From Imagination to Abstract Analysis: How Natural Language Enhances Spatial Intelligence Through Enhancing Abstract Reasoning and Spatial Rotational Ability

Zhuohao Yuan[1,a,*]

[1]*University of California San Diego, San Diego, California, 92093, United States*
a. z8yuan@ucsd.edu
**corresponding author*

Abstract: Spatial intelligence is traditionally conceptualized within the IQ framework as innate and unaffected by experiential factors; it encompasses two primary faculties: abstract reasoning and spatial rotational ability. Contemporary evidence challenges this notion, positing that language, an acquired experiential factor, coherently and systematically augments these two capabilities. Specifically, language encoding and verbalization shift abstract reasoning from a primarily habitual process to a state that is distinctly more abstract and analytical. In parallel, relational language descriptors (e.g., "above", "below") aid in transitioning spatial rotational ability from a primarily imaginative domain to an abstract, analytical one. While previous studies have shown language's influence on discrete faculties in spatial intelligence separately, a comprehensive understanding of its systematic enhancement remains elusive. This paper attempts to bridge this gap, proposing that IQ determinants are not innate. Moreover, this paper shows that language uniformly and methodically enhances all facets of spatial intelligence through the same medium (transformation to an abstract-analytical task space) and that this task space proves more productive than its imaginative or habitual counterparts.

Keywords: Spatial intelligence, IQ framework, Relational language descriptors, Abstract-analytical task space, Language encoding

1. Introduction

The longstanding view in cognitive science has been that spatial intelligence is primarily innate, encompassing abilities like abstract reasoning and spatial rotational ability. However, emerging evidence suggests a pivotal role for language in shaping these skills, contrary to traditional models that treat language and spatial intelligence as distinct. This research delves into language's systemic influence on transitioning spatial intelligence from habitual and imaginative to abstract-analytical realms, potentially transforming our understanding of spatial intelligence.

The goal of this paper is to uncover whether language uniformly enhances spatial intelligence and if an abstract-analytical approach is superior to habitual and imagination-based problem-solving. This inquiry is significant as it confronts established beliefs in cognitive science, suggesting a profound impact of language, a posteriori, on preconceived, a priori capabilities. The findings could revolutionize educational tactics and cognitive training, highlighting the necessity of linguistic elements in learning strategies and further studies on individual language impacts on cognition.

In the ensuing discussions, the analysis is categorized into four distinct sections, each discussing one faculty of spatial intelligence and its transformation into an abstract or analytic task-space. For example, the first two sections discuss abstract reasoning with the first one focusing on how it transforms into an abstract task-space, followed by the second one discussing the transformation into an analytic task space. Similarly, for the latter two sections, spatial relational ability is addressed, and its transformation to an abstract and analytical task space is discussed, respectively. This structured approach provides a clean and systemic understanding of the interplay between language and all aspects of spatial intelligence.

2. Transformation to an abstract task-space (abstract reasoning)

When faced with a problem, the initial stage involves formulating a representation that is manageable and encompasses all pertinent facts or data associated with the issue at hand. Next, a "schema" refers to a methodically structured blueprint that captures the various aspects of the problem. It serves the purpose of systematically arranging relevant information, thereby creating a unified portrayal of the problem's "world". The precision of this portrayal is paramount, as it underpins the subsequent analysis and the identification of potential solutions [1]. As a problem is stated verbally or reasoned verbally, problems with all their inner relations are being captured and represented by language. Consequently, language constructs a schema, organizing the complex interrelations intrinsic to the problem. This schema thereby provides a foundational framework that guides the subsequent analysis of the problem, adhering to the structural cues established by this linguistic formulation.

This is an example of such a cognitive process: Missionaries and Cannibals Problem: five missionaries and five cannibals must cross a river in a small boat holding only three at a time. If cannibals outnumber missionaries at any stage, the missionaries are eaten. The solution involves a "driver" strategy, ensuring a safe ratio at every point: The "driver" starts by taking a missionary across first, then comes back alone to pick up either another missionary or a cannibal, and keeps going back and forth until everyone has crossed [1].

A similar strategy can be applied to the Jealous Husbands Problem which involves three couples crossing a river, ensuring no woman is left with another's husband without her own present. The husbands, acting as "drivers", maintain the safe configuration (think of the husbands as the "missionaries" and the wives as "cannibals") [1].

