among left-handers[20].

It was also found that handedness affects the imitation response in humans and the mirror systems for motor function are developed differently. Sensorimotor associative experiences pertain to how people associate observed actions with their motor programs and then imitate those actions. Different sensorimotor associative experiences modulate the mirror property and associative learning in individuals and motor imitation tasks are found to be facilitated differently in people based on handedness. Individuals' handedness was assessed with the Edinburgh Handedness Inventory (EHI) which checked for hand dominance in daily activities. Using this criterion, left-handers demonstrated faster reaction times for imitating right-handed actions compared to left-handed actions, while right-handers did not show a significant difference in their reaction times. The ability for mirror systems to be developed differently based on handedness also implies that the mirror property is more plastic for motor functions that can be modified through different sensorimotor associative experiences[21].

Apart from specialized movement patterns, differences in perception of movement have also been attributed to handedness. Asymmetries in the perception and reproduction of movement exist predominantly in males. Right-handed males have more effective perception in their dominant hand and a higher velocity for the response to perceived signals in their dominant hand. These asymmetries are hypothesized to be caused by input processing and structural differences. Intrinsic or structural differences refer to the anatomical and neurophysical qualities in each hemisphere that tend to be specialized and cause asymmetries[22].

Haptic processing has specialized elements distributed in the two hemispheres. Experiments show that the right hemisphere is responsible for local haptic processing and the left hemisphere is responsible for more global haptic processing. Judging the texture of surfaces is an example of local haptic processing, and an advantage of this specialization is found in the left hand. For the right hand, there is an advantage for judging the center of masses of objects, a global haptic processing discrimination, and therefore this haptic informational processing is based on the contralateral hemisphere. The haptic modality differences among hemispheres were found to be less severe in left-handers where handedness was assessed using EHI. In general, left-handers tend to have fewer asymmetries and a lesser degree of lateralization observed for bimanual tasks[23].

Other parts of the motor regions are also found to be conducted differently between right and left-handers. In terms of the effective connectivity of the motor system, the consistent lower asymmetry observed in left-handers suggests that their underlying mechanisms for motor control may differ from those in right-handers. A notable difference in activation and processing in motor regions is observed in right-handers, characterized by stronger synchronization or coordinated neural activity of the contralateral supplementary motor area with other motor regions during dominant hand movements. The supplementary motor area is shown to be engaged in pacing and movement sequencing. However, left-handers do not exhibit this form of neural coupling, and it is also absent during movements in the non-dominant hand for both right and left-handers[24].

Numerous speculations have arisen regarding a left hemisphere dominance model for motor planning. The model predicts that the left hemisphere is dominant in motor function planning and strategizing of movements, but there has been a lot of contradictory data and mixed evidence for this hypothesis without sufficient analysis of this model to confirm it. Some studies yielded results supporting the model, while others indicated no difference in dominance for motor planning. In fact, some earlier studies demonstrated better task performance in left-handers, suggesting that the right hemisphere might be dominant for motor planning, as left-hand motor control is associated with the right hemisphere[25]. Therefore, due to the mixed conclusions, it is currently believed that motor planning distribution between hemispheres is not lateralized and both hemispheres contribute to movement planning for different tasks. Experiments still indicate that right-handers and left-handers show different effective planning patterns for certain movements involving hand rotations although more research is needed to conclude if these differences are due to asymmetric hemispheric distribution for motor planning[25].

Interhemispheric connectivity

Bilateralization suggests a more balanced and shared involvement of both brain hemispheres for functionality and informational processing and this phenomenon is more commonly observed in left-handers. Specifically, their motor speech area seems more bilateral as compared to right-handers[26]. Left-handers also exhibit greater interhemispheric connectivity, although there is controversy regarding specific types of connections observed in the brains of left-handers. While emotions exhibit slight lateralization, overall, motor functions are observed to be more strongly lateralized than cognitive, sensory, or emotional functions[12].

Both hemispheres communicate through their interhemispheric connectivity to carry out various cognitive functions and respond to stimuli. Handedness can influence interhemispheric transfer times (ITT) when stimulating the motor cortex. A study by Demis Basso and colleagues in 2006 showed that when transcranial magnetic stimulation (TMS) is applied to the motor cortices in right and non-right handers, the ITT increases for both groups. Elevated reaction times were observed for the stimulation of the left primary cortex, and it was also noted that the dominant hemisphere exhibited more pronounced effects. In the two groups, each exhibited a more significant effect on the ITT from TMS in the contralateral hemisphere, and their associated ITT latencies differed between right and non-right-handers. Right-handers showed an increase in ITT in both left and right cortex stimulation while in individuals that were not right-handed, the effects were primarily observed from the left cortex stimulation[27].

