Assessing the Impact of Cognitive Training on Driving Performance: Insights from a Pilot Study

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Abstract

Driving is a complex task necessitating an intricate interplay of sensory, motor, and cognitive abilities. Extensive research has underscored the role of neurocognitive functions, including attention, memory, executive functions, and visuospatial skills, in driving safety and performance. Despite evidence suggesting cognitive training's potential in enhancing driving abilities, comprehensive cognitive training's impact on driving performance in young adult drivers remains unexplored. Our study aimed to fill this gap by implementing an intensive, 8-week, multidomain computerized cognitive training program and assessing its transfer effects on the driving performance of young adult drivers, using a high-fidelity simulator. The study employed a randomized controlled trial design, with passive control group. The mixed-design analysis of variance (ANOVA) revealed a notable interaction between the time of testing and the respective participant groups concerning driving performance. Post hoc analyses showed that, compared to the control group, participants undergoing cognitive training demonstrated significantly fewer traffic infractions in the post-training evaluation. These findings suggest that cognitive training could be a useful tool for enhancing driving safety and performance in young adult drivers. Further research should aim to address the limitations posed by the absence of an active control group.

Keywords: cognitive training, driving performance, neurocognitive functions, CogniFit, young drivers, driving safety.

1. Introduction

Operating a motor vehicle is a multifaceted activity that places extensive demands on sensory, motor, and cognitive skills (Cuenen et al., 2016; Ettenhofer et al., 2019). It requires the simultaneous integration and coordination of visual, proprioceptive, vestibular, and auditory information to navigate the vehicle successfully (Markkula et al., 2019; Navarro et al., 2018; Wei & Agrawal, 2017; Wolfe et al., 2022). Moreover, drivers must maintain heightened situational awareness, promptly perceiving and responding to dynamic environmental stimuli, execute adept movements, and make rapid decisions under time constraints (Ghawami, Shoaa, et al., 2022; Mäntylä et al., 2009; Stanton et al., 2001). Given these requirements, it is hardly surprising that driving is susceptible to human error.

Most scholars concur that human error may account for up to 90% of traffic accidents (Dingus et al., 2016), with attention deficits specifically being the cause of about 50% of injury-related incidents (Pépin et al., 2017). As a result, several studies have undeniably revealed that specific cognitive domains are crucial for enabling safe driving performance (Anstey et al., 2005). These domains, ranging from attention and memory to visuospatial skills and executive functions, are interlinked with the brain's complex architecture. For instance, attention allows drivers to continuously monitor the road, quickly detect hazards, avoid distractions, and has been shown to correlate with driving performance metrics such as lane keeping and hazard detection times (Khan et al., 2018; Peng et al., 2021; Ross et al., 2014; Uc et al., 2006; Yi et al., 2015). Memory supports learning and retrieving driving knowledge, recognizing routes, and recalling traffic rules (Scott et al., 2023), and serves as a strong predictor of driving performance in young drivers during challenging situations (Tapia & Duñabeitia, 2023). Visuospatial skills allow drivers to judge vehicle position and movement, estimate distances, and navigate effectively (Khan et al., 2018). Lastly, executive functions, including problem-solving, planning, and impulse control are necessary for making quick, appropriate decisions on the road (Ghawami, Okhovvat, et al., 2022; Ghawami, Shoaa, et al., 2022; Mäntylä et al., 2009).

Research on brain interconnectivity provides insight into the relationship between cognitive domains and their influence on driving. Neuroimaging studies demonstrate that driving consistently activates various brain areas involved in sensory, motor, and associative functions (Bostan & Strick, 2010; Freedman & Ibos, 2018; Hintzen et al., 2018; Milardi et al., 2019; Navarro et al., 2018; Nelson & Kreitzer, 2014; Ohata et al., 2022; Yuan et al., 2016). These areas are instrumental in processes such as motor coordination, visual interpretation, and cognitive control. Navarro’s team (2018) associated these neural activation patterns to the Michon´s (1985) framework that differentiates strategic, tactical, and operational driving control. Strategic control, involving high-level route planning and risk assessment, activates planning-related regions of the brain. Tactical control, which includes decisions on maneuvering such as lane changes and turning, engages visual processing areas. Lastly, operational control, which covers the second-to-second handling of the vehicle, including steering and braking, relies on areas crucial for sensorimotor control.

Bridging cognitive science with applied research, an expanding body of studies investigates the impact of targeted cognitive training programs, which involves standardized task practice, on driving skills like attention, memory, and processing speed in various populations, showing promising results (Nouchi et al., 2019). For instance, Nozawa et al. (2015) conducted a study to explore the effects of three different types of cognitive training on the cognitive function, brain structure, and driving safety of elderly daily drivers. The study revealed that onboard cognitive training notably enhanced processing speed, working memory, and driving safety among the elderly. In a similar vein, Nouchi et al. (2019) assessed a 6-week TV-based cognitive training program's effects on driving skills, cognitive functions, and emotional states in older people. Contrasted with the active control group, participants in the cognitive training group exhibited noteworthy advancements in driving skills and cognitive functions like processing speed and inhibition.