In the realm of analogical thinking, language plays a pivotal role in denoting various entities, abstracting their interrelations, and therefore allowing problem solvers to identify similarities between different problems. In the context of verbal logical problems, language elevates the abstraction level of the task-space. This is because language itself is an abstract depiction of the fundamental structures of the problems at hand. Moreover, having an abstract linguistic representation of problems enhances problem-solving more effectively than operating without such a representation. For instance, understanding the solution to the Missionaries and Cannibals Problem (original verbal logical problems) becomes a conduit for resolving analogous challenges like the Jealous Husbands Problem (future logical problems), owing to the structural similarities that language captures. It is this linguistic schema, organizing the intrinsic complexities of problems, that becomes the bedrock for dissecting the problem, allowing for future use on problems with similar structures.

3. Transformation to an analytic task-space (abstract reasoning)

In the subsequent sections, the role of language is elucidated as a catalyst in enhancing the level of analyticity in abstract reasoning, thus facilitating efficient problem-solving. Two primary mechanisms underlie this interplay. First, language offers a structured framework that promotes controlled reasoning, curbing the tendency to rely on habitual or automatic cognitive processes. Second, verbalization fosters metacognitive awareness, wherein individuals engage in introspective analysis of their own cognitive processes. This act of reflection upon one's thought patterns further augments analyticity within the context of abstract reasoning.

3.1. Controlled Reasoning

In the process of solving the Tower of Hanoi (TOH) problem, participants engage in both controlled and habitual reasoning. Controlled reasoning predominates when participants are further from major sub-goals, necessitating calculated decision-making for sequential moves [2]. Conversely, as participants approach these sub-goals, the reliance on calculation diminishes, and habitual, intuitive reasoning takes over.

Verbalization, articulating thoughts aloud in one's own language, shifts the dynamic significantly. It curtails habitual reasoning, promoting a controlled approach throughout the problem-solving process, including during seemingly minor moves. By compelling participants to express their rationale, verbalization forces participants to engage in controlled analysis that mitigates the propensity for errors that higher reliance on intuition or habits might invite. This shift from an intuitive to an analytical task space enhances accuracy in deduction [2].

The critical role of verbalization emerges from its foundational reliance on language. Without the medium of language, there’s no conduit for the verbalization process, underscoring the role of linguistic processes (spoken or internal) in refining thought. In essence, the act of thinking with language enhances control over reasoning processes and minimizes the potential for non-conscious errors, providing a clearer, more precise path through the problem-solving landscape.

Thus, evidence suggests that language’s facilitative role in verbalization promotes precision in thought processes. It acts as a buffer against the ever-present potential for habitual reasoning, inherent in human cognitive processing. This underscores the significance of language in augmenting logical reasoning and decision-making efficacy.

3.2. Metacognition

The pivotal role of language in fostering metacognition has significant implications for problem-solving processes. First, metacognitive awareness, augmented by language, facilitates introspective reflection on one's cognitive patterns. This introspection not only imparts flexibility in thinking but also drives individuals to be more strategy-oriented, harnessing a diverse array of cognitive strategies. Second, metacognition, facilitated through language, enhances the synergy between logic and attentional focus. This harmonized coordination is imperative for the seamless integration of various information processing stages during problem-solving, as evidenced in a recent study on depression. The findings from such studies underscore the validity and significance of metacognition in effective problem-solving and underscore its essential role in cognitive tasks.

3.2.1. Metacognitive awareness

In Roger L. Dominowski’s study involving Katona’s card problem, participants’ use of language through verbalization illuminated the pivotal role of metacognition in enhancing problem-solving strategies [3]. The task required arranging cards to follow a specific sequence, revealing distinct approaches among participants. While the control group primarily used rudimentary guessing and swapping strategies, the metacognitive group demonstrated advanced techniques, including card orientation recognition and consistent paper verification for sequence confirmation. These findings suggest that metacognition, accessed through verbalization, significantly shifts problem-solving from impulsive guessing to strategic contemplation. Participants became more aware of their thought processes, abandoning ineffective strategies for more analytic and deliberate ones. This progression underscores the essential role of language in facilitating metacognitive awareness, leading to refined, effective problem-solving as tasks grow in complexity and demand more abstract reasoning. The transition from simplistic approaches to complex, introspective methods exemplifies how language and metacognition enabled by it enhance the analyticity level in abstract problem-solving tasks [3].

