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Exploring the Impact of Think-Aloud Protocol in Engineering Design Problem Solving

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ABSTRACT

This full empirical research paper will explore the impact of think-aloud protocols in engineering design problem solving experiences of undergraduate engineering students. The think-aloud protocol has emerged as a crucial research tool for analyzing how students approach engineering design tasks. This method requires participants to verbalize their thought processes while solving problems, offering researchers detailed insights into their cognitive strategies. Prior studies have identified patterns in students' problem-solving approaches, such as transitions between scientific inquiry, biomimicry, and the engineering design process. However, there remains a lack of research comparing design problem solving behaviors during think-aloud protocol-based problem-solving.

In this study, 110 students participated in completing three open-ended design tasks. This paper will focus on one of these tasks, the Midwest Flood listing problem. Preliminary analysis reveals that students who employed the think-aloud protocol produced more effective solutions than the students who solved the task through pencil and paper alone. These findings offer insights into the influence of verbalization on design performance, highlighting implications for engineering education aimed at enhancing design capabilities.

Key words: Think-aloud protocol, engineering design, problem solving

Introduction

Design is a fundamental process that distinguishes engineering from other disciplines by focusing on creating solutions to complex, real-world problems [1, 2]. It plays a critical role in engineering education, providing a platform for students to apply theoretical knowledge and develop critical thinking, creativity, and problem-solving skills [3, 4]. As engineering evolves to address sophisticated technological challenges, cultivating design proficiency in students becomes essential to preparing them for their future professional roles [5]. Engineering design involves iterative processes of ideation, evaluation, and optimization, requiring cognitive engagement and decision-making at every stage [6]. Unlike routine problem-solving tasks, design challenges are typically open-ended, ill-structured, and require innovative thinking [7]. Given its interdisciplinary nature, design integrates knowledge from various fields, promoting the development of holistic thinking and technical fluency in students [8]. Recognizing this, several educational initiatives have incorporated design-based tasks into engineering curricula to enhance students' understanding of STEM concepts and their ability to navigate complex problem spaces [9].

In recent decades, researchers have sought to understand how students engage in the engineering design process. This quest has led to the adoption of diverse methodologies, including retrospective interviews, written design journals, and observational techniques [10, 11]. Among these, verbal protocol analysis (VPA) has emerged as a prominent research tool due to its ability to capture detailed, real-time cognitive processes [12]. VPA encompasses a range of methods, including concurrent think-aloud protocols (CTAP) and retrospective verbalizations, each providing unique insights into the cognitive strategies employed by designers during task execution [13]. Think-aloud protocols, in particular, have gained traction in engineering education research due to their capacity to elicit direct, in-the-moment verbalizations of participants' thought process [14]. Unlike retrospective methods, concurrent verbalization minimizes the influence of post-task reflection, offering a more authentic depiction of the cognitive pathways followed during problem-solving [15]. Studies employing think-aloud protocols have provided valuable insights into various facets of design cognition, including the transitions between problem framing and solution generation, decision-making strategies, and the role of prior knowledge in design ideation [16].

However, despite the established importance of engineering design and the growing interest in verbal protocol analysis, there are limited studies exploring the impact of think-aloud protocols specifically in the context of solutions of engineering design problem solving. Most existing research has focused on general problem-solving behaviors or professional design practice, with relatively few studies addressing how undergraduate engineering students utilize think-aloud protocols during design tasks [17]. This gap in literature underscores the need for further investigation to better understand how verbalization affects design performance and cognition in student designers.

