Investigating the Impact of Time Constraints on Sudoku Solving: A Multimodal Analysis of Cognitive and Affective States

Deepika YADAV, Tushar PATLE *, Sonika PAL, Amit PAIKRAO, and Ritayan MITRA
Centre for Educational Technology, Indian Institute of Technology, Bombay
*95tusharpatle@gmail.com

Abstract: Time constraint during problem solving is an active area of research and has been found to affect performance, emotion, and cognition in students. In this study, we use galvanic skin response (GSR), eye tracking, and retrospective interviews to investigate such effects during Sudoku problem-solving. A within-subjects experimental design was employed, where participants solved 4x4 Sudoku puzzles with and without time constraints. The results indicated a significant increase in skin conductance and pupil diameters, with large effect sizes (GSR and pupil diameter values, dz = 3.09 and 1.98, respectively), reflecting substantial rises in stress and cognitive load under time constraints. Analysis of gaze patterns and interview responses revealed no notable change in problem-solving strategies between conditions, indicating stability in individual approaches. Together, these findings contribute to the understanding of the impact of time constraints on problem-solving behavior with implications for designing adaptive learning systems and educational practices that optimize cognitive load management and enhance learner engagement.

Keywords: Time-constrained problem-solving, 4X4 Sudoku, Eye Tracking, Galvanic Skin Response (GSR), Cognitive load, Stress

1. Introduction

In the realm of education, time constraints play a pivotal role in shaping the learning experience and outcomes. The imposition of time limits can significantly influence cognitive processes and emotional responses, impacting how students engage with and approach problem-solving tasks (Sweller, 1988). Time pressure can enhance cognitive load and induce stress, potentially hindering performance and learning (Beilock & Carr, 2005; Sinha et al., 2016; Maule & Hockey, 1993). Some research has suggested that the introduction of time constraints can potentially heighten cognitive load and stress, consequently affecting the individual's ability to employ effective problem-solving strategies (Mann & Tan, 1993; Maule & Hockey, 1993; Sweller, 1988). For instance, Speier et al. (1999) examined the influence of task interruptions on individual decision-making, concluding that time constraints can lead to information overload and impaired decision quality. Conversely, appropriate time constraints may stimulate efficient problem-solving and improve focus (Mann & Tan, 1993). Investigating such effects in more detail can provide valuable insights into designing learning environments that optimize performance while avoiding stress and cognitive overload.

Existing research has explored the impact of time constraints on learning and problem-solving in various contexts, highlighting their significant role in shaping cognitive processes and emotional responses (Gonzalez, 2004; Maule & Hockey, 1993). Rothstein (1986) found that time pressure increases cognitive load and negatively impacts judgment/decision quality under time pressure, while Sinha et al. (2016) showed that time constraints heightened emotional arousal, evident in increased skin conductance.

Time-constrained tasks like timed tests, rapid decision-making tasks, and high-pressure simulations help understand their impact on problem-solving. Sudoku puzzles, which require rapid logical reasoning, are widely recognized as cognitively demanding and suitable for such research (Patil et al., 2020). The cognitive processes involved in solving Sudoku puzzles have drawn interest from researchers aiming to understand the intricacies of human problem-solving and decision-making abilities (Chandra Prakash et al., 2017; Kalia et al., 2019; Leu et al., 2014). Sudoku offers a controlled setting where variables can be manipulated to examine their effects on cognitive load, emotional arousal, and strategy use. The theoretical underpinnings of this study are rooted in cognitive load theory (Sweller, 1988) and the well-established relationship between cognition and affect (D'Mello & Graesser, 2011).

Several studies have explored cognitive processes in Sudoku solving (Shakti et al., 2019), shedding light on its cognitive demands and strategies. Tran (2023) identified strategies like scanning rows/columns, box-checking, and logical deduction. However, the impact of time constraints on these processes remains largely unexplored. Beyond research, Sudoku has also been used pedagogically to engage students in developing logical deduction skills in mathematics classrooms (Kwan, 2010).

