Driver-Vehicle Interaction: The Effects of Physical Exercise and Takeover Request Modality on Automated Vehicle Takeover Performance between Younger and Older Drivers

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***Abstract*— Semi-autonomous vehicles still require manual takeover intervention. For older drivers, age-related declines may make takeover transitions difficult, but the current literature on takeover and aging is mixed. Non-chronological age factors, such as engagement in physical exercise, which has been shown to mitigate perceptual and cognitive declines, may be contributing to these conflicting results. The goal of this pilot study was to examine whether age, physical exercise, and takeover request alert modality influence post-takeover performance. Sixteen younger and older adults were divided into exercise and non-exercise groups, and completed takeover tasks with seven different types of takeover requests. Overall, older adults in the physical exercise group had shorter decision-making times and lower maximum resulting jerk, compared to seniors in the non-exercise group. Takeover request type did not influence takeover performance. Findings may contribute to theories on aging and inform the development of next-generation automated vehicle systems.**

Keywords—aging; automated driving; multimodal display; non-chronological age; human-machine interface

I. Introduction

Adults aged 65 years or older have become the fastest-growing age group [1]. The proportion of older adults is expected to reach 16% of the global population by 2050, compared to only 9.3% in 2020 [1]. Aging often raises concerns about how the performance of daily tasks, such as driving, may be impacted. This is because, in general, perceptual declines, such as decreased visual acuity, can limit older drivers' ability to distinguish surrounding vehicles, especially during the night time. Also, cognitive declines, such as slower information processing speeds, may inhibit the ability to make timely decisions. Finally, physical declines, such as diminished movement control, can reduce how precisely vehicle maneuvers are made [2].

These age-related changes may still have negative consequences for interactions with automated vehicles, given that these semi-autonomous vehicles will occasionally require drivers to resume control of the vehicle under certain circumstances (e.g., entering construction zones, experiencing extreme weather conditions) [3]. As shown in Fig. 1, the takeover process, which consists of a signal response and post-takeover phase, significantly utilizes perceptual, cognitive, and physical resources in order to 1) perceive and process takeover requests that are presented in any combination of visual, auditory, and/or tactile forms (also known as multimodal displays [4]); 2) regain environment/situation awareness and, decide and execute the appropriate maneuvering plans. Thus, older adults may have more difficulties with this complex process.

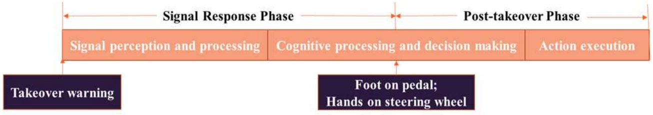

Fig. 1. The vehicle takeover process (adapted from [5], [6])

However, the rate of decline of perceptual, cognitive, and physical abilities are often not homogeneous across individuals (e.g., [7]). In other words, chronological age, or the number of years of life, may not be the best predictor of task performance for older populations. In fact, the few studies that have investigated chronological age and takeover performance have found conflicting results in both the signal response and post-takeover phases [8]–[12]. For example, for the signal response phase, [10] found that older adults had longer response times compared to younger adults, but no age differences were found in [8] nor [9]. Similarly, in the post-takeover phase, older adults had larger maximum lateral and longitudinal accelerations in [8], but maximum lateral acceleration was not found to be different in [9]. It is possible that non-chronological age factors, which reflect differences in cognitive and physical abilities, may be contributing to these conflicting results.

The aging literature provides evidence that non-chronological age factors may mitigate age-related declines [13]. Most notably, engaging in aerobic physical exercises, such as jogging or swimming, has been found to be positively correlated with better executive function, perceptual and processing speeds, attention, and motor control (see a review, [19]). However, the benefits of physical exercise have mainly been reported for simple cognitive tests, such as the Mini-mental state exam [15]. Thus, it is unclear whether this positive effect can be observed in more complex tasks, such as during automated vehicle takeovers.

Recent studies examined the impacts of engagement in physical exercise on the perception of semi-autonomous vehicle takeover requests during the signal response phase between younger and older adults [16], [17]. In response to seven different types of takeover requests (visual, auditory, and tactile, visual-auditory, visual-tactile, auditory-tactile, and visual-auditory-tactile), older adults had longer response times compared to younger adults and engagement in physical exercise was not found to benefit signal perception. The

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authors did not measure takeover performance, but explained that the benefits of engagement in physical activity are more likely to appear in post-takeover performance because this phase involves decision-making components, such as deciding the appropriate course of action, as well as the utilization of physical resources to manually execute the planned maneuver.