Think-aloud protocols

Think-aloud protocols involve instructing participants to verbalize their thoughts while performing a task, providing researchers with a rich dataset for analyzing cognitive processes [12]. This method has been extensively utilized in cognitive psychology and design research to explore problem-solving behaviors, decision-making processes, and strategy use [18]. In engineering education, think-aloud protocols have been applied to assess students' design capabilities, particularly in open-ended tasks where multiple solution paths exist [7, 17]. The application of think-aloud protocols is not without challenges. Ensuring that participants maintain a natural flow of thought without interference from the researcher requires careful protocol design. Excessive prompting or directing participants during the task can alter the natural sequence of cognitive processes, leading to biased data [12]. Additionally, training participants to effectively verbalize their thoughts without introspection is critical to obtaining valid and reliable data [19]. Think-aloud methods have yielded significant insights into engineering design processes, revealing patterns in how students approach problem framing, ideation, and decision-making. For example, studies have shown that novice designers tend to adopt more linear approaches, focusing heavily on generating solutions without adequately exploring the problem space [20]. In contrast, experienced designers exhibit more iterative behaviors, frequently revisiting the problem space to refine their understanding and improve solution quality [21]. The current study was conducted to examine whether verbalizing thoughts affects solutions of an open-ended engineering design task.

Methodology

This study employed a qualitative research method to investigate the impact of think-aloud protocols on the engineering design problem-solving experiences of undergraduate engineering students during an open-ended design listing task. The qualitative approach was selected to explore the nuanced and metacognitive processes displayed during problem-solving. Data collection centered on rich textual and verbal data derived from think-aloud recordings.

Data analysis was conducted using an existing coding scheme to code the written responses [22]. This approach enabled a detailed understanding of the impact of think-aloud protocols on students problem-solving experiences, highlighting differences between the data. By adopting this qualitative methodology, the study offers an in-depth exploration of the complexities of engineering design problem-solving, emphasizing the role of think-aloud protocols within the design process.

Setting and Participants

This study was conducted at the University of Cincinnati within the College of Engineering and Applied Science. The participant pool consisted of undergraduate engineering students from both first-year and final-year cohorts across various engineering disciplines. Recruitment was facilitated through the distribution of flyers strategically placed throughout the college. Ethical approval for conducting this research was obtained from the University's Institutional Review Board (IRB), ensuring compliance with ethical guidelines for research involving human subjects.

Data Collection

Of the 110 participants who completed the task, a subset of 56 participants were selected to participate in the verbal protocol component of the study using a non-probabilistic sampling technique. This subset included 30 participants from the first-year cohort and 26 from the final year cohort. The participants engaged in a concurrent verbal protocol while working on three open-ended engineering design tasks [22]. For this study, the analysis will focus on a single design task: the Midwest Flood listing task. This design task was chosen for analysis because it allows students to do more extensive problem definition in the context of a broad-based real-world problem [23]. In this task, participants were instructed to identify and list key factors to consider when designing a retaining wall for the Mississippi River to mitigate flooding in the Midwest. Participants were permitted to use internet resources to gather relevant information, with the requirement that they cite all sources in their answer sheets and refrain from plagiarizing any published content. The complete problem statement for this design task is below:

> "*Over a typical summer the Midwest experiences massive flooding of the Mississippi River. What factors would you take into account in designing a retaining wall system for the Mississippi?*".

This aspect of the study was conducted individually with each participant in a neutral, quiet environment within the college premises. The selected room was free from distractions, ensuring that participants could maintain focus throughout the task. With participants' consent, all sessions were both video- and audio-recorded to facilitate detailed post-task analysis. The analysis of each participant's session involved the following systematic steps:

i. Transcription – The verbal protocols from the video recordings were transcribed from the recording.

ii. Segmentation – The transcribed verbal data were segmented into contextual units that could be systematically analyzed using a pre-defined two-dimensional coding scheme [24].
iii. Coding – Each segmented unit was coded using a coding scheme adapted from Atman et al. [24] and presented in Table I. The coding framework categorized the data by physical location and frame of reference.

To ensure coding consistency and reliability, two independent coders analyzed each participant's responses. After independently coding all segments, the coders compared their results to ensure that they agreed on at least 90% of the assigned codes. Discrepancies were resolved through discussion. The interrater reliability was calculated using Cohen's Kappa, yielding a value of 0.965, which indicates an exceptionally high level of agreement between the coders. This strong interrater reliability demonstrates a robust and consistent approach to assessing participants' design problem-scoping behaviors.

