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Systematic Review

Driving Under Cognitive Control: The Impact of Executive Functions in Driving

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Abstract: This review will explore the role of executive functions and the impact they have in facilitating the skills of vehicle operation. Executive functions are critical for the decision-making process, problem-solving, and multitasking. They are considered the primary factors in driving cases that demand drivers to react quickly and adapt to certain situations. Based on the PRISMA 2020 guidelines, this study aims to investigate, analyze, and categorize higher mental skills and their qualities directly related to driving. The literature review was performed in the following databases: PubMed, Web of Science, Scopus, and Google Scholar, using the article collections' snowball search technique. The results suggest that key executive functions like working memory and inhibitory control are closely related to risky behavior and driving errors that lead to accidents. This review adds valuable insight by highlighting the significance of their contribution to future research, driver educational programs, and technology for improving driver safety. Consequently, collecting recent data will contribute to understanding new parameters that influence driving behavior, creating the possibility for appropriate proposals for future research.

Keywords: executive functions; safe driving; metacognition

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1. Introduction

In a constantly changing environment, the individual should focus on new elements that arise, and after finding that a strategy does not work, redefine their actions. It requires real-time information management and processing to reshape the response scenario. The combination and engagement of various executive skills allow focusing of attention, planning, and the shifting or flexible readjustment of actions to achieve a targeted task [1].

Executive functions (EFs) are higher cognitive processes that control lower-level functions to guide behavior in planning, organizing, and carrying out an objective. They exhibit shared connections, distinct functions, and individual differences [2].

Several neuroimaging studies using non-invasive functional neuroimaging methodologies have identified the association of EF performance with the activation of neural networks in the prefrontal cortex in both healthy and clinical subjects [3]. In particular, executive skills cover a wider network of brain regions, involving the prefrontal cortex, parietal cortex, basal ganglia, amygdala, and hippocampus [2,4–6].

Driving is a challenging endeavor where mental processes are crucial [7]. It is an elaborate process whose outcome relates to different personality traits and executive function factors that demonstrate a valid predictive role in driver behavior [8]. The executive mechanism coordinates the management of complex tasks, such as driving, promoting uninterrupted attention to a task, and filtering information related to it, bringing about adaptation to varying conditions [9].

A significant proportion of human involvement (95%) is implicated in traffic accidents. Dangerous behaviors while driving bring negative to tragic results. Studies focus on parameters related to an individual's temperament, such as aggression, impulsivity, and sense of danger, as well as social and cognitive dimensions of personality and demographic characteristics related to age and gender. Therefore, it is imperative to examine the reasons behind the occurrence of these behaviors [10].

According to research, significant reasons for behavior are fulfilled by metacognitive strategies and situational awareness since they facilitate driving behavior [11]. In particular, the driver's metacognitive ability contributes to the self-regulation process by focusing and maintaining their attention in the present moment, enhancing inhibitory ability by intercepting unnecessary data and contributing to road safety [12].

Disorders that affect cognition, visual perception, and motor function, such as Alzheimer's or Parkinson's disease, autism spectrum disorder, or attention-deficit/hyperactivity disorder increase the risk of driving accidents. The effects of such disorders are particularly felt in the driver's information processing at various stages [9,13]. Any abnormality of the prefrontal cortex immediately impacts skills related to self-regulation, inhibition, working memory, attention, planning, organization, evaluating situations, and, by extension, decision-making. A limited development of executive functions partly explains reduced risk perception and poor driving performance [14].

Young drivers have been statistically associated with more accidents, showing limited risk perception and ability to anticipate potentially dangerous situations while driving [7]. Furthermore, the literature demonstrates that EF is significantly reduced in normal aging, which affects driver behavior [15].

Therefore, training drivers through assistive technology in specific executive functions that are lagging could reduce the negative consequences of driving, constituting alternative intervention methods in the driving domain [9]. In addition, metacognitive skills-training approaches through driving simulators and digital tools contribute to new information utilization, built on the representation of previous data, constructing beneficial metacognitive experiences for safe driving [11].

The main objective of this study is to investigate executive skills that affect driving efficiency, utilizing a systematic-narrative hybrid model reviewing sources according to the PRISMA 2020 principles. In particular, we searched for sources in the following databases: PubMed, Web of Science, Scopus, and Google Scholar, using the snowball survey method. Research findings indicate that limited functioning in specific executive skills affects safe driving. The study's contribution is essential in the driving and executive functioning research fields, as it combines the study of basic executive skills and their impact on driving. At the same time, it highlights the role of metacognitive awareness in the action of driving and the correlation of metacognition with executive skills, the combination of which appears to influence driving outcomes.

Section 2 includes a theoretical approach to executive skills and a reference to indicative factors that inhibit or enhance their performance. It is followed by Section 3, which outlines the research methodology. Finally, the study concludes with Sections 4–6, which relate the results, discussion, and research conclusions.

2. Theoretical Knowledge

This section includes a theoretical approach to executive skills. Also, a brief mention is made of factors that affect the functioning of the executive mechanism by improving or hindering its functioning. Finally, a subsection connects executive functions with driving.

2.1. Executive Functions

Executive skills are mental processes that enable the brain to utilize an individual's innate abilities to achieve an objective in a dynamic setting. Evidence from neuroscience shows the possibility of the effect of executive functions on brain plasticity as they manage internal and external environmental inputs [4].

Executive functions are also known as executive or cognitive control and constitute a set of higher mental functions. According to research, the main ones are inhibition, which includes selective attention and cognitive inhibition; working memory (WM); and cognitive flexibility directly related to creativity [16,17]. However, executive processes also involve other skills such as reasoning, problem-solving, planning, and decision-making [3,5,16,18].

