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Development of Inner Speech and its Neural Correlates

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ABSTRACT: Inner speech is the production and experience of language within one's mind without overt articulation. Despite being an integral part of human cognition, there is limited knowledge of inner speech development or the brain regions involved in its production. Inner speech usage increases as private speech is used less and reaches its height around seven years old, maintaining a similar activity level. Inner speech is a self-regulatory process that aids in completing non-verbal language tasks such as rhyme identification and other reading tasks. Past research has shown that much inner speech is associated with activity in the left inferior frontal gyrus, the left angular and supramarginal gyri, and Wernicke's area. It has also been found that an increase in the activation of the left inferior frontal gyrus is associated with tasks that require more inner speech. These areas are connected via the dorsal language stream, which appears to mature parallel with inner speech; however, the possible correlation has yet to be studied further. Further studies into inner speech may explore the correlation between the dorsal language stream and inner speech to confirm the relation and better understand how the brain regions work together to produce the phenomenon.

KEYWORDS: Behavioral and Social Sciences; Cognitive Psychology; Inner speech; Neural Development.

Introduction

"Doe" and "Dough" are homophones, but overt speech is not needed to determine that. If someone said these words inside their head to see if they are pronounced the same, they used inner speech. Similarly, inner speech may also be used each time one processes a desire or want, such as what one wants for lunch; however, the use of inner speech can vary depending on the individual or specific situations. Due to its use in various circumstances, inner speech is one of the most prominent neurological processes in our everyday lives, yet it isn't easy to study. Inner speech is challenging to study compared to other psychological fields due to the possible inaccuracy in a participant's results and the inability to explore it in other animals since we do not know if they share the subjective experience. Inaccuracy within participant's results could be due to variability in the amount of inner speech a participant uses to perform tasks or imprecise self-reporting of their results. As a result, the field of inner speech is significantly less researched than others. However, studying inner speech will help scientists better understand one of the most prominent neurological processes in our everyday lives. Research methods of inner speech have greatly improved in the past few decades with the introduction of innovations like functional magnetic resonance imagining (fMRI), which measures the amount of oxygen used in an area, and transcranial magnetic stimulation (TMS) which temporarily disrupts the function of targeted brain areas.

Knowing the developmental origin of a function may help us understand how it works. Over time, many theories have emerged on how inner speech develops in children. John B. Watson, who established behavioral psychology, believed that the behaviors of organisms should be focused on in psychology rather than internal processes.[32] His theory was that inner speech results from continually diminished private speech until it becomes silent and present only in the mind.[32] This theory implies that inner speech is produced nearly the same way as overt speech but excludes the motor cortices. Another popular theory was initially developed by Lev Vygotsky in his book *Thought and Language* (1934)[2], which states that inner speech arises due to internalizing linguistic exchanges between a caregiver and the child, explaining inner speech as a self-regulatory process. This internalization begins as private speech, where someone will speak to themself aloud, and then loses its overt aspect as it transitions into inner speech.

Researching the development of inner speech in children may give insight into the purpose of inner speech as a process and how it differs from overt speech in function. Furthermore, identifying the brain areas involved in inner speech and their functions helps to elucidate how inner speech occurs and reveals similarities and differences in the structures involved in overt and covert speech. Analyzing the development of these areas within the perspective of inner speech allows more information about the importance of each function in inner speech to be found. Future research on inner speech may seek to further explore the development of brain areas and language to determine whether inner speech is a direct result of language acquisition or ingrained in human DNA. This review aims to analyze current research on inner speech to determine what is known about the neurological phenomenon and how to proceed in its study.

Discussion

Development of Inner Speech in Children:

Vygotsky developed one early theory regarding inner speech. In his 1934 book, Vygotsky theorized that small children internalized conversations with their caregiver and began to talk to themselves out loud to learn and solve problems independently, a process he termed "verbal mediation".[2] This theory is built upon a previous idea by John B. Watson stating inner speech develops from overt, private speech that grows silent until it

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becomes a thought.[32] Although Vygotsky saw "verbal mediation" as a precursor to inner speech, he found Watson's theory wrong because he believed that inner speech was more complex than the mere dampening of verbal mediation and changed drastically in its mechanism as it transforms from overt to covert speech.[2,5]

One early experiment conducted by Vygotsky found that young children use private speech while performing cognitively challenging tasks, revealing a transitional stage between internalizing speech from an overt nature to one purely of thought.[2] He theorized that this transformation is accompanied by changes to the form of the speech itself, which he classified into three main areas: private meanings of words that have greater prominence than conventional public definitions, the development of hybrid words with complex meanings (known as agglutination), and the infusion of sense (where a word may be infused with a feeling, such as an exam enticing feelings of anxiety when spoken internally).