However, the youth demographic presents a different set of challenges. Walshe et al. (2017) highlighted that vehicular crashes are alarmingly high among adolescents, primarily attributed to the ongoing development of their executive functions. This developmental phase means that teens display notable shortcomings compared to their seasoned counterparts in essential areas such as hazard anticipation, hazard mitigation, attention maintenance, self-awareness, and vehicular control (Fisher et al., 2017). In light of these challenges, numerous training programs have been developed to target these specific gaps. While the potential of cognitive training to improve driving skills is undeniable, much of the early research was centered on the elderly population. Yet, in recent decades, studies focusing on novice drivers has proliferated.

These targeted training programs, which aim to address the vulnerability of newly licensed adolescents on the road, not only enhance cognitive skills in controlled evaluations but also demonstrate promising translations to tangible reductions in real-life crashes. To illustrate, hazard anticipation programs employing videos, simulators, and computer software are structured to instruct teens on swiftly identifying concealed dangers. A PC-based initiative, dubbed Risk Awareness and Perception Training (RAPT), significantly honed teens' anticipation skills, as validated by driving simulators and on-road evaluations (Taylor et al., 2011). Impressively, a mere 17 minutes spent on hazard perception training reduced crash incidences by 32-43% among 16–18-year-old males, as evidenced in a randomized controlled trial involving 5000 participants (Thomas et al., 2016). On another front, hazard mitigation training centers on aptly handling imminent dangers, leveraging tactics such as speed adjustments or braking. For instance, training that emphasizes speed modulation within simulators has been found to curb reckless acceleration behaviors, simultaneously bolstering the headway conservation among teens (Muttart, 2013). In tandem with anticipation training, mitigation initiatives amplify the proficiency in hazard response, both on the road and within simulator settings (Isler et al., 2011). Other training modules, like Focused Attention and Concentration Learning (FOCAL), specifically target attention maintenance, thereby cultivating focus, vigilance, and a resistance to diversions. Post such PC-based sessions, adolescents registered fewer prolonged off-road gazes for up to three months during simulator-based driving assessments (Pradhan et al., 2009). Moreover, this brand of attention training was linked with a downturn in self-reported crashes, especially among teens grappling with ADHD (Epstein et al., 2022). Self-awareness training modules cater to the prevalent overconfidence syndrome seen in fledgling drivers. Programs honing resilience have proven to sharpen insights into one's motivations and behavioral patterns. Remarkably, an initiative pivoting on risk-awareness managed to reduce novice-related crashes by a significant 44% (Senserrick et al., 2009). Techniques such as commentary driving further polish insights into potential hazard situations (McKenna et al., 2006). On the terminal end, training that focuses on foundational control skills, such as speed modulation and lane adherence, rectifies the specific weak spots often witnessed in novice drivers, enhancing these elemental driving competencies (Isler et al., 2011).

Despite the inherent interconnectedness of cognitive domains while driving, a significant portion of prior research has predominantly centered on isolated cognitive constructs such as attention or hazard perception, bypassing the broader neurological interplay integral to the driving experience. Although the results from various interventions are suggestive, we still face challenges in bringing together individual interventions into a unified training framework that provides comprehensive benefits for driving skills. Furthermore, it is important to highlight that while there is a consensus that cognitive training often results in near transfer (improvements in tasks similar to those trained), some meta-analyses suggest limited evidence for far transfer (improvements in untrained tasks, typically related to daily life activities) (Nguyen et al., 2022). This inconsistency may be attributed to the significant variability in methodology and design, as well as the diversity of the study populations. In this regard, a second-order metanalysis suggests that younger populations might experience greater benefits from cognitive training (Sala et al., 2019). Additionally, the meta-analysis by Basak et al., (2020) of randomized controlled trials showed that multicomponent cognitive training programs have greater effects compared to single-component training programs.

To address these gaps, the present pilot study aims to establish an intensive 8-week multidomain cognitive training regimen tailored for young adult drivers. To ascertain the efficacy of the training, driving metrics will be assessed in a high-fidelity simulator both before and after the training session, providing a robust platform to gauge the training's transfer effects. Comparative outcomes will be drawn between a cohort subjected to the cognitive training and a control group devoid of any such intervention. Our central hypothesis posits that the comprehensive cognitive training will foster tangible enhancements in driving performance. More precisely, we anticipate that post-training, the intervention group will register a marked dip in driving infractions and embody safer driving etiquettes when juxtaposed against their baseline performance and the control group's metrics.

2. Materials and methods

2.1 Participants

The participants for this research study were recruited from the University of Nebrija, Spain. To gather participants, recruitment activities such as distributing flyers and sending emails to college campus list services were conducted. Interested individuals were directed to an online screening questionnaire. To achieve a balanced representation, participation was restricted to individuals between the ages of 18 and 30, with an evenly split number of men and women. Only individuals with valid driver's license were eligible for inclusion in the study.

A total of 50 participants completed the study, of which 22 were women. The mean age of the participants was 21.1 years (SD = 2.36), their average driving experience, measured as the number of years since obtaining their driving license, was 2.84 years (SD = 1.61), and their average annual mileage was 5920 km (SD = 4716). All participants had normal or corrected vision, normal hearing, and did not have any motor or cognitive impairments as shown by the results in the initial Cognitive Assessment Battery (CAB) (CogniFit, San Francisco, US). To acknowledge the participants' contribution to the study, they received financial remuneration for their time and efforts.