3.2.2. Effectiveness at this enhanced level of analyticity

To understand the cognitive impairments affecting abstract reasoning in depression, a unique card-based game was utilized. This game assessed participants' logical reasoning and information synthesis capabilities.

In the study conducted by Silberman, participants engaged in a card game designed to test deductive reasoning. The game involved a deck of 16 cards, each adorned with two symbols that varied based on form, color, size, and position. Among these characteristics, one specific property (such as "big" or "blue background") was designated as "correct" [4]. The players' objective was to discern this correct property. However, the challenge was heightened by the limited feedback provided only for selections on cards 1, 6, and 11, indicating whether or not they included the correct attribute. For instance, if a participant correctly identified "blue background" on card 1, they received positive feedback, but direct feedback was unavailable for other cards. Players had to rely on their logical reasoning and the sparse feedback from these specific cards to make inferences about the remaining cards [4]. The ultimate aim was to deduce the correct property from among eight options, underscoring the necessity of sharp analytical skills and strategic thinking in achieving success in the game.

The card study by Silberman revealed that depressed individuals performed poorly, primarily due to their impaired focus. Unlike the control group, these participants didn't show improved concentration after early trials. Their diminished focus hindered their problem-solving capabilities, particularly in tasks requiring "intersection logic", which involves synthesizing information from various feedback rounds to rule out false assumptions [4]. This outcome highlights the crucial role of synergizing information in complex tasks. Importantly, this synergy is in harmony with metacognition's tenets. Given that tasks frequently involve stages with different information, metacognition assists in the broad view of these stages, leading to assessments based on synthesizing information at discrete stages. This implies that the presence of metacognitive activity ensures a comprehensive analysis of the entire problem-solving sequence, contingent upon the combination of information across various stages within the entire procedure. Such introspection is unattainable without the merging of information from successive phases, which allows for understanding and scrutiny. This convergence of information throughout a problem is fundamental, as evidenced by the card study, for ruling out ineffective strategies preconditioned on bad assumptions. Ergo, the higher level of analyticity promoted by metacognition is valid and effective from the perspective of coordinating between logic and attention and is, in essence, a high level of intersection logic.

4. Transformation to an abstract task-space (spatial rotation)

A comprehensive study by Gentner et al. delved into the cognitive underpinnings of spatial relationship comprehension among Turkish homesigners, a demographic that has constructed its sign language system without traditional linguistic input. The researchers contrasted these individuals' spatial reasoning capabilities with those of hearing Turkish children who employ standard linguistic devices for spatial relation expression [5].

The Turkish language encompasses two primary spatial relation types: directional and static. The former denotes movement (e.g., walking towards an object), while the latter signifies fixed positions (e.g., an object being on top of another). The experiment's crux was to discern whether homesigners, analogous to hearing children, would utilize gestures reflecting these complex spatial constructs linguistically expressed by their hearing counterparts [5].

Gentner et al. employed a robust methodology involving 48 video vignettes, subsequently requiring participants to recount the viewed occurrences. The focus was directed at gestures (deaf participants) and speech (hearing participants) during these recitations. Notably, while both groups could articulate 'directional' relations, homesigners struggled with "spatial" concepts, a likely consequence of their non-exposure to conventional sign language encompassing these specific signs [5].

This finding propelled further inquiry: Does the dearth of spatial linguistic constructs impair these children's non-linguistic spatial task performance? The hypothesis rested on the premise that linguistic nuances significantly influence spatial representation cognition. Thus, those devoid of spatial language should theoretically falter in related tasks. Subsequent testing via the Loewenstein and Gentner Spatial Mapping Task revealed telling trends. Generally, preschoolers grapple with this task, but linguistic cues (e.g., "top", "middle") substantially bolster performance, aiding precise spatial mental mapping. Conversely, ambiguous language yields poorer results. Remarkably, in cross-mapped evaluations, hearing participants outperformed their deaf counterparts, a discrepancy unattributable to task misinterpretation, as confirmed by control trials.