TABLE I
CODING DIMENSIONS AND ITS DESCRIPTION [25]

Physical Location	**Description**
Wall	The wall itself, what affects it, other options for having a wall, where to put it.
Water	River's length, aquatic fauna, flood (but not effects on flood on other locations), pressure problems (without mention of the wall).
Bank	Earth immediately adjacent to river, earth below the river (riverbed), wall's interface, river's edge, river's width.
Surroundings	Everything far from water, residential units, items along water, particular impacts of the flood to bank.
Frame of Reference	**Description**
Technical	Engineering or technical terminology such as design problems, choices about construction of the wall
Logistical	Expenses, financing, process of construction, maintainability issues, resources needed.
Natural	Water's level (volume), destruction, effects of flood, geography, animals, flora, climate, and climate projections.
Social	People, people's safety, views, cities, living areas, policies

Coding

In previous research studies, a two-dimensional coding scheme has been widely used to characterize the breadth with which participants scope this particular design problem [25, 26, 27, 28]. This study adopted the same coding framework, in which each participant's response was coded along two dimensions: physical location and frame of reference. The physical location codes were used to identify the specific physical area on which participants focused while addressing the design problem. These codes consisted of four categories: wall, water, bank, and surroundings. The ordering of these codes reflects a progression in participants' focus from the detailed elements of the problem (i.e., the retaining wall itself) to the broader environmental context. Specifically, the categories of wall and water represent detailed, localized components of the problem, characteristic of bounded engineering problems that emphasize core engineering science aspects.

The frame of reference codes captured the broader perspective participants adopted when thinking about the design problem. These codes were divided into four categories: technical, logistical, natural, and social. Like the physical location dimension, these categories were arranged to reflect a shift in participants' thinking from detailed, problem-specific considerations (technical and logistical) to broader contextual factors (natural and social). Technical and logistical codes correspond to specific engineering and operational issues, whereas natural and social codes are related to environmental and societal contexts. Table I provides a summary of the two-dimensional coding scheme, illustrating the four physical location codes and the four frames of reference codes used in the study [22]. This coding scheme allowed for a systematic analysis of how participants transitioned between detailed problem elements and broader contextual considerations during the design task.

Results

As illustrated in Figure 1, first year engineering students generated an average of 9.10 coded segments and final year students generated 12.85 coded segments on average. When analyzing the segments independently based on their focus, it was observed that participants devoted more attention to detail-focused (technical) aspects compared to context-focused segments. A Mann-Whitney test indicated a statistically significant difference between the number of detail-focused and context-focused segments ($p<0.01$, $r = 0.34$), with a small to moderate effect size. Further analysis showed that, on average, students addressed all four of the detail-focused nodes, with first-year students covering more context-focused nodes, on average, (10 out of 12) compared to final-year students (8 out of 12). This finding suggests that while students covered all the technical details nodes, they also considered a significant portion of the broader contextual factors, with first-year students demonstrating a slightly broader scope of contextual considerations.