2.2 Cognitive training program

For the cognitive training program, the CogniFit patented dynamic training system that tailors exercises to individuals' specific needs and performance was used. The effectiveness of this training method has been extensively demonstrated in both clinical and healthy populations (Bahar-Fuchs et al., 2017; Conesa & Duñabeitia, 2021; Hill et al., 2017; Li et al., 2022; Peretz et al., 2011; Shah et al., 2017; Tapia et al., 2024; Westwood et al., 2023) and demonstrated transfer benefits to everyday activities such as reading comprehension, emotional well-being, sleep quality, mobility or daily functioning (Marusic et al., 2022; Reina-Reina et al., 2023; Tapia, Puertas, et al., 2023; Tapia, Taberner-Bonastre, et al., 2023; Wei et al., 2022). Due to resource limitations, the study was designed as a randomized controlled trial with two arms: a cognitive training intervention arm and a passive-control arm.

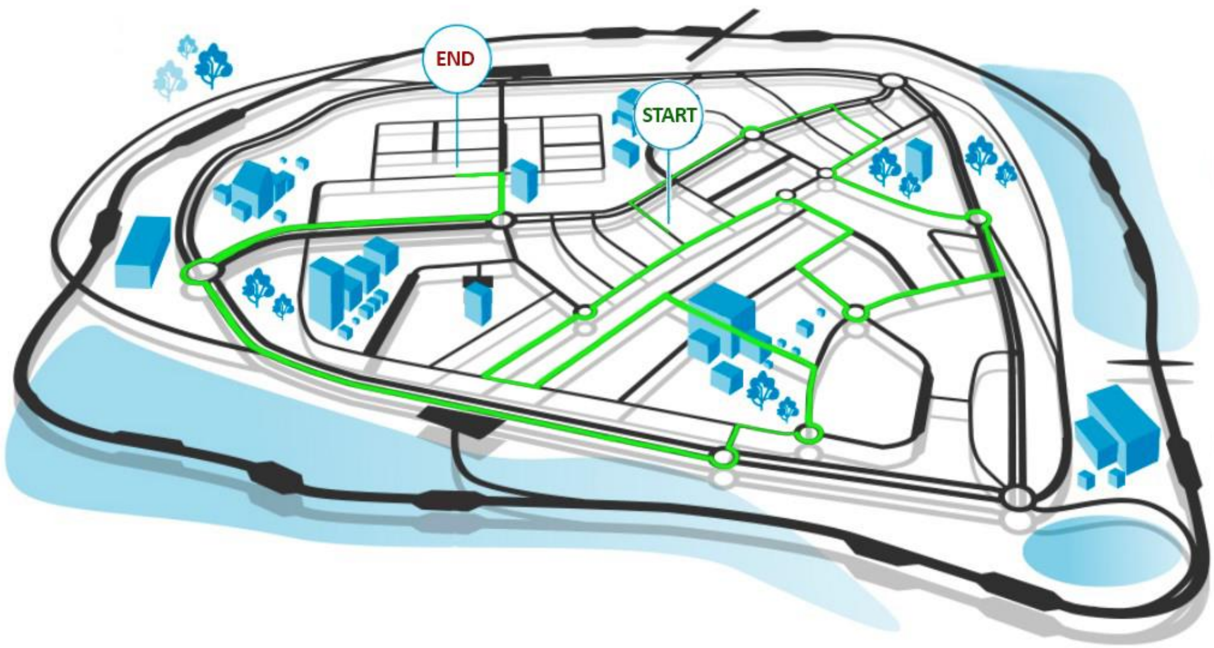
Our study utilized 41 different games or exercises with adaptive difficulty levels. These exercises were selected based on input from CogniFit as well as the expertise of a neuropsychologist within our research team. Our aim was to target cognitive functions considered essential for driving (Dawson et al., 2010; Fausto et al., 2016), including executive function, attention, memory and visuospatial abilities. The training regimen adopted a multidomain approach, integrating tasks that simultaneously engaged various cognitive skills rather than isolating individual abilities. Prior to commencing the training, participants underwent baseline cognitive evaluations to assess their initial cognitive functioning across different domains. Leveraging these assessments, personalized training protocols were tailored to each participant's specific cognitive profile, adjusting task difficulty dynamically throughout the intervention period to optimize engagement and effectiveness. The exercises and the cognitive abilities to be trained by each one can be consulted at https://doi.org/10.6084/m9.figshare.23791725.

Every participant was given a personal online account on the web platform, where they could log in and complete their daily training activity. Each game was set to run for five minutes or concluded when the participant reached their unique target. A single training session comprised three activities selected from the pool of 41 games. The choice of activities for each session is determined by the Individualized Training System™ (ITS), taking into account the user's cognitive profile and avoiding repetition of previously presented activities. This 15-minute daily training regimen was consistently implemented, repeating five days a week for a total duration of 8 weeks. Feedback regarding participant’s performance was given after every activity. Once a training session concluded, a reward of 1€ was showcased on the screen, and the aggregate sum of all such rewards provided motivation for ongoing engagement.