This study aims to bridge this gap by employing a multi-modal approach that combines eye-tracking, GSR, and interviews to investigate the effects of time constraints on cognitive load, stress, and problem-solving strategies in Sudoku puzzle-solving, where a within-subjects experimental design was employed (Charness et al., 2012; Paikrao & Mitra, 2023), wherein participants solved Sudoku puzzles under both conditions (with and without time constraints). The research questions are as follows:

RQ1. How do time constraints affect cognitive load and stress during Sudoku puzzle-solving?

RQ2a. What are the different strategies employed by the participant for solving Sudoku?

RQ2b. Do participants employ different problem-solving strategies when solving Sudoku puzzles with and without time constraints?

2. Study design and Methodology

2.1 *Procedure*

The study sample comprised individuals from the engineering student population, aged between 23 and 32 years. The sample consisted of 6 male and 2 female participants. We have selected participants based on their prior experience (Basic level experience) in solving Sudoku puzzles. A convenience sampling approach was used; although non-probabilistic, it yielded a mix of participants, adhering to ethical and privacy guidelines. Participants provided informed consent before the commencement of the study, and their identities were anonymized. To minimize arousal from external factors such as temperature and noise, the study took place in a controlled environment (air-conditioned, noise-canceling/absorbing rooms). Two stimuli were presented: Sudoku-1 without time constraints and Sudoku-2 with time constraints. Before starting, the participants were instructed to remain calm and composed while their eye movements were monitored using an eye-tracker and a GSR sensor was afixed to the non-dominant hand. The study activities were recorded with 'OBS Studio' screen-capture software. After completing the puzzles, participants participated in semi-structured retrospective interviews. During these interviews, they watched video recordings of their puzzle-solving sessions, which helped elicit insights into their problem-solving strategies, emotional responses, and cognitive processes, as shown in Figure 1.

2.2 *Presentation of Stimulus (Sudoku)*

The stimuli used in this study consisted of a set of 4x4 Sudoku puzzles, presented using Tobii Pro Lab software. There are two categories of Sudoku puzzles: Sudoku-1 (S1) without time constraints and Sudoku-2 (S2) with time constraints. Both categories are of easy difficulty level. The participants interacted with the Sudoku puzzles by selecting numbers (1 to 4) from a virtual keyboard displayed on the screen, positioned centrally to the right side of the Sudoku grid, as depicted in Figure 2. Upon completion of S1, participants would press the "fn + F10" button to advance to S2, which automatically progressed after a gap of 45 seconds. Before each puzzle, the participants would see a slide containing information about the activity, ensuring clarity regarding the task requirements. The sequence of stimuli presented to participants is outlined in Figure 3.

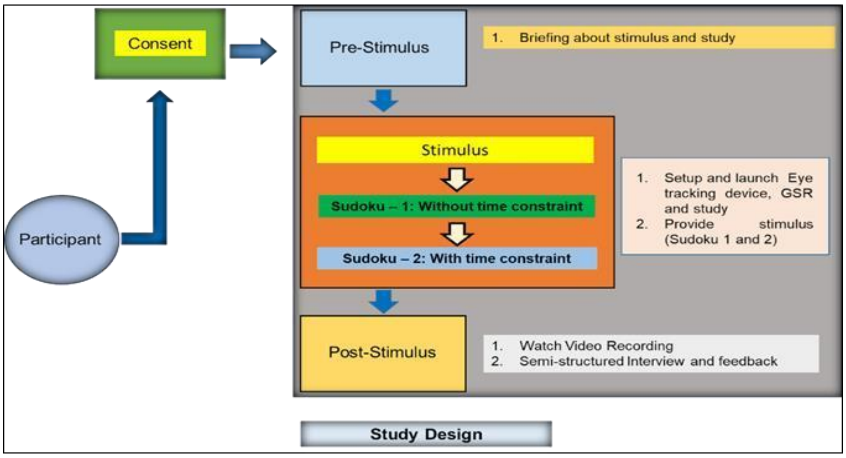

Figure 1. Study Design.