The study above shows that by using language to code for imaginative spatial relationships like "on top of" or "in the middle", people are much more precise in generating a holistic understanding of various spatial relationships. This transforms the original task-space of imagination and mental rotation into a task-space that contains abstractions about spatial relations. This abstraction is a cognitive tool that Turkish homesigners lack, hence showing poorer spatial rotational ability [5].

5. Transformation to an analytic task-space (spatial rotation)

The research by Stieff et al. delved into the potential of targeted strategy training to bridge sex differences in spatial problem-solving, a crucial skill in STEM fields. The study posited that comprehensive strategy training, merging imagistic and analytic methods, could neutralize these differences by offering a diverse strategic arsenal, mirroring the versatility experts employ in complex problem-solving.

The experiment involved 372 students, segmented into three distinct training groups: Imagistic, Analytical, and Combined Strategy Interventions. Pre-intervention, students heavily favored imagistic strategies (48%), with sparse use of analytic ones (3%). Post-intervention findings indicated a surge in both strategies, more pronounced in analytic usage. The Combined group embraced more imagistic strategies, while the Analytic group leaned towards its intervention's focus. These trends validated the hypothesis of increased reliance on spatial-analytic strategies post-instruction [6].

Regarding overall academic performance, both sexes improved under all interventions, but the extent varied per intervention type and student sex. A structural equation model highlighted that sex disparities in achievement were influenced by differences in both spatial ability and strategy adoption, with females more inclined towards spatial-analytic strategies, enhancing overall success [6].

Language makes it easier to access and use such analytic strategies by abstracting various spatial relations as fundamental blocks that human analysis could use. As spatial-analytic strategies take place, participants are not merely imagining, but are analyzing. Ergo, in the process of analyzing, language enhances controlled reasoning and enables metacognition, as argued above, to further increase the level of analyticity. Such analyticity is then more effective than pure imagination as this study shows that analysis (not just imagining rotations) is conducive to mental rotational ability.

6. Conclusion

This research paper revises the traditional notion of spatial intelligence as a purely innate component of IQ, underscoring the critical role of language in enhancing spatial cognitive skills. It demonstrates how language systematically transforms spatial intelligence, moving it from habitual and imaginative processes to more abstract and analytical domains. Through detailed studies and analyses, the paper shows that language not only improves abstract reasoning but also enriches spatial rotational ability, arguing for a more dynamic understanding of intelligence where experiential factors like language play a crucial role in cognitive tasks. However, the research doesn't account for cognitive variations introduced by different languages. Future inquiries should investigate the specific impacts of individual languages on cognition, explore the neural mechanisms influenced by language, and examine how language training affects spatial intelligence, thereby providing deeper insights into language's cognitive influence.

References

[1] *Condell, J., Wade, J., Galway, L., McBride, M., Gormley, P., Brennan, J., & Somasundram, T. (2010). Problem solving techniques in cognitive science. Artificial Intelligence Review, 34(3), 221–234. https://doi.org/ 10. 1007/s10462-010-9171-0*

[2] *Stinessen, L. (1985). The influence of verbalization on problem-solving. Scandinavian Journal of Psychology, 26(1), 342–347. https://doi.org/10.1111/j.1467-9450.1985.tb01173.x*

[3] *Hacker, D. J., Dunlosky, J., & Graesser, A. C. (2018). Metacognition in educational theory and Practice. Lawrence Erlbaum.*

[4] *Silberman, E. K. (1983). Thinking disorder in depression. Archives of General Psychiatry, 40(7), 775. https://doi.org/10.1001/archpsyc.1983.01790060073009*

[5] *Gentner, D., Özyürek, A., Gürcanli, Ö ., & Goldin-Meadow, S. (2013). Spatial language facilitates spatial cognition: Evidence from children who lack language input. Cognition, 127(3), 318–330. https://doi.org/ 10. 1016/j.cognition.2013.01.003*

[6] *Stieff, M., Dixon, B. L., Ryu, M., Kumi, B. C., & Hegarty, M. (2014). Strategy training eliminates sex differences in spatial problem solving in a STEM domain. Journal of Educational Psychology, 106(2), 390–402. https://doi.org/ 10. 1037/a0034823*