2.3 Driving evaluation

Driving performance was assessed within a virtual driving environment using on the Simumak® Simescar lite version open cockpit driving simulator, equipped with an HP EliteDesk 800 G5 TWR i5 computer with 16 GB RAM and an NVIDIA GeForce GTX 1660 Ti video card. The simulation was displayed on three 27” IPS Full HD HP monitors. The open cockpit includes a seat, 3 pedals, a gear lever with 5 speeds, and a steering wheel with a complete dashboard. It also integrates a motion system that utilizes bass frequencies to induce vibrations throughout the structure, simulating engine rumble and road tremor. Both side and center rear-view mirrors were present in the simulated environment. Such simulators are well-validated tools, extensively employed to probe driver behavior and gauge driving performance across a spectrum of scenarios (Godley et al., 2002; Shechtman et al., 2009; Yan et al., 2008). Notably, multiple studies have harnessed the capabilities of the Simumak Simescar simulator, often using its infraction metrics as indicators of driving safety, further highlighting its efficacy in dissecting driving behaviors (Lee et al., 2021; Zepf, El Haouij, Lee, et al., 2020; Zepf, El Haouij, Minker, et al., 2020). This simulator provided a realistic driving experience, allowing participants to navigate through an urban driving route spanning 3.7 km (Figure 1). The environmental conditions simulated moderate rain with slight fog and heavy traffic, replicating challenging real-world driving scenarios. A video showcasing the virtual environment is provided at https://doi.org/10.6084/m9.figshare.23791725.

Figure 1. Virtual route in the driving simulation environment.



Participants were instructed to drive safely while following the GPS indications provided by the simulator. The driving route included a total of four triggered events strategically placed along the route, simulating potentially hazardous circumstances that participants needed to react to promptly and appropriately, such as a running pedestrian, another vehicle found in a roundabout, a cyclist crossing the road or a police car in a junction. The duration of the driving evaluation encompassed approximately 12 minutes, during which participants were required to demonstrate their driving skills and navigate through the designated route. The simulated driving experience aimed to encompass a wide range of driving performance aspects, including the ability to navigate hazardous situations effectively and adhere to traffic regulations diligently. The driving evaluation was conducted one day before commencing the cognitive training and immediately after its completion. The variables assessed as indicators of driving performance included: a) Speed: an infraction is recorded if the vehicle exceeds the speed limit by more than 10% of the posted limit, with a monitoring interval set to check every 5 seconds after initial detection; b) Failure to respect right of way: an infraction is recorded if the vehicle's trajectory intersects with another vehicle within the intersection, with a predefined threshold of less than 2 meters distance between trajectories; c) Failure to yield to pedestrians at crosswalks: an infraction occurs if the vehicle's position intersects with the designated crosswalk area while a pedestrian is crossing, with a predefined threshold of less than 1 meter distance from the crosswalk and the pedestrian's path; d) Failure to maintain a safe distance from other vehicles and cyclists: In general traffic, when traveling over 5 km/h, a braking distance is calculated using the formula $d_{breaking} = \frac{speed^2}{180}$. For interactions with cyclists, a minimum distance of 1.5 meters is enforced if the vehicle's speed exceeds 10 km/h. Continuous monitoring every 3 seconds adjusts the infraction count based on these parameters; e) Running red lights: this is considered an infraction when the center of the vehicle exceeds the line of the traffic light while it is red; f) Driving in restricted lanes: this includes lanes designated for buses, bikes, or other restricted access. It is considered an infraction when the center of the vehicle crosses the restricted lane line; g) Off-road driving: considered an infraction when the center of the vehicle crosses the lane line and exits the road; h) Aggressive driving behaviors: Includes rapid acceleration, sudden braking, and sharp steering movements. Thresholds are set at more than 2.74 m/s^2 for acceleration and braking, and over 100 degrees per second for steering wheel movements to detect and record these actions as infractions; i) Collision: any contact with another vehicle, pedestrian, or stationary object that results in a detectable impact is recorded as a collision infraction. Furthermore, the average speed was also considered as a metric of driving performance during the evaluation.

