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The relationship between cognitive functioning and street-crossing behaviours in adults: A systematic review and meta-analysis

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ABSTRACT

Background: Pedestrians are vulnerable road users, with 26 % of global road fatalities being pedestrians (and other vulnerable road users). It is argued that pedestrians are involved in crashes due to errors in decision-making due to deficits in cognitive skills. To date there has limited research into pedestrian decision-making. There currently stands no theoretical model to help understand how cognitive function impacts on pedestrian street crossing decisions.
Objectives: The aim of this review was to synthesize the literature on the relationship between cognitive functioning and street-crossing behaviours, in two population groups: all adults, and older adults with or without a cognitive impairment.
Data sources: Published literature from three databases (PsycINFO, PubMed and Medline) was searched in February 2022. Studies were required to have investigated the relationship between cognitive functioning and street-crossing behaviours.
Results: Nine studies were identified for the systematic review, with four cognitive domains and nine street-crossing behaviours examined. Findings from the systematic review suggested that poorer processing speed and visual attention predicted increased unsafe street-crossing behaviours across the two population groups. Additionally, most studies demonstrated a non-significant relationship between executive function and street-crossing behaviours. Results from the meta-analysis on all adults, demonstrated a small effect size for the strength of the relationship between overall cognitive functioning and street-crossing behaviours, with stronger effects noted in individual domains of selective attention and inhibition.
Limitations: The small number of studies in this space combined with considerable variability in cognitive domains measured, assessment tools utilized, and street-crossing behaviours examined across studies limit conclusions about patterns of the relationship between cognitive functioning and pedestrian safety.
Conclusions: Findings highlight the important role of visual attention in enabling the engagement of safe street-crossing behaviours, which may assist in the development of targeted interventions to reduce risk of harm to pedestrians. Given unexpected findings regarding the influence of executive functioning, as well as limited findings on other cognitive domains such as mental status and memory, future research should aim to elucidate their role in pedestrian safety. Further research into cognitive function and pedestrian street crossing behaviours is critical if we are to develop a theoretical framework for how pedestrians make road-crossing decisions. If we can

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better understand the factors that influence street crossing decisions, roadway infrastructure and training programs can be developed to improve outcomes for this vulnerable population.

1. Introduction

Vulnerable road users, including motorcyclists, cyclists and pedestrians, account for approximately 26 % of road fatalities worldwide (World Health Organization, 2018). A pedestrian is defined as an individual who travels on foot through walking or running, or with mobility aids such as walkers and canes (Unterberger & Johnston, 2015). Daily, most individuals interact with the roadway system as pedestrians (Unterberger & Johnston, 2015). Pedestrians are particularly vulnerable to injury as they lack protection in the event of the crash (Unterberger & Johnston, 2015). This is particularly the case for older adult pedestrians who are more fragile and therefore collisions are more likely to be fatal for these individuals (Kim, 2019). Given that pedestrians have an elevated level of risk compared to other more protected road users, it is important to understand the factors that can impact on their safety. In investigating this it is prudent to examine both the system-based factors and the individual characteristics which can affect safety. From a systems approach, modelling has been demonstrated to be useful in examining how the behaviour of the entire social system (drivers, pedestrians, and other road users), as well as roadway design and infrastructure interact with one another to understand how crashes occur; Goughnour et al., 2021; Helbing et al., 2015; Meneses & Burlan, 2022). This modelling however is only as good as the research on behaviour that underlies it. When investigating individual characteristics, research has tended to focus on the impact that failures in drivers have on crashes with pedestrians (Amado et al., 2020), and less focus on the impact that failures by pedestrians might have on their safety. It is therefore important to investigate the errors in decision-making made by pedestrians (Dommes et al., 2015a).

1.1. Street-crossing behaviours

To safely navigate the roadway system, pedestrians need to employ a variety of safety behaviours. Common street-crossing behaviours include looking before crossing a street, waiting at red lights, crossing at green lights, not using mobiles or headphones when crossing, correctly identifying hazards, selecting safe crossing gaps, and compliance with road rules (Education and Aware, 2013). Researchers have studied street-crossing behaviours using a variety of dependent measures; start-up delay (i.e, slower response when starting to walk), hazard perception (i.e, the ability to identify approaching hazards such as oncoming vehicles; Rosenbloom 2015), near-side crossings (i.e, approaching vehicle closest to the pedestrian starting point), far-side crossings (i.e, approaching vehicle opposite side of the road), unsafe street crossing decisions (i.e, inappropriate head movements or smaller safety gaps when crossing), time-to-contact (i.e, shortest time remaining to be hit by a vehicle), close calls and hits (i.e. almost or colliding with a vehicle; Geraghty et al., 2016; Ford et al., 2017). These measures allow researchers to understand how failure to effectively implement street-crossing behaviours may result in harm. Pedestrians engage in a wide variety of different behaviours which can either mitigate or increase their risk of being in a collision, there is a dearth of research into some key pedestrian behaviours, such as hazard perception, relative to research on drivers (Moran et al., 2019).