Implications of the Differences

Although the consequences of handedness have not been understood fully yet, various theories suggest possible outcomes of handedness. Specifically, the Right Shift Theory associates the RS+ gene with certain disorders, including dyslexia, autism spectrum disorder, and spatial reasoning[28]. Other reports about populations with neurological disorders like autism have shown an increased incidence of pathological left-handedness and ambiguous-handedness. Pathological left-handers are individuals who prefer the use of their left hand even though they might not be naturally left-handed[29].

Discussion

The existing findings about the intricacies of information processing in right and left-handers pose contradictions, with conclusions often conflicting in various studies. For example, the debate over left hemispheric dominance for motor planning in right versus left-handed subjects remains unresolved, and genetic linkage theories of handedness have also been widely debated. More research about controversial aspects of handedness needs to be conducted to make conclusive arguments about its implications. Conclusions about disorders associated with left-handedness due to the Right Shift Theory need to be reconsidered as more recent studies about the correlation of handedness with dyslexia, autism, depression, and certain other disorders have been disproven. Other studies involved more participants thus making them more reliable and refuting the consequences attached to the Right Shift Theory. Therefore most health issues cannot be attributed to handedness[7]. The limitations faced in numerous studies conducted about motor functions involve methodological challenges, sample size variations, and the diversity of tasks assessed. Due to the minority of left-handers, several studies do not get sufficient left-handed subjects, contributing to our limited conclusions in different experiments. Further research should be conducted to address these limitations, exploring more standardized methodologies, focusing on more diverse brain regions for research, and using a broader range of motor tasks to enhance the understanding of the relationship between handedness, motor functions, and hemispheric specialization.

Conclusion

In summary, handedness introduces several implications in informational processing for individuals. Handedness influences factors like interhemispheric transfer times, haptic processing, motor movement, and perception, impacting specific aspects of neural processing. Other significant differences associated with the two brain hemispheres, especially the motor regions can produce differences between right and left handers. Specializations in the two hemispheres that contribute to this are specific asymmetries in various motor regions and processing differences. For example, the right hemisphere controls more local haptic processing while the left hemisphere controls global haptic processing. Apart from strict right or left-handedness, ambidexterity yields certain differences in controlled movement and overall less lateralized functions in hemispheres. These differences between right and left-handers contribute to the fundamental uniqueness of our brain functionality.

The left hemisphere is commonly deemed more 'optimal' because it specializes in speech control and the prevalence of right-handers. Therefore, left-handedness demonstrates the brain's remarkable neuroplasticity and adaptability to alter lateralization and functionality based on handedness. The theories and studies that have been analyzed in this paper focus on the benefits for left-handers when comparing the differences in motor control based on handedness. This methodology helps us better understand neuroplasticity by conveying our brain's adaptability to the altered lateralization in left-handed individuals.

Methods

To conduct a review of the existing literature involving handedness and hemispheric specialization, a systematic search was performed across several key databases and resources. Databases like PubMed and UK Biobank were used to learn more about previous studies on variations in informational processing based on handedness. Other academic journals such as ScienceDirect, JSTOR, Scopus, and Nature Journals were used to gain a comprehensive understanding of and explain the history and distinct theories on the phenomenon of handedness. The search for the literature was based on a combination of keywords such as "Brain lateralization", "handedness", "motor functions", "hemispheric specialization", and "cognitive tasks" to streamline the results toward studies exploring variation in functionality caused by handedness. This led to about 288 total search results. The inclusion criteria involved filters for search that only included peer review and reputable scientific journals, literature written in English, and studies that were more recent to ensure the latest research findings would be analyzed in this paper. The exclusion criteria included papers whose subjects did not pertain to the topic of interest and duplicate papers. Potential biases in articles were addressed by providing alternate explanations, acknowledging limitations in existing experiments, and a thorough search of each type of study to capture diverse perspectives. Cross-checking similar studies and their results to confirm that the data is replicable helped ensure the reliability of the data and research presented in this study. The validity of the results was ensured by evaluating the methodology used in each selected study. The final number of scientific papers using this specific methodology is 29 articles. Most of the experiments involving motor functions used the same standard assessment to determine handedness in subjects—the EHI test—which was a considerable drawback because it prevented the comparison of various tests to analyze the most effective one. Future studies should include a more diverse group of participants, different procedures to establish handedness, and a broader range of statistical analysis methods.

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