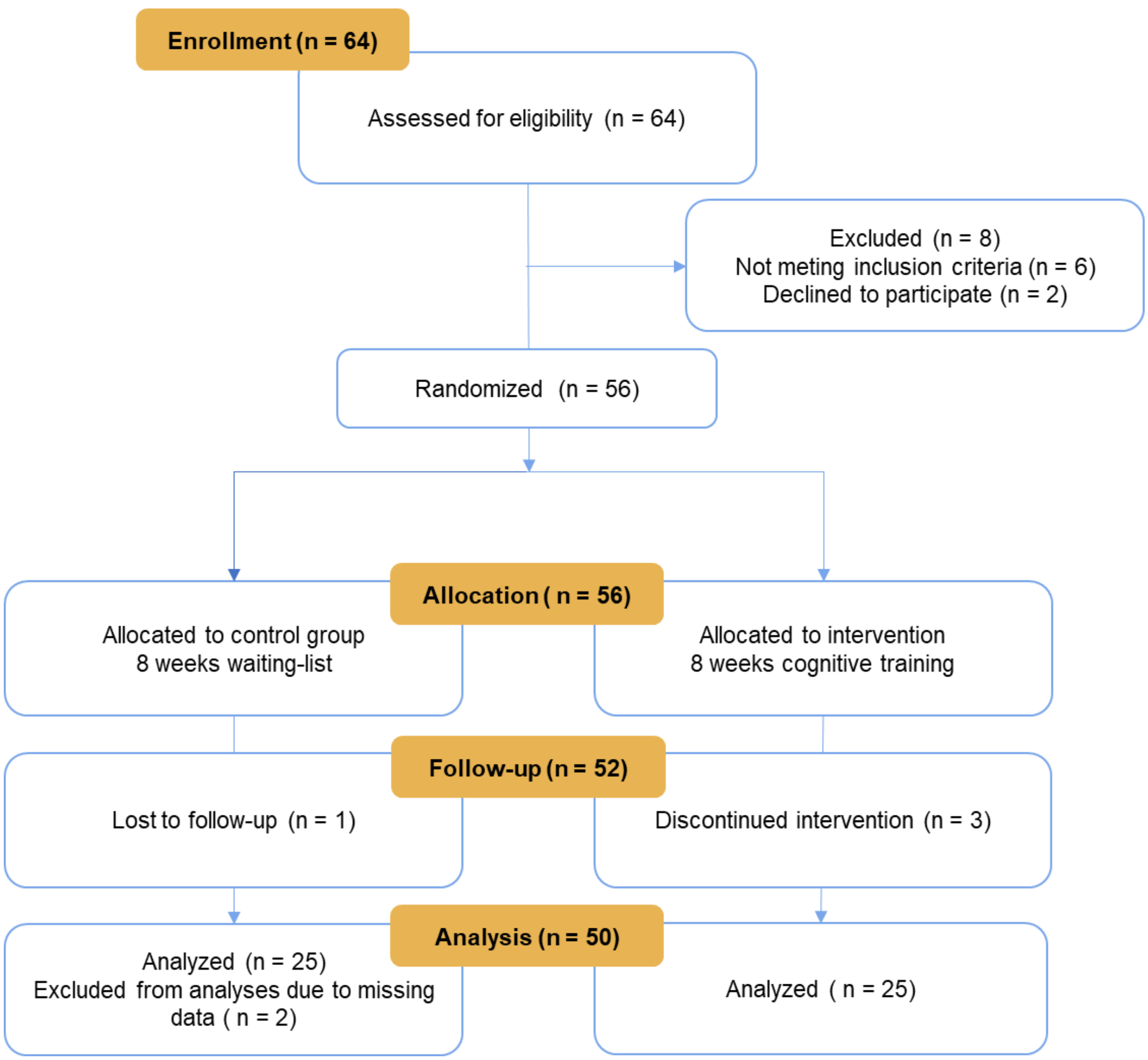
2.4 Procedure

All interested participants undertook the initial online Cognitive Assessment Battery (CAB)® PRO (CogniFit Inc., San Francisco, CA, USA) to ensure their cognitive performance and determine eligibility. This assessment gathered sociodemographic information including the type of driving license held (e.g., car and light vehicle, moped or motorcycle, commercial vehicle), the duration since obtaining a car driving license, and average annual mileage. Out of the initial group, six participants were excluded for not possessing a car driving license. The remaining 58 participants were invited to the laboratory, where they received a study overview and signed a consent form. However, two participants opted out.

Consequently, the study commenced with 56 participants. In the first instance, participants underwent a 5-minute practice session in an urban simulated driving environment to familiarize themselves with the equipment. If no motion sickness was reported, they proceeded to the driving evaluation detailed in the previous section. Upon completion, participants were guided to continue the process autonomously, following the online platform's instructions. The CogniFit platform was structured such that participants were randomly assigned to either the experimental or control group upon registration, using a computer-generated random number sequence. This assignment was entirely random, ensuring unbiased group allocation. Furthermore, the platform generated a unique ID for each participant, enabling researchers to remain unaware of individual group assignments.

Participants assigned to the experimental group received information about the training program procedure. They were instructed to conduct their computerized cognitive training at home using their personal mobile phones. The participants were directed to complete one training session per day, five days a week, resulting in a total of 40 training sessions over the program duration. To prevent overtraining, a 12-hour countdown was implemented after each training session. Upon finishing the last training session, a prompt appeared, urging them to contact the researchers for post-evaluation scheduling. Conversely, participants assigned to the control group did not engage in any specific activity during the 8-week period between the driving evaluations, aligning with the use of passive or waiting list control groups in previous studies (Combourieu et al., 2018; Declercq et al., 2022; Lukas et al., 2021; Molloy et al., 2019). They received a notification with an 8-week countdown, signaling to reach out to the researchers for scheduling a post-evaluation in the following 3 days. All participants were advised against revealing their group affiliation during post-evaluation. At post-evaluation, all participants underwent a driving evaluation scenario mirroring the baseline assessment, following the same route, albeit with slight variations in traffic dynamics due to the randomized nature of the platform algorithm. The four triggered events remained constant as baseline evaluation. No participant reported motion sickness during either the practice or experimental evaluations, and no feedback was provided post-evaluation. The study's design is illustrated in Figure 2.

Figure 2. Consort diagram.



2.5 Data curation and statistical analyses

The data was processed using RStudio (RStudio Team, 2020). The dataset comprised the following variables: age, gender, experimental group, driver's license category, duration since obtaining the car driving license, annual mileage, cognitive score, baseline driving score, and post-test driving score. The cognitive score was calculated from the z-score provided by the CAB®. The driving score was determined by summing the total traffic infractions identified by the driving simulator. The traffic infractions included were as follows: exceeding the maximum speed, failure to respect right of way, failure to yield to pedestrians at crosswalks, failure to maintain a safe distance from other vehicles and cyclists, running red lights, driving in restricted lanes, off-road driving, aggressive driving behaviors (e.g., sudden or fast acceleration, abrupt braking, and sudden wheel movements), and collisions (including collisions with urban objects, with other vehicles, and with bicycles and pedestrians).