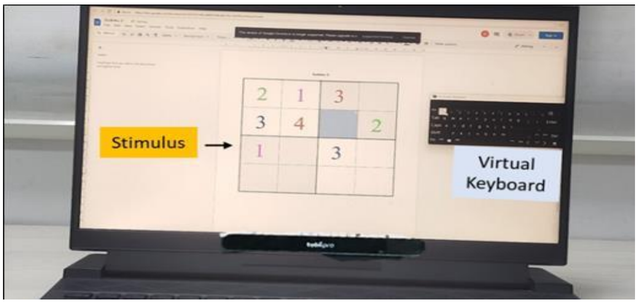

Figure 2. Presentation of the Stimulus on Tobii Pro Lab software.

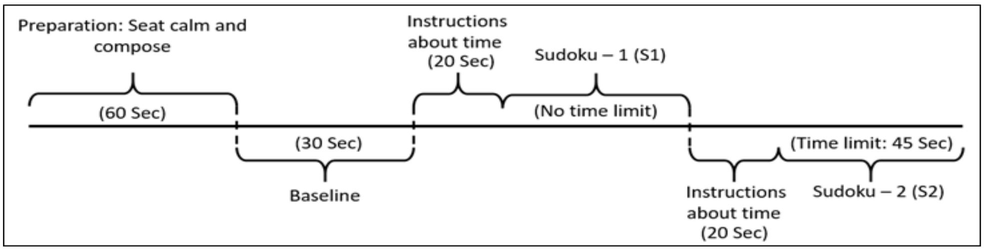

Figure 3. Sequence of tasks.

2.3 *Data Collection and Analysis*

A Shimmer3 GSR+ sensor (120 Hz) was used to measure arousal, which has been shown to indicate stress, engagement and cognitive load. Baseline GSR values were measured before each stimulus to establish a reference point. A Tobii Pro Nano (60 Hz) eye-tracking device was used to measure pupil diameter, gaze patterns, and fixation durations. These metrics provided insights into visual attention, cognitive load, and problem-solving strategies. Semi-structured retrospective interviews were conducted after the completion of study to understand strategy selection and emotional arousal, such as stress or increased cognitive load due to time constraints.

To ensure the data was ready for analysis, we performed basic pre-processing on the GSR and eye-tracking data. For GSR, baseline values were recorded before each task and used to standardize the data, allowing us to compare participants' responses across the timed and untimed conditions. For the eye-tracking data, we used Tobii Pro Lab’s built-in filters to automatically remove blinks and missing gaze points. Pupil diameter values were standardized for each participant to allow meaningful comparisons. Only those portions of data where the tracking accuracy was high (over 90%) were included in the analysis. The integration of multimodal data and their role in answering our research questions is depicted in Figure 4.

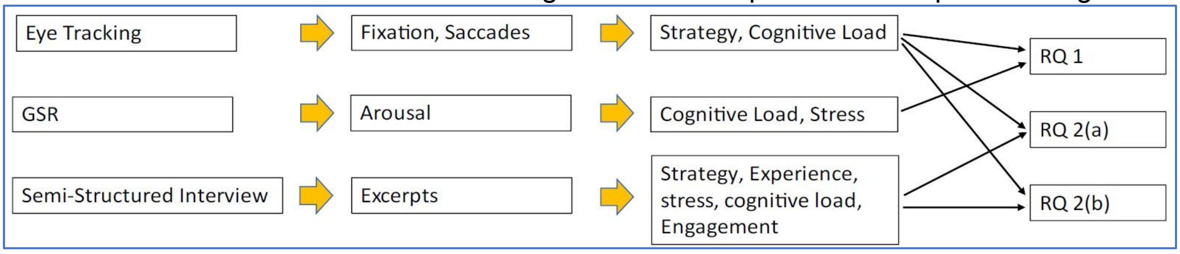

Figure 4. Mapping of Data analysis and tools with RQs.

3. Results

3.1 *Analysis of GSR Data*

Standardized GSR increased continuously during play and was higher in S2 than S1. A paired-samples t-test showed significantly higher mean standardized GSR under time constraints, $t(7)=8.74$, $p<.001$, $dz=3.09$ (Figure 5, 6). This robust effect size underscores the increased stress induced by temporal pressure (Sinha et al., 2016).

