The Effects of of Working Memory Capacity on Situation Awareness During Takeover in Human-Machine Co-Driving Systems

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Abstract. This study investigates the influence of working memory capacity on drivers' situation awareness during takeover in a human-machine co-driving environment. Using Prescan, a simulated autonomous highway driving scenario was created, where 26 participants engaged in 25 minutes of autonomous driving and performed takeover in response to sudden incidents. WMC was assessed via the Automated Operation Span Task, while SA was evaluated using the Situation Awareness Global Assessment Technique (SAGAT) combined with eye-tracking technology. Results indicated that participants with high WMC outperformed those with low WMC in SA scores, fixation count, fixation duration percentage, and scanpath length, demonstrating superior visual scanning and environmental perception abilities. These findings provide theoretical support for optimizing takeover mechanisms in autonomous driving systems.

Keywords: Working Memory Capacity; Situation Awareness; Autonomous Driving; Human-Machine Co-Driving

1 Introduction

Human-machine co-driving refers to a stage under partially automated driving conditions where both the driver and the intelligent vehicle control system share control over the autonomous vehicle, meaning decision-making and control authority are jointly held by the human and the machine[1]. In this mode, the driver's role gradually shifts from active control to passive monitoring, requiring rapid takeover of vehicle operation when the autonomous system encounters complex or unexpected situations.

However, this role transition introduces new challenges. Particularly during prolonged monotonous driving, passive monitoring can lead to driver fatigue caused by sustained low stimulation and lack of active engagement, resulting in decreased attention, slowed reactions, and delayed responses when takeover is required[2]. Körber et al.[3] found in simulated autonomous driving experiments that drivers begin to exhibit signs of passive fatigue, including declines in attention and reaction ability, after about 20 minutes of continuous autonomous driving.

Working memory capacity (WMC) varies considerably among individuals, typical-

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ly ranging from about 3 to 4 items[4]. Situation awareness (SA) is defined as an individual's ability to perceive environmental elements within a specific spatial-temporal context, comprehend their meaning, and predict future states, structured in a three-level cognitive model including perception, comprehension, and projection[5]. Individuals with higher WMC generally manage complex tasks better, maintain higher SA, and respond more quickly and accurately in unexpected situations. Conversely, those with lower WMC are more susceptible to cognitive overload[6]. For instance, higher WMC has been associated with more efficient monitoring of multiple dynamic elements in the driving environment, which is critical for timely and accurate takeovers in semi-autonomous vehicles.

Investigating the influence of WMC on SA in human-machine co-driving is meaningful. A deeper understanding of the relationship between WMC and SA can provide theoretical support for optimizing human-machine interaction design in autonomous driving technology, thereby improving system safety and emergency responsiveness.

2 Experimental Design

2.1 Experimental Equipment and Participant Recruitment

The experiment utilized Prescan software to generate autonomous driving and hazard scenarios. WMC was measured using E-prime, and eye movement data were collected with a Tobii Nano 60Hz portable eye tracker. A total of 26 licensed drivers participated in the study. Since WMC typically peaks after age 20 and may slightly decline with age[7], this study selected participants within a narrow age range of 23 to 28 years (mean age 25.6) to minimize age-related variability and ensure sample homogeneity. Participants' driving experience ranged from 2 to 5 years, with an average of 3.4 years.

2.2 Measurement of Working Memory Capacity

This study used the Automated Operation Span Task (AOSPAN) by Unsworth et al.[8] to measure working memory capacity. The task automates the traditional version, making it simpler and reducing experimenter involvement, with good reliability ($\alpha = 0.78$, $r = 0.83$). Participants remember unrelated letters while solving simple math problems, then recall the letters in order. Each trial shows a math question (e.g., "(1×2)+1=?") which participants quickly judge as correct or not. After each math problem, a letter appears for 800 ms to memorize. During recall, participants select the letters in order from a letter matrix. The program sets a personalized time limit for math based on practice times plus 2.5 standard deviations to avoid over-rehearsal. The test has training and formal sessions; training includes separate practice of letters and math, then combined practice before the formal test. This task assesses the capacity to temporarily store and manipulate information under dual-task conditions, reflecting core aspects of working memory.

2.3 Human-Machine Co-Driving Experimental Design

This study simulated a monotonous autonomous driving environment on a six-lane bidirectional highway, with simple and repetitive roadside scenery to create visual monotony. Traffic flow was limited, vehicle spacing was large, and speeds were steady to avoid complex traffic and frequent lane changes, thereby reducing driver active involvement and promoting passive monitoring. Based on Körber et al.'s theory, a 25-minute autonomous driving task without non-driving-related tasks (NDRTs) was designed, during which drivers only monitored the system to simulate monotony and fatigue experienced in daily driving. At the 25th minute, a sudden, random traffic accident occurred, with two vehicles colliding ahead, triggering an alarm and requiring the driver to take over immediately. The unpredictable nature of the event ensured effective evaluation of driver performance under passive fatigue.