Therefore, the goal of this study was to serve as a follow-up pilot study to that of [16] and quantify the effects of age, engagement in physical exercise, and takeover request alert modality on post-takeover driving performance. We expected that, while age-related differences may exist, engagement in physical exercise and multimodal warning signal (compared to unimodal) would be associated with better post-takeover quality [3], [8].

II. Methods

A. Participants

A total of 16 participants were recruited for this pilot study, with eight younger and eight olde adults. Younger adults (mean age: 24.5) were students recruited from Purdue University, while older adults (mean age: 73.1) were healthy residents of the Lafayette/West Lafayette, Indiana area. Based on the score of the Godin Leisure-Time Exercise Questionnaire [18], which quantifies both frequencies and intensities of weekly aerobic exercises, participants were categorized into exercise and non-exercise groups. To qualify for the exercise group, volunteers were required to have a score of 24 or more on this assessment (identified as the active group in [18]), while non-exercise group members only needed a score 14 or less (marked as the sedentary group). Additional eligibility requirements included: 1) possession a valid U.S. driver's license; 2) no sensory or cognitive impairments; and 3) normal or correct-to-normal vision. All participants were paid $30/hour for their time. The study was approved by the Purdue University Institutional Review Board (IRB Protocol ID: 1802020214).

B. Apparatus/Stimulus

Driving simulator: A National Advanced Driving Simulator (NADS), simplified cab miniSim, was used to conduct this study. The driving simulator is equipped with three 48-inch monitors, which displays the main driving scene, and one 18.5-inch, which serves as the vehicle dashboard display. This system also includes, a steering wheel and associated driving foot pedals, an adjustable seat, and a control panel (see Fig. 2). Driving data was collected at 60 Hz.

Takeover requests: Takeover requests (TOR) were presented as visual, auditory, and/or tactile stimuli. As shown in Fig. 2, the visual cue (V) was a 200 × 200 pixels red dot presented on the center main display. The auditory cue (A) was a 0-100 dB 6-burst, 400 Hz beep. The tactile cue (T) was vibrations presented using two C-2 tactors developed by Engineering Acoustics, Inc, with an intensity range of 30-48 dB. Tactors were attached to a belt placed on participants' lower back center area (see Fig. 2). The intensities of both the auditory and tactile cues were selected by participants through a crossmodal matching task (see details in [28]), using the visual cue as the reference stimulus. All takeover requests lasted for 1 second.

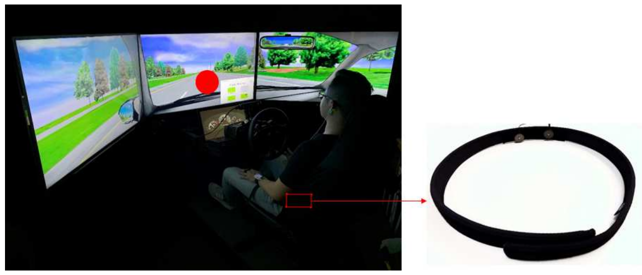

Fig. 2. Experimental devices and setup (featured: miniSim (left) and C-2 Tactors (right))

C. Experimental Design

The study employed a 2 (age group: younger and older) × 2 (exercise type: exercise and non-exercise) × 7 (TOR signal type: V, A, T, VA, VT, AT, and VAT) full factorial design. During the experiment, participants rode in a simulated SAE Level 3 automated vehicle in the center lane of a three-lane highway. The traveling speed of the vehicle was 60 mph. The subject vehicle was followed by two fleets of vehicles in both left and right adjacent lanes with an equal distance from the subject vehicle. At the same time, a leading vehicle was randomly 4 and 7 seconds (or 352 and 616 feet, respectively) ahead of the subject vehicle. A construction zone occasionally appeared in the center lane, but its view was obstructed by the leading vehicle. In this case, the leading vehicle immediately stopped in front of the construction zone. The subject vehicle would then issue a takeover request. Once participants perceived and processed this TOR, they were instructed to first tap the brake pedal to deactivate the automation, then control the vehicle as they would in manual driving. During the time, the two fleets of vehicles in both adjacent lanes had then changed their headway and were at different distances with respect to the subject vehicle (see Fig. 3 for example takeover scenario, where the left fleet was at 88 feet away from the subject vehicle and the right fleet was 264 feet away, representing a trailing headway of one second and three seconds, respectively). To avoid both a rear-end collision and a collision with the leading vehicle, drivers needed to determine which lane to move into by scanning the environment using the side-view and rear mirrors, and deciding which of the two adjacent lanes had the most available space. Once participants changed to an adjacent lane, they were asked to remain in that lane at a speed of 60 mph until they passed the construction zone, and then move back to the center lane and reactivate the automation. They were also informed that their handling of the vehicle during the takeover process was being monitored. Given that there were seven different types of TOR alerts, each participant completed a total 28 takeover events (e.g., [11]), separated by an average 2-minute time interval. Each TOR was randomly presented in four similar driving blocks (i.e., 7 takeovers per block). Participants were given 5-minute breaks between blocks.