A few essential executive skills are listed below.

- Working memory

Working memory is a multidimensional system that allows the temporary retention and processing of information, facilitating the performance of complex cognitive functions. It is distinguished by differences in storage capacity and executive control processes, highlighting the essential contribution of attentional control [19–21].

- Cognitive flexibility

Cognitive flexibility is the capacity to quickly transition between different thought processes and act in a way that is appropriate for the situation at hand. It is somehow identified with versatile behavior, directing the individual to high levels of resilience and performance in various areas of his life. In the literature, cognitive flexibility is a term directly linked to attention and is referred to as attentional flexibility, attention switching, and attention set-shifting [1].

- Inhibitory control

Inhibitory ability interacts with working memory and cognitive control to observe adaptive behavior. It suppresses unwanted impulsive responses and unnecessary or irrelevant information from memory [5].

- Attention

One way to define attention is the concentration of the mind on a situation, event, or object at a given moment, where the person achieves maximum cooperation and integration of higher mental processes [22]. Since working memory is a selected subset of all available representations in memory, it is also a form of attention by definition. Consequently, attention is a mutually accessible resource for memory maintenance in central function when shared between storage and processing processes [23].

- Self-regulation

Self-regulation is a higher cognitive process associated with creating goals, sticking to them while ignoring impulses, and pursuing their completion. It involves cognitive and behavioral mechanisms such as inhibition, memory, and behavioral regulation according to external stimuli and internal processes [24].

- Planning

Planning entails mental processes associated with action formulation, assessment, and selection that lead to completing actions required to achieve a goal [5].

- Problem-solving

Problem-solving is an even higher cognitive skill used to deal with a situation that differs from the given circumstances. It includes the sequence of cognitive processes that interact and readapt to adopt a strategy to deal with a problem or situation [25].

- Reasoning

Reasoning combines generalization and deductive strategy, revealing concept creation and creative thinking [5].

- Decision-making

Decision-making is a complex process in which the individual is called upon to find immediate solutions depending on circumstances and information available, influencing an outcome at a critical moment. According to research, the decision-making process includes rational decision-making based on logic, dependent decision-making that connects to the beliefs and expectations of the individual, intuitive decision-making that is influenced by emotional states, and decision-making related to decision-making procrastination [26].

Executive skills are classified as “hot EF” and are activated when situations arise that are associated with motivation and intense emotional processes requiring self-regulation. Meanwhile, “cool EF” includes cognitive skills that involve neutral emotional conditions and are governed by more logical and mechanistic processes [18,27,28].

It is made evident that working memory and inhibitory control coexist and support each other in achieving goals. In addition, working memory performance requires the cooperation of selective and focused attention, and in general, working memory and attention are directly connected [16,29]. Moreover, cognitive flexibility effectiveness presupposes the involvement of inhibitory control and WM [16]. Considering that executive functions are interrelated and work together to achieve a goal, when they malfunction, they affect the person’s social and cognitive behavior [5].

Executive skills develop gradually over the course of a person’s life. Therefore, any dysfunction detected in childhood or adolescence has a noteworthy impact on adulthood if not identified early. Indicatively, we mention the cases of neurodevelopmental disorders such as autism spectrum disorder (ASD), attention-deficit/hyperactivity disorder, and obsessive-compulsive disorder characterized by deficits in executive function, some of which involve attention, inhibition, cognitive flexibility, and working memory. However, their valid and immediate treatment with appropriate educational interventions significantly improves and limits any abnormalities [1].

Training approaches aimed at neural stimulation of the prefrontal cortex lead to improvement in executive skill performance. Some interventions shown to be effective in improving the cognitive mechanism by focusing on executive abilities are those related to neurofeedback, music therapy, neuro-linguistic programming, mindfulness training, using digital technologies, and virtual environments [6].

2.2. Factors That Inhibit or Enhance Executive Mechanism Functionality

Executive skills show fluctuations in their development related to individual differences. Initially, genetic factors influence executive system development. Then, environmental conditions and parameters play a decisive role in enhancing or limiting its function. Research evidence suggests that high levels of executive functioning promote goal achievement and academic success [30].

Several studies emphasize the importance of diet and general lifestyle in cognitive development. In particular, the results show that this is evident in older adults, where there is a deterioration in cognitive function, which is offset by developing cognitive skills and forming wholesome lifestyle habits [31]. Establishing a healthy lifestyle creates physiological responses, limiting long-term ailments and enhancing executive skills such as inhibition, working memory, and cognitive flexibility. However, a reciprocal relationship often develops since executive function is a prerequisite for initiating and maintaining healthy attitudes and behaviors [32].

According to Wright et al. [33] poor quality nutrition inhibits executive control function, affecting memory and learning. In contrast, adequate intake of nutrients containing omega-3 fatty acids, monounsaturated fatty acids, vitamins, folic acid, selenium, plant polyphenols, and choline is beneficial for cognitive development and brain function.

A study by Gasmi et al. [34] typically states that food combinations that include nutrients and are precursors in neurotransmitter synthesis contribute to brain health. As a result, they promote cellular growth and survival, enhancing cognitive function and improving a person’s emotional state [35]. The impact is generally evident in cognitive development, emphasizing executive skills [36,37].