Private speech begins to be observable when a child reaches 2-3 years old.[5] Then, between the ages of 3 and 8, private speech takes an observable turn from task-irrelevant speech to task-relevant speech (i.e., self-guiding comments) and then to minor external expressions of inner speech such as whispering or inaudible muttering. Private speech most frequently occurs in five-year-old children, then notably declines. This decline in the frequency of private speech is associated with a simultaneous increase in the occurrence of inner speech.[7]

Around the age of 7, a phonological similarity effect begins to occur when children begin to use inner speech more frequently. Children who were given a set of images to remember and images that represent phonologically similar words were more challenging to recall sequentially.[8] This signifies a shift towards using inner speech as a strategy to remember sequences, as children below this age do not express a phonological similarity effect.

In accordance with the previous study, it has also been shown that private speech increases in frequency in relation to task difficulty in children.[9] This further facilitates the theory that children use private and inner speech to exhibit self-control and plan how to approach an activity; however, the use of inner speech may vary from person to person. Adults have been observed to use inner speech to switch between tasks with different responses and rules, aid with memorization and self-guidance, and facilitate self-control.[5] This measurement of inner speech was determined by measuring changes in the "switch cost" between tasks with different arithmetic rules with the deployment of articulatory suppression.[5]

It has also been suggested that inner speech may present itself in two ways: in a fully specified form and a highly condensed form.[10] The former consists of highly specific syntax, semantics, and phonology similar to overt speech or oral reading. Meanwhile, condensed inner speech contains reduced phonology and syntax compared to expanded inner speech. While both forms of inner speech are thought to initially arise in children as overt, private speech, different brain regions produce overt speech and inner speech. The observable transition

becomes a thought.[32] Although Vygotsky saw "verbal mediation" as a precursor to inner speech, he found Watson's theory wrong because he believed that inner speech was more complex than the mere dampening of verbal mediation and changed drastically in its mechanism as it transforms from overt to covert speech.[2,5]

Brain Areas Involved in the Production of Inner Speech:

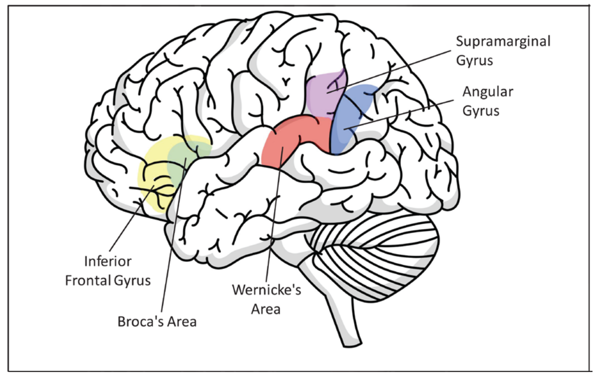

Figure 1: The image is a diagram of brain regions and their location within the human brain. It should be noted that Broca's Area is located within the left Inferior Frontal Gyrus.

A diverse range of studies have been conducted to pinpoint areas of the brain that contribute to the process of producing inner speech. For example, measuring brain activity by fMRI while performing tasks such as silent word repetition, word stem completion, and silent reading has identified the involvement of the left inferior frontal gyrus (IFG) as well as the left angular (AG) and supramarginal gyri (SMG) which are in close proximity to each other as shown in Figure 1.[4] However, these studies pertain directly to task-dependent internal speech in which participants use inner speech to solve a task, rather than spontaneous inner speech, where participants use inner speech for other purposes such as thinking about more personal experiences. There are fewer studies researching spontaneous inner speech.

In a 2012 study, fMRI was used to study the correlation between brain activation and internal processes such as mental imagery and inner speech.[11] During this study, they found brain activity fluctuations in a network, including the temporoparietal junction (the location of the AG and SMG), left IFG, and superior temporal regions. In addition, an earlier study showed that bursts of activation in the bilateral auditory cortex were observable as participants lay inside a scanner without performing any tasks and while no specific external stimuli were present, implicating a role of the auditory cortex in the production of spontaneous inner speech.[12] Activation of the superior and middle temporal gyri and the left IFG and superior temporal sulcus have also been identified in a detailed study containing a single participant experiencing spontaneous inner speech.[13] Another study using fMRI to compare the areas involved in producing spontaneous inner speech versus those involved in task-dependent inner speech found that the left IFG activates in task-dependent inner speech rather than spontaneous inner speech.[14] These studies reveal that task-dependent inner speech, or inner speech due to current external stimuli, involves different brain regions than spontaneous inner speech, resulting from more personal concerns.