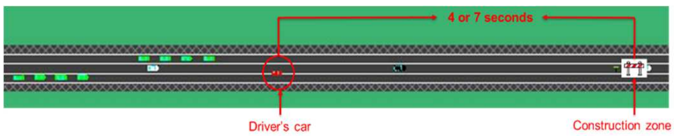

Fig. 3. Example of one takeover scenario

D. Procedure

Participants were first asked to sign the consent form, then fill out a pre-experiment questionnaire that queried demographic information and their engagement in daily activities (i.e., physical exercise and driving experience). Afterwards, they performed the crossmodal matching task and a 15-minute training session to become familiar with experiment equipment and takeover procedures. During the experiment, participants were required to place their hands in their laps and feet on the base of the driving simulator until they were presented with a takeover request. To divert participants' attention away from the road (to avoid being prepared for a takeover event in advance), they were also required to play a game located in the right-hand corner of the main screen. The game required participants to select, from multiple-choice options, the one item that was different from the other three, in terms of the color and locations of different shapes, and the spelling of words. This task was representative of drivers being engaged in a non-driving related task.

E. Dependent Measures

Decision-making time: Decision-making time (in milliseconds (ms)) was measured as the time between when participants deactivated the automation and the first steering input made towards an adjacent lane.

Maximum resulting jerk: Maximum resulting jerk (in m/s^3), the maximum time rate of change of longitudinal and lateral accelerations, is an indicator of post-takeover quality, such as shift quality and ride comfort [20]. A smaller value represents better vehicle control and higher takeover quality.

F. Data Analysis

A linear mixed-effects model was used to compare the effects of age and exercise type (between-subject factors), and TOR signal type (within-subject factor) on the two dependent measures. The significance level was set at $p < 0.05$.

III. Results

A. Decision-Making Time

Decision-making time was not significantly affected by age (F (1, 260) = 2.220, p = 0.138, partial η^2 = 0.001), exercise type (F (1, 260) = 0.005, p = 0.942, partial $\eta^2 < 0.001$), nor TOR signal type (F (6, 260) = 1.977, p = 0.069, partial η^2 = 0.040). However, there was a significant age × exercise type interaction effect (F (1, 260) = 21.752, $p < 0.001$, partial η^2 = 0.080). As shown in Fig. 4, the mean differences in decision-making times between older (mean = 2088.03 ms, standard error of mean (SEM) = 256.68) and younger (mean = 1548.81, SEM = 266.55) adults was larger in the non-exercise group compared to the exercise group (older adults: mean = 1995.98 ms, SEM = 256.09; younger adults: mean = 1794.44 ms, SEM = 187.84).

B. Maximum Resulting Jerk

Age had a significant main effect on maximum resulting jerk (F (1, 260) = 40.792, $p < 0.001$, partial η^2 = 0.140), Fig. 5. Specifically, older adults had a higher maximum resulting jerk (mean = 72.44 m/s^3, SEM = 9.62) compared to younger adults (mean = 64.45 m/s^3, SEM = 8.95). There was also a significant interaction effect between age and exercise type (F (1, 260) = 12.844, $p < 0.001$, partial η^2 = 0.050) (see Fig. 5). Here, older adults tended to have a higher maximum resulting jerk (mean = 77.65 m/s^3, SEM = 12.42) than younger adults (mean = 66.26 m/s^3, SEM = 10.01), but only in the non-exercise group. No significant main effect of TOR signal type on maximum resulting jerk (F (6, 260) = 0.225, p = 0.968, partial η^2 = 0.001) was found.