Incorporating exercise into daily life is highly beneficial, reducing the risk of chronic diseases and helping to maintain and improve cognitive and executive function [32,38]. Similar results were shown by the meta-analysis of Xiong et al. [39], suggesting that the application of aerobic exercise had beneficial effects on inhibition, working memory, and cognitive flexibility. Furthermore, the combination of mind-body exercises significantly improved working memory performance.

However, the findings of some studies point to the negative consequences of certain habits and factors, such as smoking and the use of drugs and alcohol, on cognitive function, mainly on the executive mechanism. In particular, the use of drugs and alcohol causes increased levels of executive dysfunction, which remain even after the detoxification of the organism [32,40].

Stress is another crucial factor that harms cognitive function, as it burdens attention control and situational awareness, decisively affecting executive function [41]. In conclusion, research highlights the impact of culture on brain function, describing that socio-cultural and economic conditions influence the shaping of the biology of cognitive processes [42].

2.3. Linking Executive Skills to Driving

Most activities in our daily lives depend on executive functioning skills. The executive mechanism is an interrelated set of cognitive processes, including planning, attention control, working memory, inhibition, reasoning, problem-solving, and monitoring, that provide humans with adaptability for a constantly changing environment. Executive skills are essential for independent, goal-directed, and self-directed behavior. Driving is a crucial activity in modern society, contributing to a person's independence and well-being [43].

Cognitive assessment procedures of driving performance, which usually involve a small sample size, suggest changes or limitations in executive function, visual attention, and processing speed that impede driving performance [44]. The level of EF development acts as a predictor of driving performance. Both executive skills and driving require the combination of various neuropsychological abilities; among them are aspects of attention, risk assessment, planning, inhibition, cognitive flexibility, updating working memory, monitoring, and error evaluation [43].

According to research, factors such as negative mood, stress, and lack of sleep affect executive function, burdening self-regulation, attention, working memory, concentration, cognitive processing, self-observation, and decision-making, creating harmful consequences for driving [45].

A study by Shirdel et al. [46] states that driving is a dynamic activity that requires higher mental skills like attention and situational awareness to ensure human safety and a safe environment. Prerequisites for safe action while driving are following the traffic rules, focusing attention and concentration on current driving conditions, and a person's attitude of responsibility. Inattention, impulsivity, and executive function deficits appear to inhibit o-driving performance in both individuals with neurodevelopmental disorders and typically developing individuals. Consequently, there is an interrelationship between executive skills with efficient driving and traffic accidents in the general populace.

Several studies pay particular attention to driver risk perception, partially identified by the drivers' awareness of potentially hazardous driving situations. This involves the capacity to recognize risky driving circumstances. Effective hazard perception involves the driver's ability to detect possible unsafe circumstances. It is a central executive function that mentally represents the driving environment. Awareness of the driving situation is an effortful and proactive process that involves working memory, attention, and inhibitory capacity, contributing substantially to safe driving [47].

3. Materials and Methods

This literature review was performed based on the guidelines of the Preferred Reported Items of Systematic Reviews and Meta-Analyses (Prisma) statement, preregistered with the Open Science Framework on 14 October 2024 (https://osf.io/86k2c/) aiming to gather recent data on the significance of executive functions and highlight their importance in driving. This study, attempts to answer the following research questions:

- RQ1. How are executive functions related to driving?
- RQ2. What is the role of inhibition while driving?
- RQ3. How does working memory affect driving?
- RQ4. How do attention and working memory relate and interfere with driving?
- RQ5. How do decision-making and metacognition affect driving?

The inclusion criteria included several elements that were established for the selection process of this literature review. More specifically, they included a selection of articles published between the years 2014 and 2024, both experimental papers and literature, which included systematic and meta-analytic reviews that were peer-reviewed, written in the English language, and specifically referred to driving vehicles and analyzing the consequences of executive functions in this task. In contrast, the exclusion criteria included studies that did not refer to driving vehicles (airplanes, drones, ships, etc.), were not written in the English language, and were not peer-reviewed, as well as those that did not refer specifically to executive functions.

The methodology performed to conduct this systematic narrative hybrid review was based on PRISMA 2020 principles (Figure 1), guiding the literature search across multiple platforms including PubMed, Web of Science, Scopus, and Google Scholar while formatting Boolean operators and various search filters using the complementary snowball research method to select the articles. Some of the core keyword definitions that were used for the search process were "executive functions", "driving", "metacognition", and combinations of these terms. A total of (n = 247) articles were identified and screened for the final selection of included articles, which concluded after the processing, inclusion, and application of representative criteria for the main group of articles (n = 44) occurred for the final selection, with further investigation and analysis. The articles selected included literature produced between 2014 and 2024.

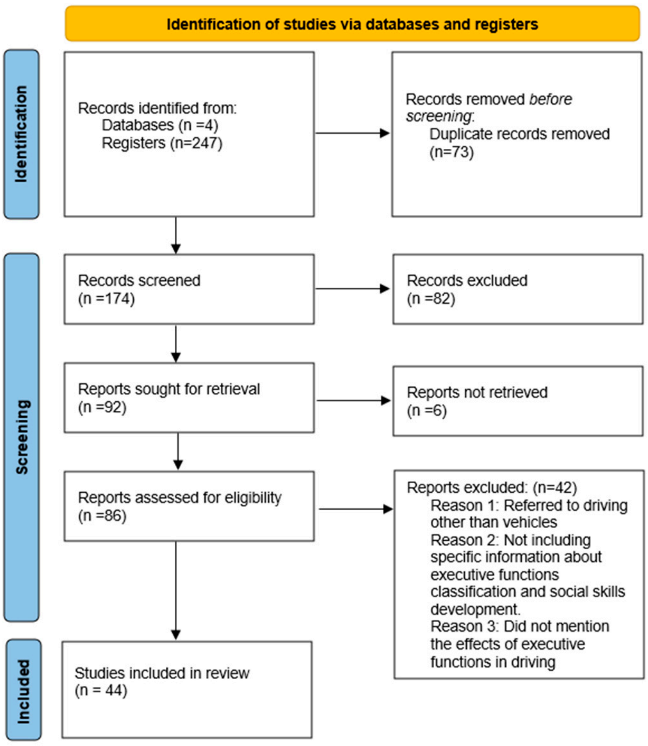

Figure 1. PRISMA 2020 chart flow.