In addition to the IFG, it is also hypothesized that Broca's area (part of the IFG), as well as Wernicke's area (located in the posterior section of the superior temporal gyrus, adjacent to the AG and SMG), are involved in inner speech as they are associated with planning for speech and comprehension of language, respectively. In another study, participants with post-stroke aphasia were tested to see whether their aphasia affected their inner speech; it was found that while some participants had an observable deficit in their capabilities to produce overt speech, their ability to produce inner speech was intact.[15] The opposite scenario was observed in the same study, where participants had noticeable damage to their inner speech while showing signs of preserved overt speech.[15] Lesions to the IFG, SMG, and local white matter tracts were associated with difficulties completing tasks requiring inner speech. Furthermore, this study found that this activation of the IFG coincided with findings from other studies that associated the IFG with phonological processing.[15] These studies indicate that distinct functions from overt speech produce inner speech.

The association of task-based inner speech with the left IFG has also been shown to be related to the task's difficulty. A 2002 study was the first to make this distinction, showing more activity while naming animals, whereas naming letters showed less activation in the left IFG.[16] The second instance is in the study by Sato *et al*. (2004), where two conditions of verbal transformations were studied. Here, one word was repeated rapidly, and participants would signal when this word began to sound like another, such as "fly" beginning to sound like "life." In the first condition, participants were asked to repeat the played word. In the second, they were asked to identify when the verbal transformation occurred, creating a situation requiring more conscious inner speech. The studies found that task-dependent inner speech could be associated with greater activation in the left IFG and left SMG.[14,16]

While many regions associated with producing and processing inner speech (i.e., IFG, temporal lobe) are also known for their functions in processing both written and heard speech, the areas involved in inner speech have been shown to affect different subregions than overt speech. The dissimilarity in regional activation when comparing overt and inner speech raises the question of why inner speech is processed differently compared to overt speech and what anatomic differences better equip these areas to produce and process inner speech. To better assess the nature of inner speech, we may also turn to the development of the brain areas responsible for it.

Development and Function of Inner Speech Brain Areas:

The brain is a complex structure with many different areas dedicated to specific tasks. Although each area's tasks seem quite simple when collaborating, they can carry out more complex functions. For example, since inner speech is a complex neurological phenomenon, it utilizes many different brain areas. As mentioned above and shown in Figure 1, the major regions that contribute to the production of inner speech consist of the left Inferior Frontal Gyrus (including Broca's area), Wernicke's area, the left angular gyrus, and the left supramarginal gyrus.

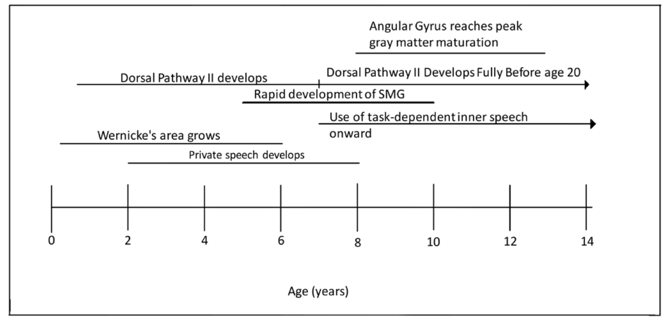

Figure 2: The timeline of the development of inner speech and relevant brain areas. It may be noted that the age at which Dorsal Pathway II develops is not precisely known. In addition, the SMG appears to grow rapidly when inner speech begins being used.

The left IFG, specifically Broca's area, is best known for its participation in producing speech and language; however, it is not yet known precisely how Broca's area carries out these roles. Despite this, its function in language comprehension and production has been narrowed down to translating speech into an "articulatory code," which motor cortices can then use to produce overt speech.[17] In other words, Broca's area does not contribute directly to motor output. Instead, it sends information about the desired phonetic output and how to coordinate muscle movements to produce the output.