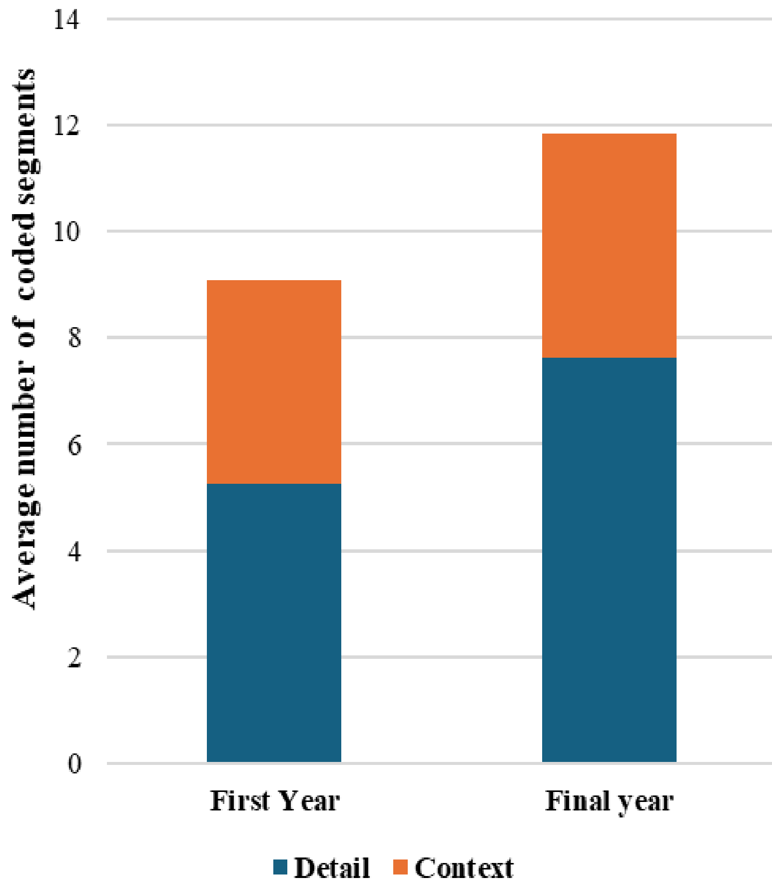

Fig. 1. Average coded pair of segments of the design task by year of study. The bar division indicates the average of detail- and context-focused segments.

Impact of Think-Aloud Protocols on the Engineering Design Task

From the purposive sampling, the data from first year students (30 participants) and final-year students (26 participants) who participated in the think-aloud protocol were analyzed separately. To explore the impact of think-aloud protocols on design problem-scoping behaviors across students who solved the task via think-aloud and through only pencil and paper, we averaged the coded segments for physical location and frame of reference. Figures 2 and 3 provide a detailed comparison of the differences in coded responses from first and final year groups when they are involved in the think-aloud process while solving the design task or when they are not. Upon examination of the data, it is inferred that the student group employing the think-aloud protocol generated slightly more detail-focused segments compared to students who solved the problem through only pencil and paper. This trend was more noticeable among first year students, suggesting that verbal protocol helped them attend more closely to core engineering design elements and detailed problem scoping. However, for final year students, the difference between think-aloud and non-think aloud groups was less pronounced, possibly indicating that they already possess more internalized strategies for design reasoning, regardless of the mode of task engagement.