The first step in the selection process was establishing eligibility criteria. A list of keywords was created to begin the search in the databases. Boolean operators and different search filters were used to maximize the results. After eliminating duplicate studies (n = 73), the selection process involved screening titles and abstracts to identify studies meeting the eligibility criteria (n = 174). The next stage of the process involved screening the full texts of articles after excluding 82. The remaining studies (n = 92) were thoroughly reviewed. Regrettably, six articles were not able to be retrieved for full-text screening. Two independent reviewers participated in the final selection process. They analyzed the full texts of n = 86 articles and discussed the applicability of the eligibility criteria. A total of 42 articles were excluded for not meeting the eligibility criteria related to not involving driving vehicles, lacking specific details about executive functions, and not discussing the impact of executive functions on driving. The final selection consisted of 44 articles. The results are outlined in Figure 1.

4. Results

Executive function is a mental system that guides the adaptive action of behavior and its orientation toward achieving a goal. The hallmark of safe driving is goal-directed conduct that uses higher mental abilities like executive functions [10].

The State of the World Road Safety 2023 report puts the number of annual road deaths at 1.19 million, down 5% from 2010–2021. Its aim is to improve road safety and halve deaths by 2030. Drivers' contribution to reducing road accidents is essential as their behavior plays a vital role in accident prevention, injuries, and deaths [48].

Injuries from traffic accidents have been continuously increasing in recent years, inevitably creating public health concerns. Outlining the causes of this situation largely focuses on driver errors and violations, age, gender, and experience. Cognitive deficits associated with distraction management, limited concentration and attention, reduced inhibition, and working memory are also accounted for [49].

Meta-analysis of neuroimaging studies highlights the involvement of different brain regions, which enable the synthesis of complex neural associations during driving. These neural networks are distinct and become active depending on the specific task being performed [50].

The behavior of a driver includes three categories depending on its characteristics. The first refers to the driver's ability to maintain driving control, the second concerns collisions and violations of the traffic code, and the third relates to attention to and reaction time for various incidents while driving [51].

Brown et al. [52] point out that many drivers tend to repeat episodes of dangerous driving, leading to accidents. However, the heterogeneity of their characteristics hinders the creation of effective intervention programs. Their study reports that factors such as personality, cognitive processes, and neurobiological processes influence the manifestation of risky driving behavior. The use of substances and alcohol; impaired inhibitory capacity; impulsivity; and dysregulation of the hypothalamic–pituitary–adrenal (HPA) axis, which is associated with risk-taking and especially cortisol secretion in stressful situations, outline different profiles of drivers with dangerous driving. This highlights the need for a customized strategy to address inadequacies.

The fundamental executive skills several studies link to driving are working memory, response inhibition and interference control, and set-shifting. Functions such as planning, vigilance/sustained attention, and visuospatial abilities have been less studied. Additionally, working memory, attention, and inhibition deficiencies are associated with a higher frequency of driving errors and accidents [9,51].

Driving is a complex process that combines cognitive skills, psychomotor skills, and visual-motor coordination. Many of these abilities slow down with age. Therefore, elderly drivers show reduced performance and increased chance of accidents [15]. However, young novice drivers have a high frequency of accidents and mortality involving various factors that explain their behavior. The main reasons are lack of driving experience; limited perception, evaluation, immediate reaction to risks; and the potential for cognitive control [53].

4.1. The Role of Inhibition in Driving

The inhibitory capacity controls and prevents intense reactions and concurrently promotes the functioning of various cognitive processes. Thus, deficits in inhibition produce impulsive behavior, aggression, and impaired self-regulation and attention with negative consequences for decision-making, all effects that impair driving [54].

In particular, impaired driving concerns information processing and the execution of or switching of complex tasks. Sometimes, the driver must react quickly by inhibiting automated responses to avoid engaging in an incident. At other times, the individual is called upon to face dangerous and unexpected conditions, combining attentional focus, error detection, inhibition of action, cognitive appraisal, and decision-making to achieve adaptation to new data [15].

Mäntylä et al. [55] investigated individual and developmental differences in young drivers, focusing on inhibition, mental shifting, and updating working memory. They used a computer driving simulation, concluding that limited executive skills cause driving errors. In addition, they found that driving performance can be predicted by inhibition and working memory, which interact and complement each other.

The later study by Ross et al. [53] focused on young novice drivers, reporting the correlation of developed braking ability with corresponding hazard detection ability and reduced collisions. Moreover, enhanced visuospatial working memory resulted in drivers exhibiting risky behavior, possibly due to overconfidence. In addition, they found that cognitive electronic control is trainable, as its functions are flexible, which has a favorable effect on driving.

Tabibi et al. [49] assessed working memory, sustained attention, and suspension in 107 drivers, approximately 30 years of age. The study's findings showed that driving behavior, including driving errors, is linked to the maintenance of attention and inhibitory ability. Of decisive importance was inhibitory control, the impulsive response to situations, of deviant behavioral reactions, which tend mainly to driving errors compared to violations.