3.2 *Analysis of Pupil Diameter and Gaze Pattern*

Standardized pupil diameter was also higher in S2 than S1. A paired-samples t-test indicated larger mean standardized pupil diameter under time constraints, $t(7)=5.60$, $p<.001$, $dz=1.98$ (Figure 7, 8). , highlighting a significant influence of temporal pressure on pupil diameter (van der Wel & van Steenbergen, 2018). This substantial effect size underscores the heightened cognitive load caused by the time constraints.

Fixation sequences can establish the order of attending to important steps during problem solving (Mitra et al., 2017; Negi & Mitra, 2022). A comprehensive manual analysis of eye gaze patterns was performed to elucidate the strategies employed by the participants. We present here two scan paths illustrating the strategies employed by the participants (Figure 9), where their eye movements, indicated by red arrows (saccades), and green circles (fixation) followed a pattern of scanning along rows, columns, and boxes to locate possible cell placements. The yellow icons represent fixations, indicating the cells where participants filled in numbers based on their deductions.

3.3.1 *Rows and Columns Strategy*

In the Row and Column strategy, participants systematically scan the rows and columns of the Sudoku grid to identify given numbers and deduce placements. As illustrated in Figure 9, participants follow a sequence of fixations and saccades along rows and columns. Initially, they scan the rows to identify possible placements (as shown by the arrows indicating the sequence of fixations from one cell to another). Subsequently, they shift their focus to the columns, continuing this methodical scanning and deducing process until the entire Sudoku grid is filled.

This strategy relies heavily on a structured approach, where participants use logical deductions based on row and column intersections to place numbers accurately.

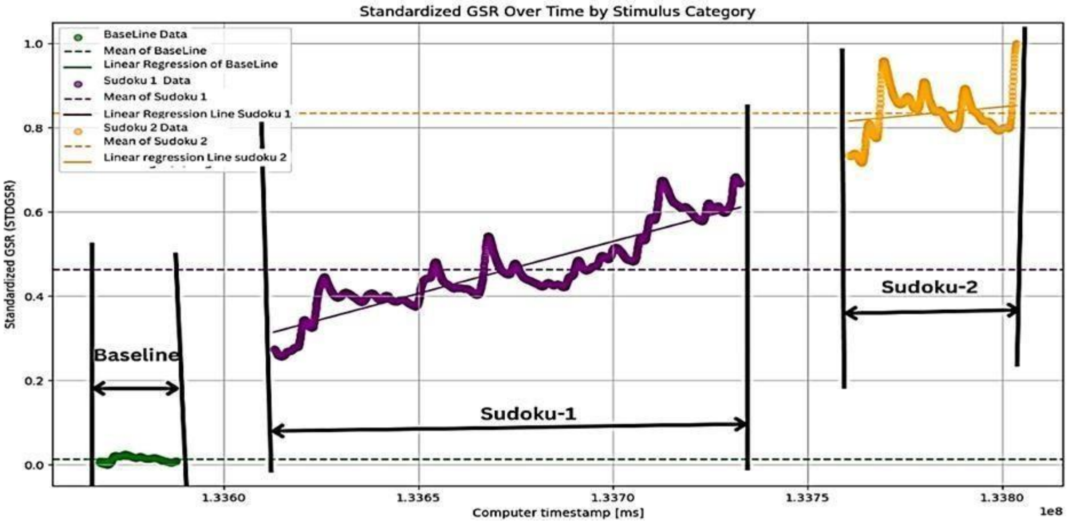

Figure 5. Plot for the standardized mean GSR values for Baseline, S1 and S2.