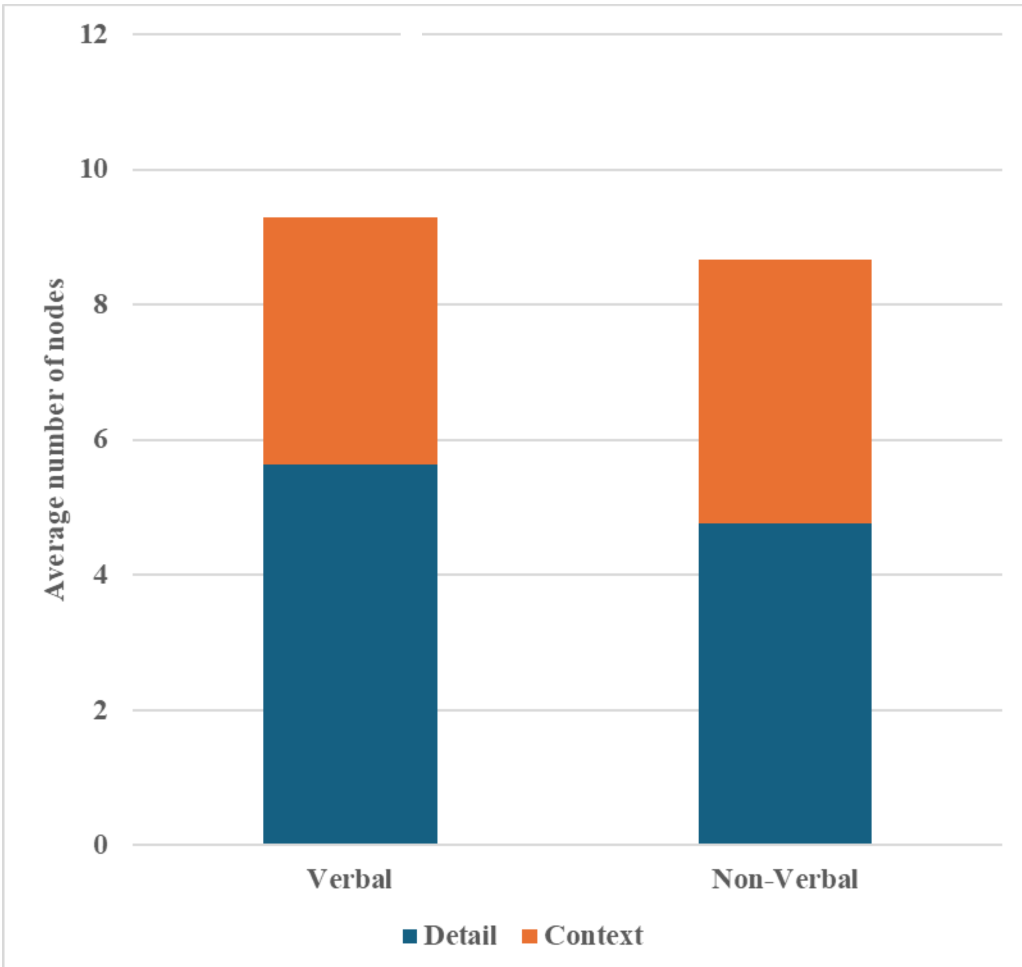

Fig. 2. Average count of coded segment pairs of the design task for first-year group. The bar division indicates the average of detail- and context-focused segments.

A Mann-Whitney test confirmed a statistically significant difference in detail and context-focused segments between these groups ($p < 0.05$). Consistent with previous observations when comparing first and final year students, all four nodes related to detail-focused areas were covered by all participant groups. On average, participants in both first and final year students addressed four out of ten nodes in the context-focused dimension.