A few years later, another study's conclusions [10] describe that risky driving behaviors are associated with a low level of executive mechanism. Also, different cognitive processes cause a variety of risky behaviors, most of which have been associated with disinhibition, which includes risk-taking, undesirable social behavior, and inhibition of internal impulses.

Another study by Moran et al. [7] approached the relationship between cognitive functioning and risk perception in younger drivers, finding that inhibitory ability predominates in predicting driving hazards. Additionally, they observed that risk perception was related to spatial skills and response time to a dangerous situation.

4.2. The Role of Working Memory in Driving

Driving combines the simultaneous organization and processing of diverse and complex information. Proficiency in retrieving data is essential for driving, as its overload affects safe driving in demanding conditions. The parallel management of driving tasks affects the driver's perception, memory, and reaction to emergency incidents and danger, particularly burdening memory function and motor response, sometimes causing grave mistakes [49].

A study by Wood et al. [56] searched for the effect of working memory capacity (WMC) on risk perception performance. They found an association between individual differences in working memory capacity and risk perception. Performance in driving is related to individual differences when high cognitive load situations occur. It is worth mentioning that working memory capacity influences the ability to control visual attention as disruptions pop up, and consequently it influences the driver's behavior. Additionally, increased cognitive load in WM was associated with effective attentional control.

The findings of a systematic review [57] suggest that higher working memory capacity is associated with situational awareness and perceptual ability, promoting safe driving. In particular, greater working memory capacity provides more attention resources, enhancing attentional control and driving performance. Essentially, working memory functions as a control of attention.

Recent research by Broadbent et al. [58] reports that engaging in additional tasks while driving increases cognitive load, affecting driving performance. Furthermore, differences in working memory capacity create various behaviors and responses during driving. Also, people with high memory capacity could respond equally well to dissimilar tasks.

Zhang et al. [57] assessed the correlation between driving behavior and the driver's visuospatial working memory, highlighting the importance of working memory and visuospatial skills. In particular, the increase in attention controlled by the central executive system in visual-spatial working memory contributes to the utilization of greater memory capacity by the driver, enhancing their ability to predict and facilitate the handling of complex driving conditions.

Several studies support the idea that drivers must continuously monitor and control the surrounding space while driving, combining visual information and mental representations of the space [59]. Therefore, visuospatial abilities play a fundamental role in driving, as spatial strategies adopted by the person can predict their driving behavior [60].

In addition, individuals with high visuospatial skills have limited driving anxiety, possess self-regulation, and demonstrate problem-solving strategies [61].

4.3. The Role of Attention in Driving

Attentional control is crucial for inhibiting distractions, shifting to different task stimuli, and updating information in working memory, when someone aims to complete a goal [56]. In his review, Oberauer [23] explains the relationship between attention and working memory. He emphasizes that the limited capacity of working memory reflects limited attention-demanding skills for information storage-processing, perceptual processing, memory retention, and attentional control.

Studies have assessed distraction as a critical factor in driving accidents. More specifically, they point out that 4 of the 11 million accidents that occur annually in the United States would not have happened if the focus had been on driving [62]. Distraction from driving has been defined as the withdrawal or mental diversion from a specific object, goal, situation, context, or course. In this case, the driver's concentration is disturbed by a rivalry in action or condition, which may or may not be related to driving. Reduced situation awareness and a delay in information processing result, which may impair one's decision-making when driving. Of decisive importance is the ability of the driver to self-regulate, returning their attention to their goal [22].

In addition, study findings report crosstalk between observation and focused attention, suggesting deficits in planning and task inhibition in driving. Careful driving involves a high degree of thinking, observing, and controlling the stimuli that arise while driving. Research findings highlight distraction as a breakdown in the observation function [63].

In particular, the visual attention component is a vital skill for efficient driving, considering that we believe about 90% of the information required for driving can be perceived via the visual channel. The analysis in studies by Ojsteršek and Topolšek [64] proved that drivers become more distracted by mobile phones and various in-vehicle information systems. In contrast, outside the vehicle, advertisements and information signs attract the driver's attention.

Studies also associate driver inattention with moments of mind wandering, which correspond to approximately one-third of a person's daily life. Mind wandering is related to attention gaps that occur consciously or unconsciously during driving, affecting concentration and burdening the cognitive load of working memory. Mind wandering involves thoughts unrelated to the current task and are an essential cause of attention loss, with consequences for driving development, particularly limited self-regulation [65].

A recent study reports that the tendency to wander within the mind seems to interact with various individual personality traits, contributing to the appearance of deviant driving behavior [66]. Remarkably, pre-existing fatigue and limited sleep act as predictors of the occurrence of mind wandering [67].

The ability to self-regulate is quite beneficial when attention has been distracted, and one can function adaptively, reducing the shift of attention to competing activities or adopting coping techniques depending on the circumstances. As a result, the self-regulation mechanism lengthens the time between distractions, improving driving efficiency [68].

4.4. The Role of Self-Regulation in Driving

The role of self-regulation in driving is crucial. It involves the ability of the driver to adjust their driving behavior, considering any physical, motor, or cognitive limitations they may have [69]. It is essential for ensuring safety on the road. Research indicates that effective self-regulation depends on the driver's capacity to update working memory, switch attention between tasks, and exercise inhibitory control [24].