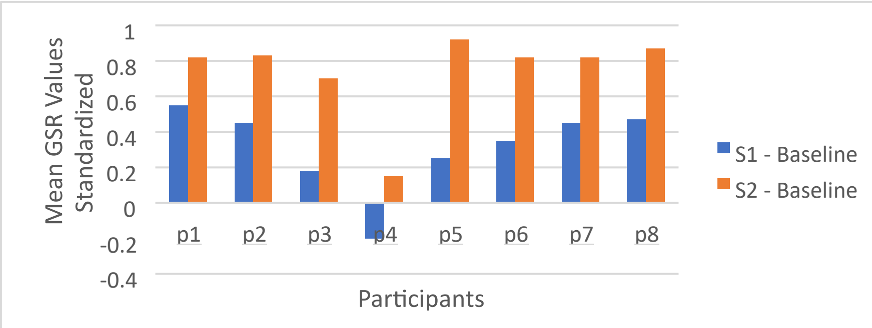

Figure 6. Bar plot of the standardized mean GSR values for S1-baseline and S2-baseline across all participants

3.3.2 *Rows, Columns and Box Strategy*

The Row, Column, and Box strategy adds another layer of scanning by incorporating the examination of 2x2 boxes within the Sudoku grid. As depicted in Figure 10, participants not only scan rows and columns but also focus on specific boxes. They start by examining the 2x2 boxes, using a combination of rows and columns scans to identify potential placements within these smaller grids. The figure shows the sequence of fixations within the boxes, highlighting the participants' methodical examination and deduction process. Once a box is solved, participants apply the same strategy to subsequent boxes, ultimately solving the entire Sudoku grid.

3.4 Analysis of Saccades

The examination of eye-tracking patterns provided valuable insights into visual attention and information processing during Sudoku solving (Krebs et al., 2021). Participants exhibited distinct gaze patterns associated with different problem-solving strategies, as evidenced by variations in fixation durations, saccade velocities, and gaze transitions. While there were variations in gaze behavior across individuals, common patterns emerged, particularly in response to time constraints. Specifically, in Sudoku-1 (S1), the average peak saccade velocity was 119.22°/s with a standard deviation of 118.62°/s, and the average saccade amplitude was 3.585 degrees. In Sudoku-2 (S2), these metrics increased, with an average peak saccade velocity of 146.70°/s and a standard deviation of 145.37°/s, along with an average saccade amplitude of 4.19 degrees.

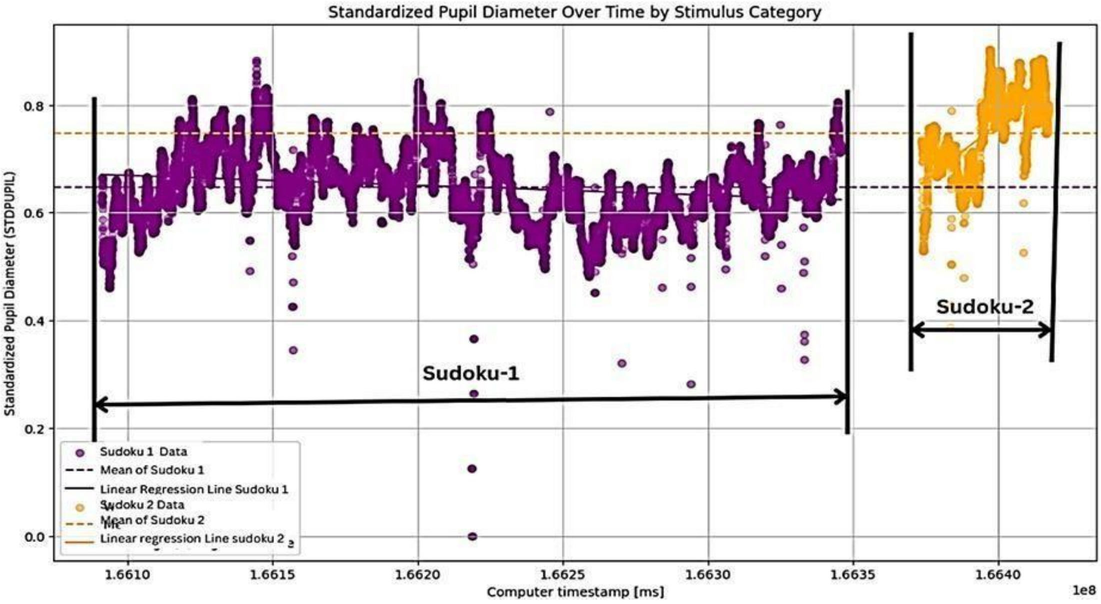

Figure 7. Plot for the mean pupil diameter values (Standardized) for S1 and S2.