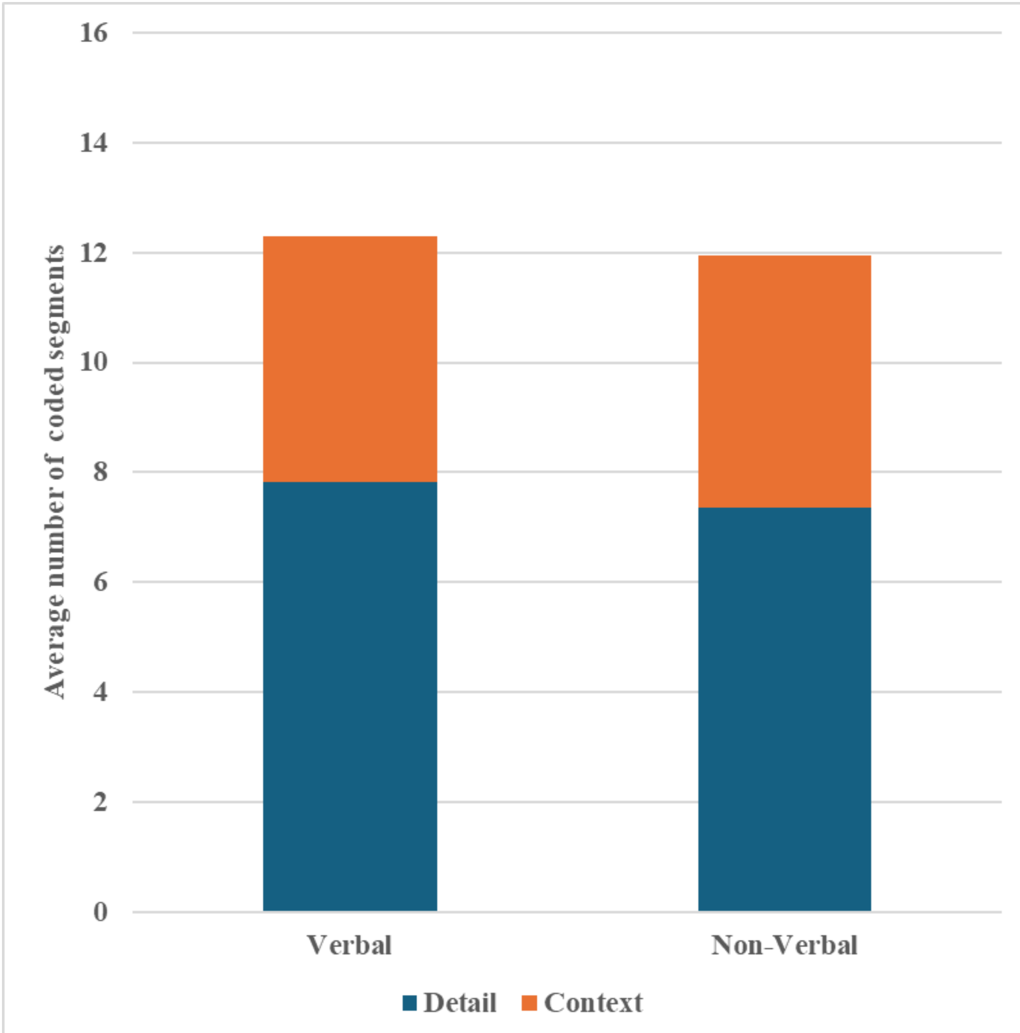

Fig. 3. Average count of coded segment pairs of the design task for the final year group. The bar division indicates the average of detail- and context-focused segments.

Discussion and Conclusion

This study provides valuable insights into how think-aloud protocols influence design problem-solving behaviors in undergraduate engineering students. Our findings reveal that, when using think-aloud protocols, participants generated significantly more detail-focused segments compared to context-focused segments, suggesting that verbal protocols may enhance their ability to concentrate on core technical aspects of design problems. These differences were statistically significant, as confirmed by the Mann-Whitney test ($p < 0.05$). These results imply that verbal protocol methods facilitate detailed articulation of problem-solving processes.

The observed effect of think-aloud protocol aligns with cognitive load theory, which suggests that externalizing thought processes can reduce intrinsic cognitive load, thereby facilitating a deeper engagement with problem details. Additionally, these findings support constructivist learning theories, which emphasize the role of active verbal engagement in reinforcing conceptual understanding. By requiring students to articulate their reasoning, think-aloud protocols may serve as a metacognitive tool that enhances their problem-solving abilities in engineering design contexts. In terms of educational implications, these results suggest that incorporating VPA into engineering curricula could help students develop both technical and contextual breadth. Specifically, structured problem-scoping tasks, such as the Midwest Flood task, can guide students in balancing detailed technical considerations with broader contextual awareness. It could also help educators improve students' ability to navigate complex design challenges.

While these findings offer valuable insights, the study has limitations, including the exclusion of gender in the study. Future research should investigate the long-term impact of think-aloud protocols on design problem-solving and explore targeted interventions to enhance students' problem-solving skills. Expanding this work to different engineering disciplines and real-world design scenarios could further enhance its applicability and impact on engineering education. By deepening the integration of verbal protocols in engineering instruction, educators can equip students with more effective cognitive strategies, fostering both technical proficiency and contextual adaptability in engineering design.

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