Given that there are similarities with the way both drivers and pedestrians need to engage with the roadway to make safe decisions, greater investigation into the factors known to affect driving behaviour in pedestrians is important. Like drivers, a pedestrian needs to identify potential hazards, assess the road environment, and perform the act of crossing efficiently (Lobjois & Cavallo, 2007). Research into hazard perception has identified similar patterns of performance in pedestrians as what has been demonstrated in drivers. Research in drivers demonstrates that hazard perception performance improves with age and experience (Cao et al., 2022; Horswill et al., 2021), this has been demonstrated in pedestrians with children having poorer performance than adults (Meir & Oron-Gilad, 2020). Furthermore, hazard perception in drivers has been argued to be a complex cognitive skill (Habibzadeh et al., 2023), with recent research demonstrating the neural complexity of hazard perception in pedestrians (Zhu, Chang & Sun, 2020). Together this suggests that like drivers, pedestrians may experience road related injuries and fatalities due to cognitive errors in their decision-making. Research has supported this contention with cognitive errors being found to be associated with unsafe pedestrian behaviours (Dommes et al., 2013). Therefore, understanding how cognitive errors impact on one's effective street-crossing behaviours may help mitigate risk of harm to pedestrians.

1.2. Cognitive function and road safety

Cognition involves a range of mental processes which underlie how individuals perceive, attend to, remember, and manipulate information (Roy, 2013). Key cognitive domains include attention, processing speed, visual-spatial processing, memory, and higher order skills such as executive function (Zucchella et al., 2018). Cognitive skills across the range of these domains have been argued to play an important role in street-crossing behaviours as pedestrians require the ability to process visual stimuli and engage in decision-making processes to keep themselves safe (Dommes et al., 2015a). One theory which could help explain how cognitive functioning can interplay with pedestrian safety is the Information Processing Model (IPM; Uc & Rizzo, 2008). Although the IPM was originally developed to understand driving safety behaviours, it is probable that it can be applied to understanding street-crossing behaviours given that both behaviours involve the recognition of hazards (i.e, an approaching vehicle; Meyer et al., 2014). According to the IPM, there are four separate stages involved in the process of identifying and responding to road hazards for pedestrians (Uc & Rizzo, 2008). These stages are 1) perceiving and attending to roadway hazards which requires attention and visuospatial skills, 2) planning responses to hazards which requires executive function and memory, 3) execution of the developed plan which requires memory, executive function, and motor skills, and 4) modification of current or future responses and requires executive function. As each stage utilises different cognitive domains, cognitive errors during any of these stages increases the risk of harm.

The IPM was originally developed to explain how cognitive function predicts driving safety in older adults with neurodegenerative disease such as dementia and Parkinson's disease (PD; Uc & Rizzo, 2008). Recent research has expanded to apply the IPM to driving behaviours across the lifespan and for individuals without neurodegenerative disorders. This is due to the developmental trajectory of cognitive function across the lifespan which follows an inverted U-shape (Ferguson et al., 2021). Research has identified that cognitive development increases dramatically from infancy into early adulthood, then peaks and plateaus around 30 years old followed by cognitive decline accelerating after the age of 60 (Salthouse, 2009; Wu et al., 2016). The inverted U-shape of cognitive development matches the U-shape curve of road fatalities. Child pedestrians are at an increased risk of being involved and therefore killed in a crash compared to adults (World Health Organization, 2023). This has been argued to be because of their underdeveloped cognitive function (Meir et al., 2023; Riaz et al., 2022; Zare et al., 2019). This trend continues as cognitive function continues to develop into the mid-to-late 20′s younger people (<25 years) being more likely to be killed in road crashes than during middle adulthood (25–65 years) where fatalities plateau (Ledger et al., 2019b). As cognitive function begins to decline in older adulthood (>65 years) road fatalities starting to rise again (Ledger et al., 2019b).