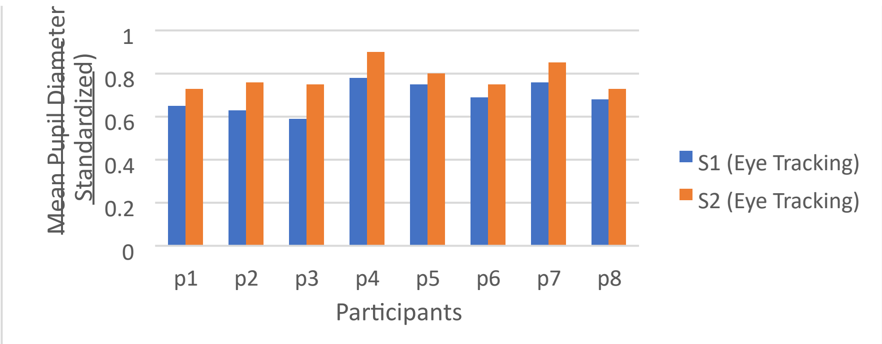

Figure 8. Bar plot for the mean pupil diameter values (Standardized) for S1 and S2

3.5 Analysis of Semi-structured Retrospective Interview

To validate the eye-tracking findings, a semi-structured retrospective interview was conducted with participants. The interviews revealed consistent problem-solving strategies employed by participants during Sudoku solving, irrespective of time constraints (Behrens et al., 2023). The interview analysis corroborated the strategies observed in Figure 9. For instance, Participant 1 stated, "*I was focusing on box and rows and followed the same strategy*," while Participant 6 mentioned, "*I was just looking at numbers and then started solving Rows and Columns. I started applying the same strategy in the time constraint problem.*" Participant 8 similarly noted, "*I started looking at the box and associated rows and columns to fill the box first and applied the same strategy.*" Other participants also reported using the same strategies for both puzzles, suggesting a tendency for individuals to rely on stable problem-solving methods regardless of temporal constraints.

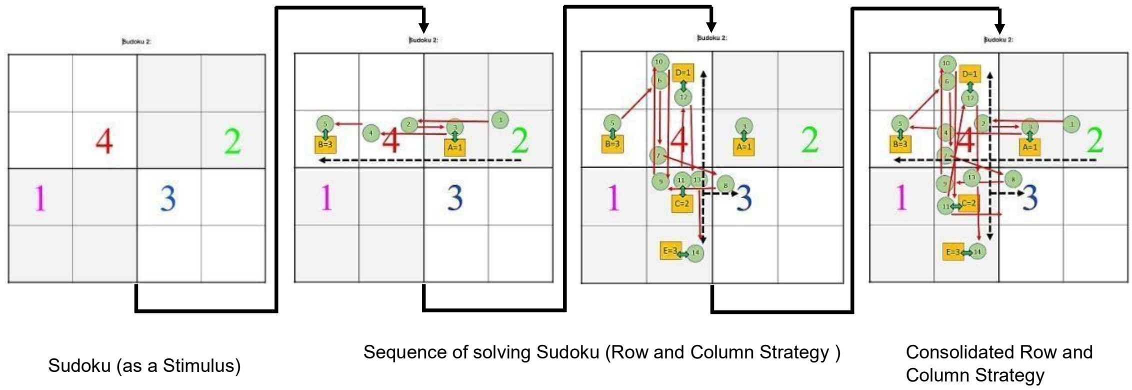

Figure 9. Problem-solving using rows and columns strategy: Participants scan the Sudoku grid by alternating between rows (horizontal arrows (ii)) and columns (vertical arrows (iii)) to identify and place numbers. The arrows indicate the sequence of fixations and saccades, showing a systematic approach to solving the entire grid.