Emotions can affect a person's cognitive performance, particularly regarding perception, memory, and attention. It is important to note that people who show reduced inhibition tend to show intense anger after its activation, impacting cognitive control, memory, and cognitive flexibility. A common belief is that driving while angry is dangerous. Research suggests that executive function, particularly self-regulation and risk cognition, plays a role in mediating the influence of anger on unsafe driving [51].

Sani et al. [54] found that aggression and emotion regulation difficulties contribute to higher rates of dangerous driving behavior and accidents, highlighting the importance of aggression in similar behaviors. However, diverting attention to unnecessary information, diminished self-control, and inhibition were associated with driving errors.

Effective driver behavior is related to higher cognitive mechanisms, including self-evaluation and awareness of impulse control in interaction with self-regulation. The driver's self-regulatory ability allows self-evaluation of their strengths and weaknesses, bringing about appropriate adaptive behavior. While involving risk perception skills and planning counter-compensatory strategies, driving is guided within safe frameworks [8].

Lazuras et al. [24] characteristically state that self-regulation regarding driving is intimately associated with the individual's ability to observe, control, differentiate, and adapt their behavior depending on the circumstances. Mental processes are closely related to the metacognitive mechanism, which controls and adjusts cognitive functions when required [70,71].

4.5. The Role of Metacognition in Decision-Making and Driving in General

It is worth noting the findings of Diamond [16], emphasizing the contribution of executive processes in achieving a goal and metacognitive strategies in observing its evolution. More specifically, the metacognitive function utilizes conscious processes that involve observation, evaluation, and control of the cognitive mechanism, as well as the participation of higher executive functions, contributing essentially to optimal decision-making [72].

Safe driving ability related to self-monitoring and beliefs about driving ability in different contexts can predict driving behavior [73]. Research reports the direct connection of decision-making with the suspension and regulation of behavior. Moreover, deficits in suspension combined with the impulsive handling of emotional situations predict risky driving decisions [26].

Metacognitive appraisal involves self-observation, self-awareness, mental awareness of cognitive mechanism appraisal, self-inhibition, flexible coping with maladaptive elements, and strategic behavior for improving cognitive deficits. Consequently, a correct assessment of the driver's abilities is especially significant because it strengthens the processes of self-control, self-regulation, and self-efficacy, promoting safe driving in dangerous environments [8].

Mindfulness, directly related to the metacognitive process, constitutes the mental process of focused attention in the present, distinguished by transparency, acceptance, and self-regulation of attention [74]. Furthermore, it is the awareness of internal and external information perceived at successive moments [75]. Situational awareness refers to perceiving and understanding a situation, enabling an individual to anticipate future conditions. Consequently, it is a mental process particularly beneficial in safe driving, and its quality is related to the monitoring of the surrounding space on the road, while it seems to depend significantly on the distribution of visual attention [76]

A study conducted by Crundall et al. [77] pointed out behavioral improvements in drivers that are produced by mindfulness training. The researchers found that increased situational awareness was associated with safe driving. In addition, they observed a positive effect on anger management, speed fluctuations, risk perception, distraction, and especially mind wandering. Similar results found in the systematic review by Koppel et al. [74] illustrated the utility of mindfulness in preventing distracted driving.

Soliman and Mathna [11] used driving strategies that integrated Theory of Mind and metacognition principles, testing situational awareness while driving. By comparing the actions of other drivers to their own, the trainees developed self-evaluation of their driving abilities. Driving offenses decreased due to increased situational awareness. Furthermore, observing, reflecting on, and interpreting similar behaviors improved their metacognitive driving strategy.

The results of the Starkey and Isler [14] study suggest that adult male drivers performed better than adolescents in executive function, accentuating the preservation of attention and inhibition, safe coping with risk, and a sense of situational awareness. In contrast, adolescents exhibited undesirable driving behaviors; risk-taking; and limited planning, self-regulation and situational awareness, but good working memory. Possibly, this is due to the gradual development of executive and metacognitive mechanisms, which peak and evolve in adulthood.

A subsequent investigation by Tsouvala et al. [78] showed that metacognitive driving experiences are affected by age, gender, and self-efficacy. In particular, men presented a reduced metacognitive assessment of their capabilities due to high self-efficacy and self-confidence. Conversely, women were more aware of their weaknesses regarding driving, perhaps due to reduced self-efficacy.

Miller et al. [79] evaluated the relationship between metacognitive ability and impulsive reactions in a sample of young drivers, using a driving simulator. Data analysis supports the importance of metacognitive self-monitoring in drivers' decision-making. The researchers observed that low metacognitive ability and impulsive action were associated with dangerous driving and crashes, making metacognitive judgment a predictor of driving development.

The research findings of Love et al. [12] showed that self-regulation of attention was proportional to drivers' experience and metacognitive abilities. Also, perceptual ability and attentional strategies contributed to their control processes. Additionally, they found that cognitive functioning awareness and metacognitive beliefs can interact with environmental stimuli, influencing attentional functioning, self-regulation, and driving behavior.

In summary, research studies [11,22,46,63,73,76–78] highlight driving as a demanding, skillful, and complex process, combining executive skills in various combinations at different times. However, attention, working memory, and inhibition play a dominant role. Emphasis is placed on the essential function of attention, which involves using different executive processes. In addition, the development of metacognitive competence provides situational awareness through self-observation and self-assessment of the driver's abilities. Prediction of future conditions promotes the ability to adapt to unforeseen circumstances (Figure 2 and Table 1).