2.4 SAGAT

The Situation Awareness Global Assessment Technique (SAGAT) is a widely used tool that evaluates situation awareness by pausing a simulated driving task and asking participants about their perception of the current environment[9]. In this experiment, the simulation was paused 5 seconds after a sudden event and takeover request. Three levels of questions were designed based on the accident scenario:SA Level 1 assessed perception of environmental elements, requiring participants to identify surrounding vehicles and obstacles in a blank driving scene;SA Level 2 evaluated understanding of dynamic relationships between elements, such as predicting the behavior of other vehicles;SA Level 3 measured prediction of future situations, including environmental developments and potential risks.

3 Data Processing and Statistical Analysis

3.1 Working Memory Capacity

In the formal test, the Automated Operation Span Task had a maximum score of 75 points. Test results were considered valid only if the participant's math accuracy was at least 85%. One participant was excluded due to a math accuracy below 85%, which did not meet the task requirements. The overall data showed a mean score of 54.72, close to the 55.25 reported by Unsworth et al., with a standard deviation of 7.79, a maximum score of 70, and a minimum score of 42. The Shapiro-Wilk normality test yielded a statistic of 0.925, indicating the data followed a normal distribution ($p = 0.066 > 0.05$). Based on Song et al.[10], participants were divided into high and low working memory capacity groups using the median (50%) as the cutoff.

3.2 SAGAT Scores

The overall data had a mean of 43.72, standard deviation of 7.91, maximum of 61.54, and minimum of 30.77. The data conformed to a normal distribution ($p = 0.098 >$

0.05). Figure 1 shows that the high WMC group scored higher on the SAGAT than the low WMC group. Normality tests indicated that the SAGAT scores of the low WMC group did not follow a normal distribution (p = 0.034), while those of the high WMC group were approximately normal (p = 0.051). Therefore, the Mann-Whitney U test was applied, revealing a significant difference between groups (U = 35.0, p = 0.014), with the high WMC group scoring significantly higher. This suggests that drivers with higher WMC perform better on situation awareness tasks, effectively acquiring and processing situational information.

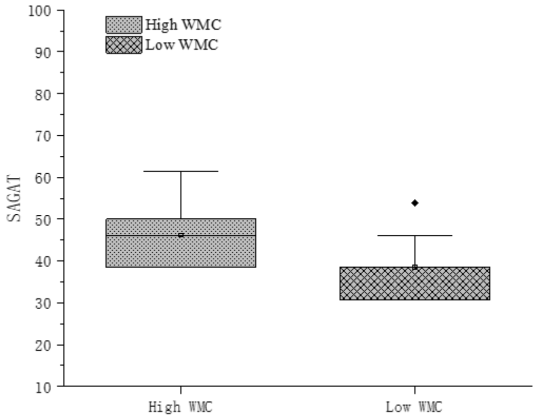

Fig. 1. Analysis of the difference in SA scores among subjects

3.3 Eye Movement Feature Analysis

Eye-tracking equipment collected various eye movement data. Areas of Interest (AOIs) were chosen during the takeover request phase. Because the experiment was dynamic, AOIs changed in size and position, so each frame was labeled separately. The AOIs focused on vehicles and road signs directly ahead of the participant's car. To keep data consistent, eye movement data for the passive fatigue group were collected during the last 20 minutes, matching the non-fatigue group's timing. Zhang et al.[11] showed that fixation count, fixation duration percentage, and scanpath length reflect drivers' situation awareness. These three measures were used to evaluate participants' situation awareness in this study.

(1) AOI Fixation Count

In the raw eye-tracking data, a fixation is when the eye stays on a target for over 100 milliseconds. Fixation count means how many times participants looked at Areas of Interest (AOIs) from the takeover request until the driving session ended. Figure 2 shows fixation counts for different WMC groups, with higher WMC linked to more fixations. Normality tests showed low WMC data were normal (p = 0.136), but high WMC data were not (p = 0.010). So, a Mann-Whitney U test was used and found the high WMC group had significantly more fixations than the low WMC group (U = 16.5, p = 0.00071). This means WMC affects how often drivers look at key areas, helping them better see and process driving information.