Research has found that the IPM is applicable in drivers across the lifespan, with significant moderate relationships found across a variety of behaviours. Zicat et al. (2018) finding poorer cognitive function (specifically executive function and visuospatial skills) predicted increased speeding in young drivers, and Ledger et al. (2019a) findings that poorer cognitive function (specifically executive function, mental status, and memory) predicted poorer overall driving ability in middle adulthood. Finally numerous studies have found that poorer cognitive function across the domains of the IPM predict poorer overall driving in older adults without cognitive impairment (Hotta et al., 2018; Ledger et al., 2019b), as well as with cognitive impairment such as dementia and PD (Uc & Rizzo, 2008). Importantly, the relationship between cognitive function and driving behaviours occurs in similar patterns, and have small to moderate in effect size, across all age groups (Ledger et al., 2019b). Taken together, this suggests that an individual's level of cognitive abilities is an influential factor in driving safety behaviours across the lifespan.

1.3. Cognitive function and pedestrian behaviours

Although the majority of research has applied the IPM theory to driving populations, there is a suggestion that the same cognitive processes required to be a safe driver, might also apply to being a safe pedestrian. For example, selective and divided attention skills may assist pedestrians in processing the necessary visual information to navigate the roadway (Dommes et al., 2013). Visuospatial processing skills may be utilized by pedestrians to perceive visual information (e.g, car position relative to a pedestrian crossing) and estimate time-to-arrival (the available time to cross a road safely) to make safe street crossing decisions (Dommes et al., 2013). Executive functioning skills may assist pedestrians to remain safe by inhibiting irrelevant visual stimuli, monitoring changing environments and allowing for quick decision-making in dangerous situations (Dommes et al., 2013). Studies with children have consistently demonstrated the importance of executive function to safe pedestrian behaviours (Barton & Morrongiello, 2011) Finally, memory skills help pedestrians to adhere to road rules and navigate familiar environments (Dommes et al., 2013). A recent review demonstrated that when there is a disruption to these cognitive processes, such as what occurs in neurodevelopmental disorders, these individuals are at an increased risk of making poorer street-crossing decisions (Wilmut & Purcell, 2021). Thus, individuals with poorer cognitive abilities in these domains may be at increased risk of harm when exposed to unsafe pedestrian conditions such as oncoming vehicles and unmarked crossings (Dommes et al., 2014).

The suggestion that cognitive processes might explain pedestrian crash risk is supported by the fact that older adult pedestrians have the highest fatality rate of any population group (Tiwari, 2020; Wilmut & Purcell, 2022). Given that older adults are experiencing cognitive decline, this increased crash risk could be attributable to this cognitive decline (Tiwari, 2020). Despite the argument that the same cognitive skills may be useful to be a safe pedestrian, there is currently no theoretical model which outlines the interplay between cognitive function and pedestrian behaviours. To date no thorough review on the relationship between cognitive function and pedestrian behaviours for adults, regardless of age and also specifically for older adults, has been conducted. A review of this sort would be a useful starting point for the development of a theoretical understanding of the role of cognitive function in pedestrian behaviours.

1.4. Rationale and aim

Understanding the relationship between cognitive functioning and street-crossing behaviours for adults is crucial for mitigating risk of harm. No systematic research has looked at the impact of cognitive ability on street-crossing behaviours in adults. Similarly, despite considerable research identifying that cognitive decline and impairment amongst older adults increases dangerous driving behaviours (Hotta et al., 2018; Bennett et al., 2016), there has been no understanding reached as to how cognitive decline and impairment specifically in older adults may impact on street-crossing behaviours.

Critically, understanding the nature and size of the relationship between cognitive function and street-crossing behaviours in adults, and specifically for at-risk older adults with and without cognitive impairment can help to identify pedestrians who are likely to be at greater risk of harm due to poorer cognitive functioning in certain domains. This may allow for the development a theoretical understanding of cognitive function and pedestrian behaviours as well as of targeted interventions on key cognitive domains which will improve pedestrian safety.

Of note, this review has been limited to research focusing on adults rather than also including children. Children comparative to adults have the lowest risk of being killed as a pedestrian (Tiwari, 2020), in part because of the protective role of parental supervision (Deluka-Tibljas et al., 2022). As such children interact with the roadway differently to adults. Furthermore, children experience rapid cognitive development with drastic changes in cognitive function evident between different ages/stages (Bjorklund, 2022). It would be more prudent to do a more comprehensive and nuanced review on the role of cognitive function and the specific behaviours of child pedestrians as opposed to grouping them in with research on adults.

Therefore, the aim of the current review is twofold. Firstly, the systematic review aims to synthesize findings on the relationship between cognitive functioning and street-crossing behaviours in all adults as well as separately for older adults and adults with cognitive impairment. Secondly, the meta-analysis aims to quantify the size of the relationship between overall cognitive function, and individual cognitive domains, and street-crossing behaviours for each of the population groups.