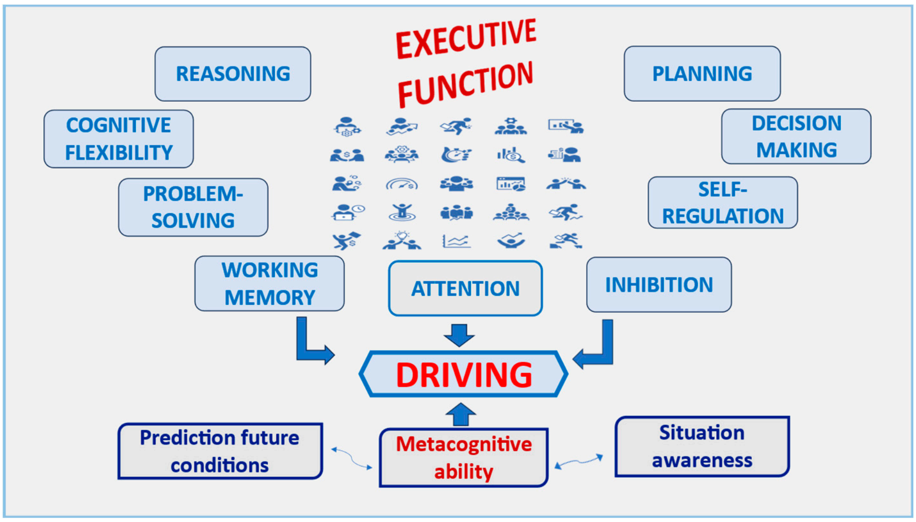

Figure 2. Utilization of executive skills—metacognitive ability in driving.

Table 1. Functionality of executive functions in driving and outcomes that derive from deficits.

Executive Functions	Function	Effect	Cause
Inhibition control, self-regulation	Behavioral control, emotional control, attention, and decision-making	Violence-aggression, impulsivity, poor decision-making, driving errors-violations, increased risk-taking	Substances (alcohol, drugs), young age of the driver, spatial skills and visual perception
Attention, working memory	Inhibition of distraction, shift attention, update information	Increased accidents, cognitive loads, prediction of complex situations, reduced situational awareness, delay in informational processing	Mobile phones, in-vehicle information systems, outside vehicle information (advertisements-information signs), mind wandering, fatigue, and limited sleep
Metacognition, decision-making	Observation, evaluation, and control of the cognitive mechanism, and the participation of higher executive functions, contributing essentially to optimal decision-making	Lack of predicted driving behavior, poor decision-making poor driving awareness, lack of driving evaluation in poor environments, difficulty in monitoring the surrounding spaces of the road	Gender differences (women assessed their performance better than men), age of the drivers (young drivers seem to lack in their metacognitive skills and decision-making)

5. Discussion

The effective use of the executive mechanism promotes the achievement of goals, the management of social interactions in various contexts, the development of interpersonal relationships, and the flexible adaptation of the individual [5]. Executive skills are a broader term that refers to higher cognitive functions that facilitate understanding of complex situations, abstract concepts, and a combination of knowledge and data, providing the ability to deal with volatile situations.

The highest mental abilities have a regulatory effect on thinking and action and, consequently, are utilized in demanding and complex conditions that require flexible and immediate adaptation, for instance, driving [15]. They develop from early childhood, reaching their highest development point in adulthood [17].

Studies spanning cultural boundaries highlight the significance of culture in the maturation of executive function [80]. Cultural differences are associated with variations in executive mechanism development, with childhood bilingualism being a potential enhancer. At the same time, their further development involves socioeconomic factors, value systems, parental care rules, and educational systems [42].

One study [81] points out that a balanced lifestyle with a healthy diet, physical activity, and sufficient sleep enhances brain function, positively affecting cognitive and executive function development. The environment has a mediating role in shaping an individual's lifestyle, and psychosocial factors may consequently affect the development of cognition [33].

However, the integration of small and targeted habits into a person's daily life facilitates the performance of executive skills. A regimen of nutritious dietary intake and regular physical activity engenders a myriad of antioxidants and anti-inflammatory agents, which serve to curtail oxidative processes within the brain and safeguard against neurodegeneration. Furthermore, there is an enhancement in neurotrophic factors, neurogenesis, and cell development [32,35]. Moreover, techniques for mindfulness reduce stressful thoughts and anxiety while increasing cognitive resources such as working memory and attention-promoting meta-awareness [41].

According to research, applying mindfulness to driving prevents deviant behaviors and increases situational awareness in the driving environment. In addition, it promotes concentration by maintaining selective and sustained attention, bringing about controlled and adaptive responses [12,74,77]. Conversely, smoking, alcohol, and substance use inhibit cognitive function, causing severe dysfunctions in decision-making, inhibition, risk perception, planning, mental adaptability, attention, visual perception, vigilance, psychomotor speed, and perseverative response [32,40,82].

Research findings indicate that the use of substances and alcohol acts as a burden on the functioning of the central nervous system and inhibits neurobiological functions related to efficient driving. The adverse consequences are felt mainly in the speed and accuracy of complex higher cognitive processes, focusing on perception, attention, and vigilance [52,82].

Considering the eighth most common cause of mortality globally for people of all ages, including children and young adults, according to a recent study, it is crucial to lessen and, more importantly, avoid such occurrences associated with reckless driving. Interventions focusing on driver education could form the basis for safe driving [69].

Studies that have researched driver errors while driving report that they emerge from psychological mechanisms and are related to cognitive errors referring to memory, perception, observation, attention, decision-making, inhibition, spatial skills, and planning. The connection of risk-taking with a sense of anger, aggressive behavior, and substance use is highlighted [49,52,54,73]. In particular, a few reasons accidents occur are the lack of concentration and attention to the target, dangerous overtaking, incorrect assessment of the fluctuation of speed and distance to the vehicles following or ahead, and generally limited metacognitive awareness [78].