From the initial enrollment of 56 participants, 6 did not complete the study, resulting in a 3.36% drop-out rate. As depicted in Figure 2, four participants were excluded from the study: three from the experimental group due to non-adherence to the training program and one from the control group for missing the post-evaluation. Additionally, two participants were excluded from data analysis due to improperly recorded driving evaluations, leaving a final sample of 50 participants.

Statistical analyses were conducted using jamovi (The Jamovi Project, 2022). To ensure group homogeneity before data analysis, independent samples t-tests were performed, focusing on annual mileage and cognitive performance. This emphasis was motivated by a prior study which suggested that drivers covering more kilometers annually tend to exhibit greater driving skills (Tapia & Duñabeitia, 2023), and by the widely recognized effect that baseline cognitive abilities can shape the outcomes of cognitive training (Chuang et al., 2022; Harvey et al., 2020; Shaw & Hosseini, 2021; Traut et al., 2021). Our analysis revealed no significant disparities between the experimental and control groups in terms of mileage ($t(48) = 0.34$, $p = .595$) or cognitive score ($t(48) = 0.16$, $p = .872$). Descriptive statistics for both the experimental and control groups are systematically laid out in Table 1.

Table 1. Demographic and cognitive characteristics of participants in experimental and control groups.

	Group	Mean	Standard deviation
Age	Control	20.00	1.83
	Experimental	22.12	2.39
License years	Control	2.280	1.40
	Experimetal	3.400	1.63
Mileage	Control	6280	4928.83
	Experimental	5560	4568.09
CAB score	Control	0.682	0.41
	Experimental	0.658	0.64

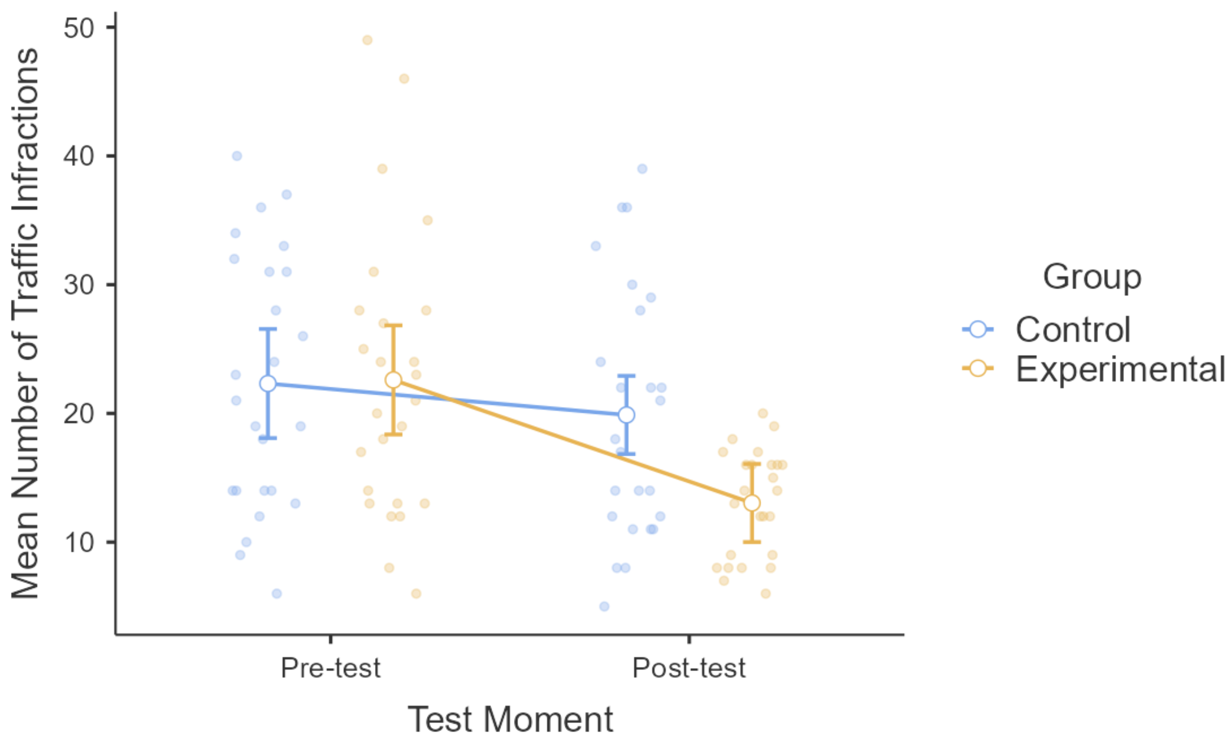
Note. Age and License years are represented in years. Mileage is given in kilometers. CAB score is presented as a z-score.

A mixed-design analysis of variance (ANOVA) was performed to examine the effects of the cognitive training program on driving performance. The design consisted of one between-subjects factor, Group (experimental vs. control), and one within-subjects factor, Test Moment (pre-test vs. post-test). This approach allowed for an evaluation of the main effects of both factors as well as their interaction. Contrast analyses were subsequently conducted to investigate specific comparisons of interest, providing insights into the effects of the cognitive training program on driving performance and any observed group differences. The significance level for all statistical analyses was set at $p < .05$. Effect sizes, such as partial eta-squared ($\partial\eta^2$), were calculated to determine the magnitude of observed effects.