2. Method

2.1. Information sources and search terms

This systematic review aimed to investigate the relationship between cognitive function and street-crossing behaviours and was conducted in accordance with PRISMA guidelines (Page et al., 2021). Three databases (PsycINFO, Medline, PubMed) were searched in February 2022 for relevant peer-reviewed literature with no date restrictions to ensure broad coverage. Boolean operators and truncation were used to identify relevant literature related to cognitive function and street-crossing behaviours. The search terms included: "Pedestrian" or "Vulnerable Road User*" AND "way-find*" OR "cross" OR "navigat*" OR "orientat*" OR "gap acceptance" OR "hazard perception" OR "crash" OR "fall" OR "collision" OR "accident*" OR "injur*" AND "Cognitive Function*" OR "Cognitive test" OR "Neuropsych*" OR "Executive function" OR "Inhibition" OR "Visu*spatial" OR "Memory" OR "Attention" OR "Processing Speed" OR "Psychomotor". Additional literature was identified through screening the reference lists of selected publications. The initial search was completed by the primary author (NV) with a review at the full text stage completed by both authors. Any discrepancies between authors were resolved by discussion.

2.2. Study selection and eligibility criteria

Eligibility of articles was determined based on the following criteria: 1) participants were pedestrians, 2) participants were adults aged 18 years and over, 3) outcome measures included a measure of pedestrian behaviour (e.g, crossing a street, head movement) and an assessment of cognitive function (e.g, visual processing, inhibition), and 4) the study examined the relationship between cognitive test performance and pedestrian behaviours. Studies were excluded if they were not in English. Additionally, papers were excluded if they were not published or peer reviewed, case studies, case reports, letters, dissertations, books, reviews, editorials, conferences and abstracts only.

2.3. Data extraction

A spreadsheet was piloted prior to commencement of data extraction. Data extracted from each publication included article details (i.e, author, year, country), sample size, participants' demographic characteristics (i.e, age range, mean age, standard deviation, population characteristics such as cognitive impairment), study design (i.e, cross-sectional, or experimental), cognitive function measure (e.g, Tests of Attentional Performance), the type of pedestrian behaviour (e.g, street crossing tendencies or looking behaviour) and main findings. Statistical information for the meta-analysis was also extracted and is discussed in more detail below.

2.4. Quality assessment

A modified version of the 'Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist (Von Elm et al., 2007) was utilised for this review. This modified version consists of 15 items and was taken from a systematic review by Depestele et al. (2020) which examines cognitive function in older adult drivers. This modified version was selected rather than the original full version as it enabled comparisons between comparable research topics in this field. The 15 items are categorised into three groupings; introduction, method and results, and discussion. Scorers gave each item a rating out of 2, with 0 (negative), 1 (mediocre) and 2 (positive). A maximum score of 30 was possible, with scores of 22 or less indicating poor-quality, between 23 and 25 indicating medium quality and 26 or higher indicating high quality. Both authors independently reviewed the articles against the criteria. Discrepancies in scores were resolved through discussion.

2.5. Meta-Analysis

Comprehensive Meta-Analysis (CMA) Version 3 (Borenstein, Hedges, Higgins, & Rothstein, 2014) was used to conduct the meta-analysis. Analyses were only conducted where there was a minimum of two studies contributing to the effect size (Valentine et al., 2010). The effect size of interest was a Pearson's correlation *r* coefficient, with up to 0.3 indicative of a small effect size, 0.5 a moderate effect size and greater than 0.5 a large effect size (Cohen, 1988). In all cases a positive relationship represents a correlation between poorer cognitive function and poorer pedestrian safety.