Wernicke's area, consisting of the gyri which form the left Sylvian fissure, is considered involved in the comprehension and production of speech. Wernicke's area is responsible for phoneme perception and retrieving the meaning of the word.[18] This area is present in three-month-old children but is not the same size in adults.[19] The growth of this region is correlated with the development of language in young children until the age of six, when Wernicke's area reaches its adult size, with the most significant growth in the first and second years of childhood.[20,21]

The Left Angular Gyrus (AG) is formed by the superior and middle temporal gyri as they continue into the inferior parietal lobe.[22] Lesions to the AG have been associated with several cognitive defects, most resulting in deficits in complex information integration and knowledge retrieval.[22] Since the area has also been found to activate during task-dependent inner speech, these results may indicate the area's involvement in semantic processing. This activation suggests that the left Angular Gyrus has a greater role in expanded inner speech due to its connection to semantic processing. Gray matter maturation in the AG appears to peak between the ages of 8 and 13 years after overt; private speech seems to convert to inner speech, as shown in Figure 2.[24,33]

The Supramarginal Gyrus (SMG) is one of the gyri superior to Wernicke's area and is more engaged when a phonological emphasis is put on words rather than a semantic emphasis.[23] In other words, this area shows a tendency to activate when the pronunciation and sounds of a word are being focused on rather than the word's meaning. Although this does not confirm the exact process of the SMG, it does link it to phonological processing.[23] Like Wernicke's area, the SMG develops rapidly

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through childhood; however, the SMG begins to develop later than parts of the frontal cortex between the ages of 5 and 10.[24] This relates to the ages when private speech begins to develop into inner speech as found in Alderson-Day and Fernyhough and demonstrated in Figure 2.[5]

Each area is popularly associated with its roles in the comprehension and production of both written and verbal language. Still, they have also been shown to be activated as inner speech is being produced. Considering how closely the SMG's development coincides with inner speech, its importance in the process can be seen. However, the SMG's involvement in phonological processing may give insight into the contents of inner speech, which are essential to the personal meaning behind the thought. Compared to overt speech, inner speech has fewer feedback mechanisms to improve the performance of inner speech. It may, therefore, increase the use of phonological and semantic processing to augment inner speech.[31] However, this may also indicate that phonological components of inner speech are used to reiterate the meaning behind a thought, reinforcing the self-regulatory effect of inner speech. In addition, due to the linguistic presentation of inner speech, it is unsurprising that its origins are intertwined with language development and that inner speech processing is similar to other types of language comprehension. However, as has been shown, inner speech relies on distinct processes, particularly for its production, marking it as a unique phenomenon rather than an extension of overt speech, as Vygotsky hypothesized.

The Dorsal Language Stream in Inner Speech:

Despite being one of the most prominent neurological processes in peoples' everyday lives, there are only a small number of papers currently that research inner speech due to its complexity as an internal neurological phenomenon. As a result of many studies, we have isolated inner speech production to four main regions of the brain: the left IFG with Broca's area,[14,15] the left SMG, the left AG, and Wernicke's area.[14,15,25,26] Despite our knowledge of their participation in producing inner speech, we do not know the exact function of each area or how they work together to produce inner speech. One leading hypothesis by Geva *et al*. (2019) contends that the dorsal language stream may be involved in the process.[4]

The dorsal language stream is a white matter tract that connects the IFG, premotor cortex, and regions at the temporoparietal junction, including the SMG, AG, and Wernicke's area, and has become associated with speech production.[4] Meanwhile, a ventral stream connects the IFG with anterior regions of the temporal lobe and is associated with language perception and processing. Each of these streams is also divided into multiple pathways depending on which specific regions are connected. Although the dorsal pathway connecting Broca's area with the temporoparietal junction, known as dorsal pathway II, is not present at birth, another study found that these pathways are present in children six to twenty-two weeks old but are not fully developed.[27,28] The development of dorsal pathway II was further explored by Brauer *et al*. (2013), where it was found that this dorsal pathway was well-developed in seven-year-old children. In this age, inner speech begins to develop covertly, as mentioned above. Despite the maturity of this pathway by the age of seven, it does not fully develop until the early 20s.[29]

The dorsal language stream is a connective tract crucial to an individual's language development, understanding, and production. It may be hypothesized that one or more dorsal pathways are necessary for inner speech to develop. Determining the exact functions of the dorsal language stream remains an active area of investigation. The underdevelopment of dorsal pathway II has led some to hypothesize that language development and acquisition depend on other dorsal pathways and the ventral pathways, so these should be considered.[29,30]

Further Researching Inner Speech:

Within the last few decades, methods of researching neurological phenomena have abounded and could help elicit more understanding in this field. These methods include studying participants with damage to certain parts of their brain, then noting what functions were impaired, and using functional magnetic resonance imaging (fMRI) to find out which parts of the brain are receiving the most oxygen, as well as a more recent development called transcranial magnetic stimulation (TMS). TMS is a non-invasive method of studying the function of a brain area by inducing a magnetic field under the skin and in the brain, temporarily changing the efficiency of the stimulated area.[1] Each of these methods can be used to identify functions of brain areas by analyzing an area of interest while participants perform an activity that targets the desired function. However, it is crucial to understand which parts are used during an experiment to assess which areas are responsible for specific functions properly. For example, the processes used when reciting a paragraph from memory instead of reading it aloud on paper. Even though both scenarios involve reading a prompt, they involve different methods and would produce different results when recorded.

With access to newer technology, researching inner speech has become much easier compared to the late 1900s or even the early 2000s. Inner speech may be further explored by identifying the order in which the areas of the brain produce it. In testing the order in which it is created, we can also determine the purpose of the other regions in inner speech. Transcranial Magnetic Stimulation (TMS) may be used to inhibit an area known to produce inner speech to conduct an experiment that identifies the sequence in which these areas activate. Then, fMRI may be used to record how other areas were affected by the inhibition of the previous site while performing tasks that promote the use of inner speech, such as silent reading. If the inhibition of an area causes a larger cascade of inhibition of activity in other areas associated with inner speech, then the area is likely important in earlier processes. If the cascade effect produced is smaller, it may indicate that the process attributed to the area occurs later in the production of inner speech. By seeing how many other areas associated with inner speech have reduced activity due to another's inhibition, a general order for the activated areas may be produced; the area whose inhibition causes the most reduced activity in other regions would be one of the first in the process. Although this experiment would not fully confirm the sequence, it could also help bring forth new questions as well or even reveal other areas that may be involved in inner speech. However, challenges with this experiment may include inconsistent external stimuli and the involvement of these areas in different processes, which may lead to false results.

Another experiment that could be conducted could test how the brain develops through the lens of inner speech. To do so, several children and adolescents may volunteer to be examined every four to six months over a few years to see how their brains have developed. During these examinations, they may perform tasks such as silent reading and set-shifting activities while measuring brain activity to identify whether an increase in inner speech (identified by a decrease in private speech) correlates with an increase in activity in areas associated with inner speech and a decrease in the activity of the motor cortices and other areas involved with overt speech. If this correlation is found, then it may suggest that inner speech is a function directly tied to human anatomy and, therefore, genetics rather than a byproduct of the ability to process language. Suppose inner speech is found to be tied to the development of brain areas. In that case, it may suggest the possibility that other organisms closely related to humans have the capacity to produce inner speech as well. One challenge of this experiment would be running longitudinal studies throughout the participants' childhood and achieving a large enough sample size to run the experiment. This experiment may pose ethical concerns regarding consent from parents and minors over long periods of time, as well as data storage and confidentiality. Other ethical concerns may come from compensation for participation in the study; however, compensation must not outweigh other considerations that the participants have and must be well informed on the experiment to provide informed consent.

Much of current research has issues regarding sample sizes of experiments and the need for more differentiation between task-dependent and spontaneous inner speech. As a result, this data could generate improper results that do not adequately distinguish two similar but separate processes and misrepresent the greater population. To address the former issue, a greater sample size may be achieved by offering participants compensation for participating in an experiment, increasing its accuracy. The latter case may be addressed by considering task-dependent and spontaneous inner speech, two different processes, and identifying which process an experiment targets before conducting the investigation. The experiment's results may be reviewed to verify which method was tested.

Conclusion

This review has outlined what is known about the processes involved in producing inner speech and how inner speech develops in children. Understanding these aspects of inner speech allows people to further investigate the topic further, as it is a complex phenomenon in nearly every part of our lives. Recent technological advancements such as TMS and fMRI have enabled researchers to identify areas implicated in producing inner speech, determine the sequential order in which areas are activated, and verify if the processes of two areas are related. While not perfect, Vygotsky's original inner speech model rings remarkably accurate after nearly a century. Further research may seek to update and merge his theories with modern neuroimaging data. In addition, understanding how inner speech works provides insight into other disciplines, such as psychology and neurology, possibly informing how to treat illnesses in which inner speech may be affected, such as attention deficit hyperactivity disorder, autism, and schizophrenia.

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