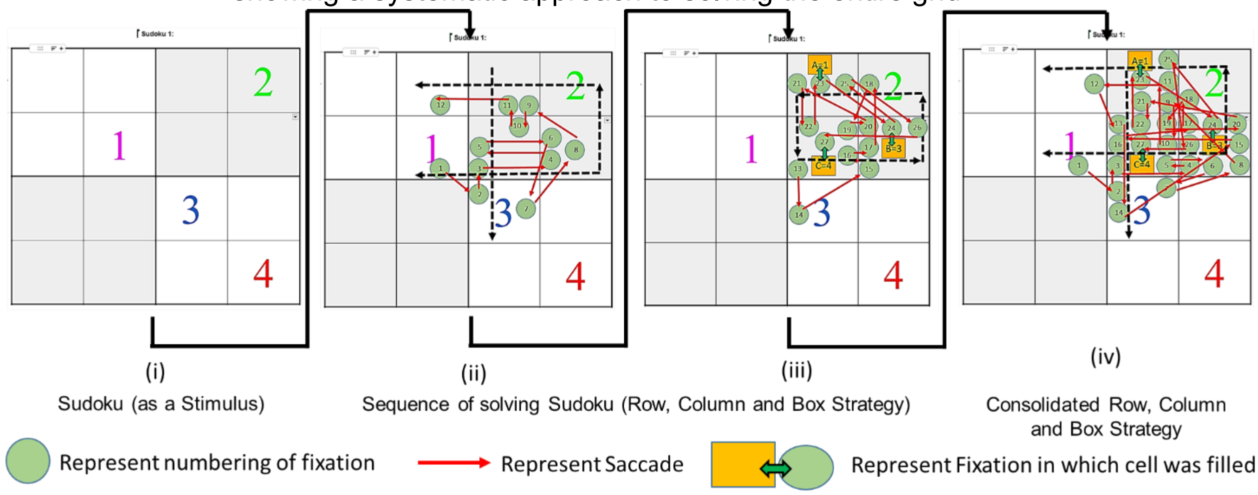

Figure 10. Problem-solving using rows, columns and box strategy: Participants start by scanning rows, and columns (ii), and examining specific 2x2 boxes (iii). Arrows show the sequence of fixations and saccades. Initially, focus on rows and columns associated with a box for deductions. The consolidated strategy (iv) shows solving the entire grid by methodically scanning and solving each 2x2 box and integrating these solutions.

Also, the retrospective interviews revealed notable affective components associated with time constraints during Sudoku puzzle-solving. Participants reported experiencing stress and nervousness due to the imposed time limit. For instance, Participant 1 mentioned, "*As there was a time limit, I was thinking about completing it fast*" reflecting a sense of urgency. Participant 4 remarked, "*Earlier I was thinking, 45 seconds are less to complete it….As time was passing, I was getting stressed and trying to solve it fast*". Similarly, Participant 6 noted, "*Initially I was nervous…then I thought, let's solve it and not think about time*" indicating initial stress followed by an adaptive coping strategy. Similarly, highlights the pressure felt due to the time constraints. These excerpts underscore the heightened stress levels, corroborating the physiological data obtained from GSR measurements. Although each modality, GSR, pupil dilation, gaze pattern, and interviews, was analyzed separately, the convergent findings across these measures support a coherent interpretation of heightened cognitive and emotional responses under time constraints.

4. Discussion

The findings of this study present a multimodal perspective on how time constraints influence cognitive load, stress levels, and problem-solving strategies during Sudoku puzzle-solving (Behrens et al., 2023). Addressing RQ1, the data presented compelling evidence that time constraints exert a significant influence on both cognitive load and stress levels. Pupil diameter measurements, a reliable indicator of cognitive load (Krebs et al., 2021), revealed larger pupil diameters during Sudoku puzzle-solving under time constraints (Sudoku-2) compared to scenarios without time constraints (Sudoku-1). This suggests an increased demand for cognitive resources when participants were under temporal pressure. Concurrently, Galvanic Skin Response (GSR) measurements, known to reflect changes in emotional arousal (stress), exhibited higher mean GSR values in Sudoku-2, indicating heightened stress levels. The robust effect sizes further underscored the profound physiological reactions elicited by temporal constraints, emphasizing the substantial impact of time pressure on the cognitive and affective domains (D'Mello & Graesser, 2011). Although GSR data can be indicative of engagement (McNeal et. al., 2014) or other constructs as well, participants categorically noted increased stress in the time-constrained conditions during the interviews. This work's novelty lies in integrating GSR, eye-tracking, and retrospective interviews within a single study. Unlike prior work examining these modalities separately (e.g., Shakti et al., 2019; Krebs et al., 2021), our triangulated approach enhances validity and offers richer insights into cognitive and affective states under time-constrained problem-solving. Additionally, we feel compelled to note here the importance of multimodal data in coming to such conclusions.