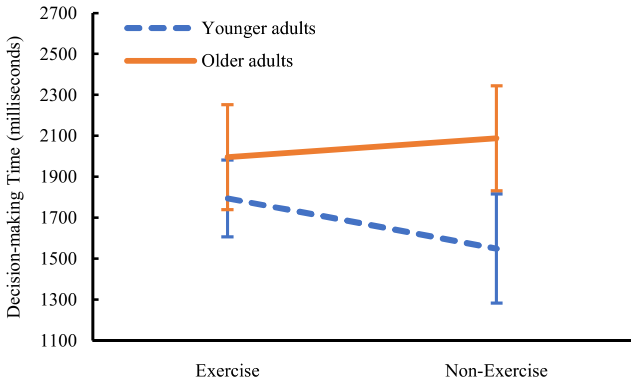

Fig. 4. Interaction effect for age and exercise type on decision-making time

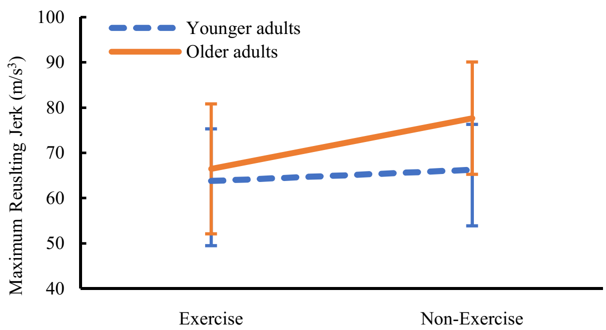

Fig. 5. Interaction effect for age and exercise type on maximum resulting jerk

IV. Discussion

This goal of this study was to collect pilot data regarding the effects of age, engagement in physical exercise, and takeover request signal type on task performance in the post-takeover phase. Preliminary results indicate that older adults had a higher maximum resulting jerk compared to younger adults. However, the differences in decision-making time and maximum resulting jerk were narrower for the exercise group (compared to the non-exercise group) between the younger and older groups. Finally, takeover request (TOR) signal type did not result in performance differences.

Even though age and engagement in physical exercise alone did not significantly affect the decision-making time, an interaction effect was found between age and engagement in physical exercise. Specifically, the difference in decision-making time between the two age groups was smaller for the exercise group compared to the non-exercise group. One possible explanation for this finding is that the benefits of physical exercise on decision-making may be more predominant in, and beneficial to, older populations. Decision-making in the takeover process requires significant utilization of many cognitive resources, e.g., information processing, working memory, and divided and sustained attention, within a short period of time (e.g., [21]). As suggested by previous research, the decline of these cognitive components may be mitigated by continued engagement in physical exercise [22], [23] and these benefits appear to be manifesting in our study. In addition, these preliminary results indicate that the benefits of physical activity also apply to more complex tasks, not just to simple cognitive tests.

With respect to takeover quality, older adults had a higher maximum resulting jerk during the manual control of the vehicle compared to younger adults, indicating a poorer takeover quality. This finding is consistent with prior chronological age studies that report that older adults may experience declines in psychomotor abilities, such as hand-eye coordination and motor control (e.g., [24]), due to biological changes that occur with age. However, similar to the results for decision-making time, there was also a significant interaction between age and engagement in physical exercise for maximum resulting jerk. In particular, the difference in maximum resulting jerk between the two age groups was larger for the non-exercise group than for the exercise group. This finding provides even more evidence that older adults who engage in active physical exercise may retain or improve their psychomotor abilities, which could be advantageous for the performance on both simple and complex tasks. Overall, the decision-making time and maximum resulting jerk findings further highlight the importance of considering non-chronological age factors in human-automation interaction research and could aid in developing theories regarding successful aging [7].

Finally, in contrast to previous studies that examined the effects of signal type on response/takeover times in only the signal response phase (e.g., [25]), the current study extended the measurement range to include the decision-making and manual driving stages. Contrary to our expectations, no significant main nor interaction effects of TOR signal type on decision-making time and maximum resulting jerk were found. One possible explanation could be that since the length of the warning signal was 1 second, its influence may have not lasted throughout the duration of post-takeover phase in order to affect decision-making and vehicle maneuver. However, more research is needed to confirm this hypothesis.

Limitations of the study

Given that this is a pilot study, a larger sample size will be achieved in a future follow-up study and thus results should be interpreted with caution. In our study, we only used one type of takeover scenario – entering a construction zone. Future work should also include other more likely events that will require takeover, such as missing lane markers, difficulty visibility conditions, and/or high traffic volume. Additionally, our study employed only abstract TOR signals, but it will be important to also investigate other types of non-abstract alerts, e.g., speech-based.

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