The study's conclusions present the predictive role of executive function and more general cognitive development in driving performance. More specifically, developed executive abilities such as attention, inhibition, working memory, and planning, as well as cognitive abilities like visuospatial skills, orientation, calculation, and knowledge recall, are associated with better driving performance [83]. Also, other cognitive abilities required for successful driving relate to perception skills, information processing, appropriate reaction time, and context recognition during driving [49].

However, three executive skills stand out for their direct connection to driving: working memory, inhibition, and cognitive flexibility, all of which enhance the individual's functioning by managing different tasks in parallel, promoting adaptation and involving various executive skills [51]. However, inhibitory ability serves a lead role in driving performance, and drivers with reduced inhibitory control have low driving scores [15]. It is also worthwhile to point out that the complex ability of attention is a crucial factor in accident occurrence [22].

Uc and Rizzo [13] accentuate the essential role of attention in both information processing and the ability to observe and evaluate the driver's actions. More specifically, they believe accurate risk determination is crucial to avoid accidents. They propose four fundamental stages of information processing: perception—attention to stimuli that leads to the correct interpretation of the situation, utilization of previous knowledge, formation of a plan to deal with the current condition action, and observation—evaluation of the result with the possibility of possible re-determining necessary actions.

Drigas and Karyotaki [84] point out the connection between executive skills and metacognition, emphasizing the vital role of metacognition in their functioning. More specifically, an enhanced metacognitive capacity may compensate for cognitive deficiencies in decision-making, flexibility, and problem-solving. It is achieved through self-observation and self-evaluation of the cognitive mechanism and the required training to shift attention to information that guides the selection of optimal strategies.

Various studies underline the importance of situational awareness in managing cognitive and physical workload. Research findings support the idea that the ability to be aware of the current situation is the most frequent cause of errors in tasks carried out and driving. It requires the cooperation of higher cognitive functions for the performance of any dynamic and complex task, constituting a fundamental metacognitive function [11,76,79]. More generally, metacognition contributes to understanding how other drivers behave through observation, enabling the possibility of choosing an appropriate reaction. In addition, it promotes the regulation and harmonization of executive function by significantly influencing the decision-making process [79].

The present study investigated the relationship of executive functions with driver performance. More specifically, briefly studying factors that affect the development of the executive mechanism contributes to a better understanding of higher mental abilities. Previous reviews have looked in isolation mainly at executive skills and their influence on driving. This research includes the effects of factors that enhance or limit executive system performance and incorporates several executive skills related to safe driving ability. Hence, it provides a more comprehensive picture of the subject. In addition, the contribution of metacognitive ability to driving has a significant role in completing the investigation of the subject. The capacity for situation awareness improves the driver's behavior and performance, contributing decisively to the qualitative development of the executive mechanism and the individual's well-being in every area.

The increased demands of a constantly changing driving environment prompt people to activate mental processes. Attention, concentration, observation, working memory, inhibition, and situational awareness dominate. Their involvement and cooperation, to the extent attributed to them, in driving promotes effective decision-making and individual action in regard to existing conditions.

Limitations and Suggestions for Future Research

Attention, inhibition, and working memory are master executive skills that complement each other in pursuing a goal, such as driving. The present study generally focused on controlling attention and its influence on driving behavior, as it is a fundamental factor in inhibition and memory function.

However, we did not refer to the four types of attention (sustained attention, selective attention, alternative attention, and divided attention) and the possible influences of their function during driving. Future studies can extensively investigate how attentional patterns correlate with other executive skills and how this affects driver performance. In addition, we did not focus our search on demographic characteristics such as gender, age, and educational level and how these factors, combined with the development of executive skills, affect driving behavior. Subsequent research could incorporate these criteria in larger sample sizes by categorizing outcomes. Focusing further studies on investigating genetic factors that predispose people to EF differences could enhance the creation of effective intervention programs.

In addition, the study of educational approaches aimed at training attention, visual-spatial skills, memory, and self-regulation, enhancing inhibitory ability and risk perception, would be helpful for the expansion of quality, safe driving. Over and above that, metacognitive skills significantly influence executive function, particularly attention, working memory, and inhibition, thereby having a notable impact on driving safety. Therefore, training a driver to be aware of their conscious process is an additional valuable viewpoint to consider while developing intervention strategies. Accordingly, appraising the results of this study, future use of age, gender, and education within cross-cultural comparisons may indicate why and how these factors influence executive functioning while driving. Furthermore, technology-based interventions, such as facilitation and training in the form of Virtual Reality [85] as well as neurofeedback training [86], seem to be very promising in showing positive effects on the executive function. Finally, it becomes a necessity to establish a universal framework for how we could access and intervene with specific skills of executive function while performing in real-life, and task-specific situations where enhancement is needed to improve performance.

6. Conclusions

The executive mechanism consists of an array of mental processes that complement each other and support the pursuit of an objective, including driving. The review of sources suggests that deficits in executive function play a dominant role in driving performance, significantly affecting road safety. Dysfunctions in attention, working memory, and inhibition are of prominent importance, as they interact and develop an inextricable relationship in the development of driving, causing a reduced sense of danger, less self-regulation, limited impulse control, and less situational awareness. However, executive skills are trainable throughout one's lifetime, accounting for individual differences. Consequently, a combination of educational approaches intended to enhance executive control and metacognitive awareness could work positively on driving performance.

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