Addressing RQ2(a), participants predominantly followed strategies such as the Rows, Columns, and Box, rows and box, or sequential solving of Rows and Columns. (Simonis, 2005; Patil et al., 2020). Triangulating retrospective interviews with eye-tracking revealed consistent strategy use, with gaze patterns aligning with self-reports and supporting prior work on Sudoku problem solving (Simonis, 2005). This multimodal approach demonstrates how combining qualitative and quantitative data yields deeper insight into cognitive processes. Importantly, it underscores the value of such methods in education: by monitoring indicators like GSR or gaze behavior, instructors can better calibrate task difficulty and timing, keeping learners challenged but not overwhelmed.

Addressing RQ2 (b), the study examined how time constraints influence Sudoku strategies. Interviews and eye-tracking revealed that participants largely relied on established methods, rows, columns, and boxes (Simonis, 2005), regardless of time pressure (Behrens et al., 2023). While core strategies remained stable, eye-tracking showed adaptations under pressure: shorter fixations, faster saccades, and more frequent gaze shifts (Krebs et al., 2021, Paikrao et al., 202). In particular, increased saccade velocity and amplitude in the time-constrained puzzle indicated heightened visual scanning to sustain the same approach within stricter limits. This aligns with findings that time pressure accelerates cognitive processing (Mahanama et al., 2022). Thus, although strategies were not fundamentally altered, participants modulated attention and search speed to manage temporal demands, illustrating adaptive cognitive control under pressure.

The integration of qualitative and quantitative data provides a comprehensive view of the cognitive processes involved in Sudoku problem-solving. The consistency in strategies, as reported by participants and supported by eye-tracking data, reflects the stability of preferred approaches across conditions. While we did not conduct integrated statistical modelling, the convergence of trends in GSR, pupil dilation, and participant reflections strengthens our interpretation. This triangulation underscores the value of a multimodal approach in distinguishing stress from engagement and capturing the complexity of problem-solving behaviour.

5. Conclusion

Our study contributes significantly to the literature by illuminating the effects of time constraints on cognitive and affective processes in task performance. First, we observed that time constraints led to heightened cognitive load and stress during Sudoku solving, as reflected in pupil diameter, GSR data, and participant interviews, aligning with prior research on the effects of temporal pressure on cognition and emotion.

Second, participants maintained consistent problem-solving strategies regardless of time constraints. However, we noted adaptive adjustments in visual attention, evidenced by subtle differences in eye movements. This suggests that individuals dynamically allocate cognitive resources in response to task demands, supporting existing literature on the flexible nature of cognitive processes.

Overall, our findings contribute valuable insights to various domains involving tasks under time pressure. By understanding how individuals respond to temporal constraints, researchers and practitioners can develop interventions to optimize cognitive and emotional regulation in educational, assessment, and decision-making contexts.

6. Limitations and Future Work

This study involved a small sample size, which may limit the range of strategy types and their variability captured, especially in the qualitative data. However, the statistically significant results, despite the limited sample, suggest a strong effect of time constraints. The use of a 4x4 Sudoku grid may also reduce task complexity and affect generalizability to more demanding problem-solving contexts. Nonetheless, the controlled structure allowed us to focus on physiological and strategic consistency. Future studies could explore more complex or open-ended tasks where strategy adaptation is more flexible. Additionally, integrating multimodal data using machine learning or latent modeling approaches could reveal deeper patterns across physiological and behavioral responses under time pressure.

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