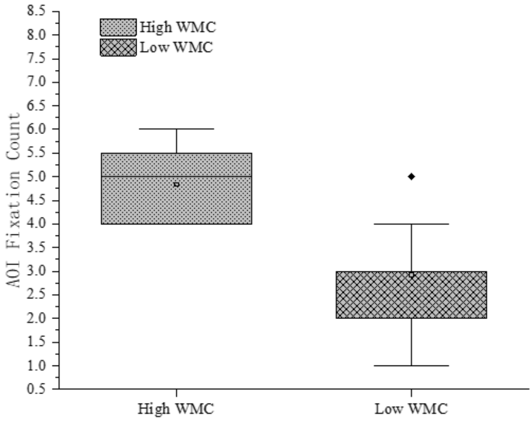

Fig. 2. Analysis of fixation count differences among subjects

(2) Fixation Duration Percentage on AOIs

Due to a traffic accident blocking the middle lane ahead, the Areas of Interest (AOIs) covered the front three lanes. Figure 3 compares fixation duration percentages on AOIs between high and low WMC groups. Tests confirmed data suitability ($p > 0.05$). A t-test showed a significant difference ($t = -2.385$, $p = 0.026$), with the high WMC group having higher fixation durations than the low WMC group. This indicates that higher WMC participants focus more on key areas while driving, helping them better process environmental information and improve situation awareness.

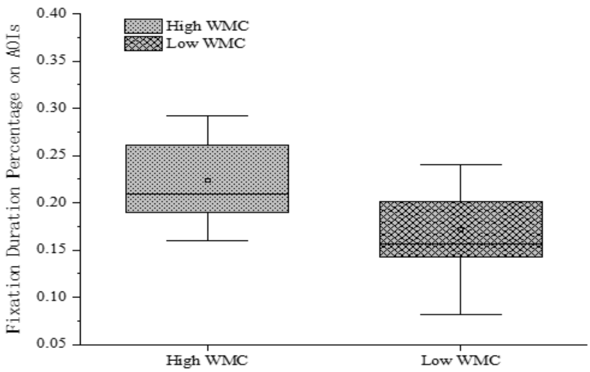

Fig. 3. Analysis of the difference in % time spent in AOIs among subjects

(3) Scanpath Length

A scanpath is the quick eye movement between two fixations, and scanpath length is the distance between these points. Figure 4 compares scanpath lengths between high and low WMC groups. Tests confirmed the data met analysis requirements ($p > 0.05$). Results showed the high WMC group had significantly longer scanpaths than the low WMC group ($t = -2.120$, $p = 0.045$), suggesting they scan the environment more broadly, which may improve their situation awareness.

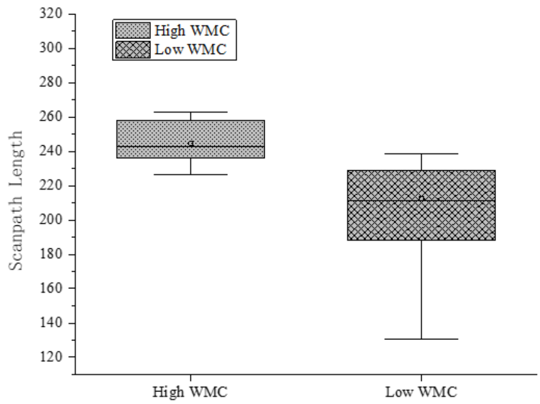

Fig. 4. Analysis of the difference in scanpath length among subjects

4 Discussion

This study examined how WMC affects SA and eye movement during autonomous driving. Results showed WMC significantly impacted SA scores, fixation count, fixation duration, and scanpath length. Drivers with high WMC scored higher on the SAGAT test, meaning they could focus better, gather more information, and react faster during takeovers. This agrees with Sohn et al.[12], who found that high WMC helps maintain attention and process information well in tough tasks.

High WMC drivers also had more fixations, showing they scanned the scene more often. More fixations mean better attention, matching their higher SA scores. Zhang et al. showed that more fixations and longer fixations in key areas (AOIs) relate to better SA. In this study, high WMC drivers spent more time looking at important areas. They not only looked more often but also longer, helping them notice changes and prepare for takeovers.

High WMC drivers had longer scanpaths, meaning they looked around a wider area. Liang et al.[13] found no link between scanpath length and thinking state, but here longer scanpaths showed better gathering and understanding of information. High WMC drivers cover more of the scene visually, which helps them stay aware and respond better in complex situations.

5 Conclusions

Driver WMC significantly affects situation awareness in autonomous driving. Higher WMC improves drivers' ability to process environmental information, enhancing their situation awareness.

During sudden traffic accidents, drivers with high WMC show stronger visual scanning abilities. They perform significantly better than low WMC drivers in fixation count, fixation duration percentage, and scanpath length, indicating more efficient allocation of visual attention and better monitoring and processing of environmental information.

These findings provide theoretical support for optimizing driver takeover mechanisms in autonomous driving systems. Improving drivers' WMC can enhance their situation awareness and decision-making in critical moments, thereby improving the safety and reliability of autonomous driving.

In addition, adaptive driver assistance systems that dynamically adjust alert timing and information complexity based on individual WMC levels may help mitigate cognitive overload and improve takeover performance.

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