3. Results

A repeated-measures ANOVA was then conducted to examine the overall effects of the cognitive training program on driving performance. The analysis revealed no significant main effect of Group, $F(1, 48) = 2.59$, $p = .114$, suggesting that the experimental and control groups did not significantly differ in terms of the number of traffic infractions. However, a significant main effect of Test Moment was found ($F(1, 48) = 13.99$, $p < .001$, $\partial\eta^2 = 0.226$), indicating a significant variation in the number of traffic infractions between the baseline and post-test evaluations. Critically, there was a significant interaction effect between Test Moment and Group ($F(1, 48) = 4.92$, $p = .031$, $\partial\eta^2 = 0.093$), suggesting that the impact of the cognitive training program on driving performance differed depending on the group. Post hoc analyses were performed to compare the mean number of traffic infractions between the control and experimental groups at both pre-test and post-test evaluations (Figure 3). At the pre-test evaluation, no significant differences were found between the control and experimental groups ($t = 0.09$, $p_{tukey} > .9$), indicating that both groups had similar levels of traffic infractions before the cognitive training program. Comparing the mean scores at the post-test evaluation, significant differences were observed between the control and experimental groups, MDiff = 6.84 (SE = 2.13), $t(48) = 3.20$, $p_{tukey} = .012$. Specifically, the mean number of infractions for the experimental group was significantly lower at post-test as compared with pre-test (MDiff = 9.56 (SE = 2.27), $t(48) = 4.21$, $p_{tukey} < .001$), indicating an improvement of driving abilities in those participants that had undergone the cognitive training program. In contrast, no differences were observed for control group between pre- and post-test (MDiff = 2.44 (SE = 2.27), $t(48) = 1.08$, $p_{tukey} = .706$). No significant differences were found in the mean speed between pre- and post-test for either experimental condition.

Figure 3. Comparison of traffic infractions before and after cognitive training



In addition to the initial analysis, further examination of specific types of infractions was conducted to gain deeper insights into the effects of the cognitive training program. Paired samples t-tests were performed to compare the frequency of infractions before and after the training intervention for the experimental group. The results revealed significant reductions in several types of infractions post-training. Specifically, there was a substantial decrease in instances of exceeding the maximum speed ($t(24) = 3.769$, $p < .001$, Cohen's d = 0.7537), off-road driving ($t(24) = 3.113$, $p = .005$, Cohen's d = 0.6226), aggressive driving behaviors ($t(24) = 2.179$, $p = .039$, Cohen's d = 0.4358), collisions with urban objects ($t(24) = 2.498$, $p = .020$, Cohen's d = 0.4995), and collisions with other vehicles ($t(24) = 3.161$, $p = .004$, Cohen's d = 0.6321). Descriptive statistics for all traffic infractions can be found in Table 2.

Table 2. Descriptive statistics of traffic infractions and speed at pre and post evaluation for the experimental group.

	Pre-evaluation	Post-evaluation
	6.24 (5.17)	2.44 (2.89)
Failure to respect right of way	1.40 (1.32)	1.36 (0.86)
Failure to yield to pedestrians at crosswalks	0.28 (0.68)	0.12 (0.33)
Failure to maintain a safe distance from other vehicles and cyclists	1.76 (3.59)	0.96 (1.21)
Running red lights	1.48 (1.58)	1.40 (1.12)
Driving in restricted lanes	4.04 (3.08)	3.96 (1.81)
Off-road driving	4.04 (3.59)	1.96 (2.26)
Aggressive driving behaviors	2.00 (2.94)	0.64 (0.64)
Collision with urban objects	0.72 (1.21)	0.16 (0.37)
Collision with other vehicles	0.56 (0.77)	0.04 (0.20)
Collision with bicycles and pedestrians	0.08 (0.28)	0.00 (0.00)
Total infraction count	22.60 (11.11)	13.04 (4.15)
Speed	20.50 (2.32)	19.70 (2.22)

Note. Values represent the mean traffic infractions registered among participants, with standard deviation shown in parentheses. Speed is represented in km/h.

4. Discussion

Driving is a multidomain task that heavily relies on various cognitive processes, emphasizing the importance of a driver's cognitive abilities for safe vehicle operation. This pilot study aimed to investigate whether a multidomain cognitive training regimen can holistically reduce traffic infractions among young drivers in a driving simulation environment.

The results revealed that participants who underwent an 8-week cognitive training exhibited a notable reduction in traffic infractions post-training when compared to their initial performance. Specifically, significant reductions were observed in instances of exceeding the maximum speed, off-road driving, aggressive driving behaviors, and collisions with urban objects and other vehicles among participants in the experimental group compared to the passive control group. However, it is noteworthy that despite observing a significant reduction in speed infractions among the experimental group after the cognitive intervention, the average speed remained consistent, thus suggesting that the effect of cognitive training snowballed driving accuracy, independently of the time taken for making decisions and executing actions. The positive effects of cognitive training encountered on driving performance build upon previous research that have proposed that training in speed of processing, memory, or reasoning can lead to a reduction in at-fault crashes (Ball et al., 2010; Edwards et al., 2009), that working memory training can aid in minimizing distractions while driving (Seidler et al., 2010), or that hazard perception training reduces crash incidences (Thomas et al., 2016), and that of the relationship between memory processes and situational awareness on traffic accidents (Gugerty, 2011). Likewise, cognitive training programs similar to CogniFit have shown promising results in improving driving performance across various age groups. Roenker et al. (2003) found that speed-of-processing training in older adults led to improvements in useful field of view (UFOV) test performance, some simulator measures, and fewer dangerous maneuvers during on-road tests, with effects persisting at 18-month follow-up. Seidler et al. (2010) demonstrated that working memory training resulted in some transfer to complex motor tasks and driving simulator measures, particularly under dual-task conditions for older adults. In a systematic review, Fausto et al. (2021) reported that cognitive training, especially focused on processing speed, was associated with a substantial reduction in at-fault crashes among older drivers. These findings collectively suggest that cognitive interventions, like the one used in our study, have the potential to yield significant safety benefits for drivers across different age groups, supporting the rationale for our investigation into the effects of CogniFit training on young adult driver. Furthermore, it aligns with the tactical and operational levels of driving control, indicating a tangible enhancement in driving safety behaviors among participants who received the cognitive training, and supports the well-established link between traffic violations and subsequent accident rates, association especially pronounced in studies on young drivers (Barraclough et al., 2016).

The limitations of our study design must be acknowledged, particularly regarding the control condition. The use of a passive control group, although common in many cognitive training studies, introduces certain limitations in interpreting the results. While our findings show improvements in the CogniFit group compared to the passive control group, this design does not allow us to differentiate between effects specifically attributable to the CogniFit training and those that might arise from simply engaging in any form of cognitive activity. An active control condition, involving a non-adaptive or different form of cognitive engagement, would help isolate whether the observed effects are due to the specific cognitive operations targeted by CogniFit or if they reflect more general benefits of increased cognitive engagement. This limitation means that our findings should be considered preliminary evidence rather than conclusive proof of the specific efficacy of CogniFit training in improving driving performance. Another noteworthy limitation was the use of a simulated driving environment to assess training effects on performance. While simulators provide a controlled context for standardized evaluation; the validity of the results depends on the fidelity of the simulation. Driving in the real-world introduces additional perceptual variables, motor requirements, and cognitive demands not fully replicated here. For instance, our simulated driving lacked vestibular and proprioceptive inputs and consequences of crashes. Therefore, while these findings demonstrate cognitive training improved young adult drivers' performance in the simulator, further research is required to verify translation of these effects to actual on-road driving. Naturalistic driving studies tracking behaviors like lane maintenance, acceleration profiles, and traffic violations before and after training could corroborate benefits in authentic settings. Moreover, future investigations should include follow-up assessments at later time points to assess potential retention of training effects and their relationship with real-life driving outcomes.

It is important to note that while our study demonstrates the potential benefits of cognitive training on driving performance, it was not designed to elucidate the specific mechanisms underlying these improvements. The primary objective of our study was to determine whether the CogniFit training program could enhance driving performance in young adults, rather than to isolate the critical cognitive processes responsible for any observed gains. This focus on determining efficacy rather than understanding mechanisms represents a common and necessary initial step in the evaluation of potential interventions. Nevertheless, we recognize that comprehending the underlying mechanisms is essential for the refinement and optimization of cognitive training programs. While promising, the current computerized multidomain cognitive training program represents just one approach to cognitive training. Further research should explore how to optimize and individualize training to maximize improvements in driving abilities. For instance, comprehensive neuropsychological assessments could identify a driver's profile of cognitive strengths and weaknesses. Training protocols could then be tailored to specifically target deficient abilities most relevant to their driving difficulties. Such customization may enhance outcomes over one-size-fits-all programs. Additionally, cognitive training could be combined with driving-specific skill practice in simulators. Integrating training on hazard perception, navigation, and vehicle handling alongside cognitive exercises may potentiate transfer effects. The optimal balance between general cognitive enrichment and driving-specific skill training should be determined. Finally, the dose-response relationship requires detailed examination. Factors like session frequency, duration, total training length, spacing between sessions, and training intensity should be parametrically manipulated to discern the ideal training regimen. Dose optimization research should also probe interactions between training parameters and individual differences in initial cognitive performance or neural integrity. Elucidating the most effective training approaches can help translate cognitive training into scalable, evidence-based interventions that maximize improvements in driver safety.

5. Conclusions

In summary, this pilot study suggests potential benefits of CogniFit training on driving performance and error reduction among young adult drivers. However, due to the limitations of our study design, particularly the use of a passive control group, these findings should be considered preliminary. While promising, further research with more rigorous control conditions is needed to fully understand the optimal parameters and applications of such training programs, as well as to verify whether these results also translate to real-world driving on the road.

Although there is potential for cognitive training to be integrated into driver education and rehabilitation, it is important to remain cautious about its widespread implementation until further empirical evidence is available. Nonetheless, exploring cognitive training as a means to enhance road safety in the interim could offer a practical approach to reducing accidents and fatalities. Continued research efforts are crucial for developing personalized and adaptive cognitive training programs that benefit drivers of all ages and skill levels.

Ethics Statement

The procedure strictly adhered to the ethical principles outlined in the Declaration of Helsinki, ensuring the protection and welfare of the participants. Prior to commencement, the Research Ethics Committee of Nebrija University granted approval with the assigned approbation code UNNE-2023-0007. Written consent was obtained from all participants, affirming their voluntary participation in the study.

Data Availability Statement

The corresponding author can provide the datasets generated for this study upon request.

Conflict of Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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