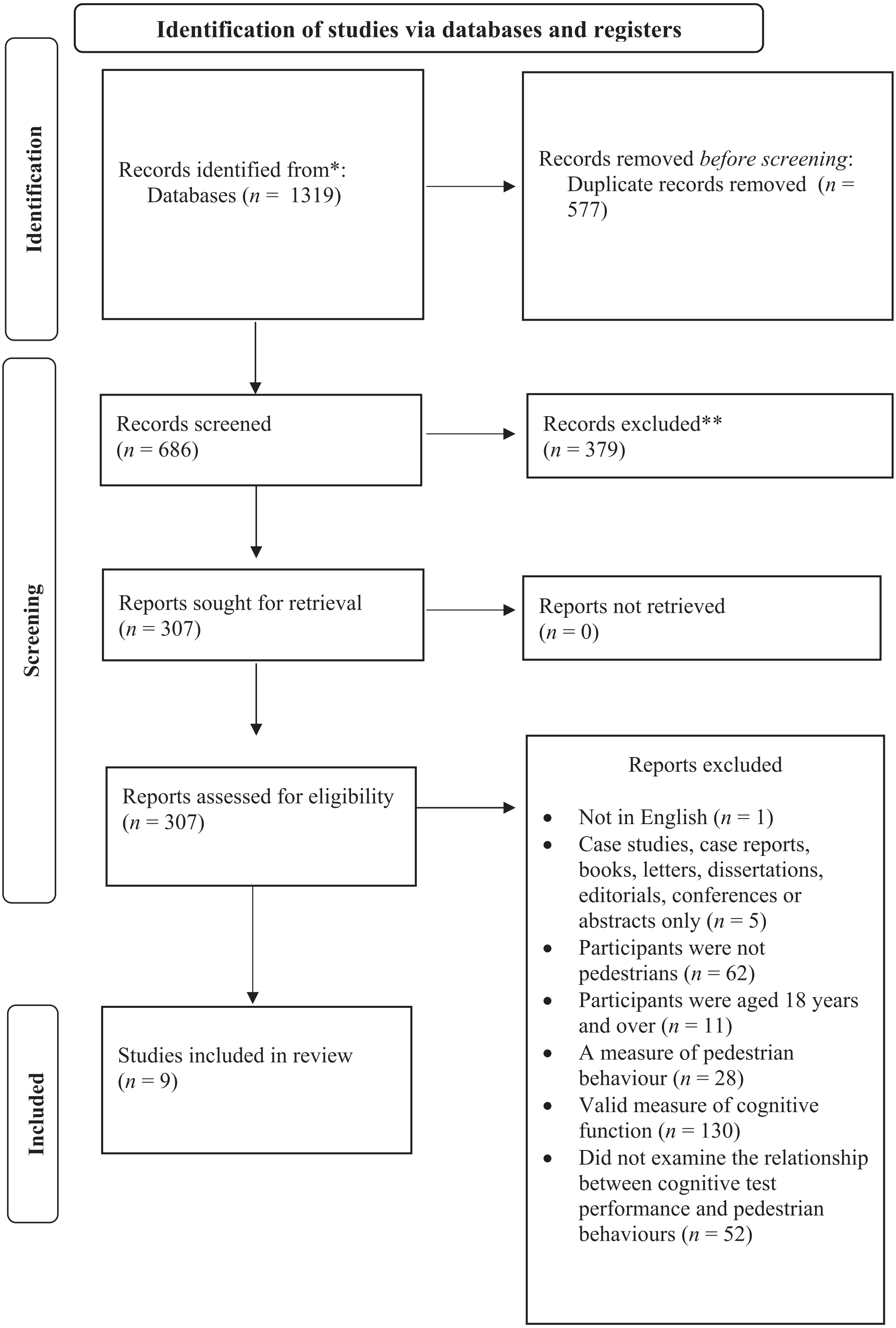

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Fig. 1. PRISMA Flowchart for Study Selection Process.

A random effects model was utilised for all analyses in line with recommendations (Borenstein, Hedges, Higgins, & Rothstein, 2021). To assess heterogeneity Q and I^2 were examined. I^2 values of 0.25 represented low, 0.50 represented moderate and 0.75 represented high heterogeneity (Higgins, Thompson, Deeks, & Altman, 2003). When studies yielded multiple effect sizes these were averaged so that each study only contributed a single effect size per analysis. Subgroup analysis by cognitive domain was conducted. Publication bias was examined via an examination of funnel plots, Egger's test, Duval and Tweedie trim and fill analysis, and classic fail-safe N tests.

3. Results

3.1. Search results

Fig. 1 shows the PRISMA flowchart outlining the search process. Findings from three databases were extracted and then references deduplicated. Nine eligible articles were found to meet eligibility criteria. Out of the nine eligible articles, four studies combined all adults together as one population group. Whereas five studies selectively differentiated between older adults with or without cognitive impairment. The study by Ford et al. (2017)[7] reported results separately for older adults without impairment and older adults with Parkinson's diseases and as such these findings are reported separately. A superscript numbering system from 1 to 9 was employed to help interpret results.

During the search there were a number of studies which were found that examined the impact of completing cognitively demanding dual-tasks whilst crossing the street, however these studies were excluded as they did not directly analyse the relationship between cognitive function in a specific cognitive domain and street-crossing behaviours. For clarity, an example of an excluded study is Dommès (2019) which examined the impact that a dual-task involving engaging in a cognitively demanding task whilst crossing the street had on the workload of pedestrians. Whilst this study includes a reaction time task, it does not examine relationship between performance on that task as a measure of attention specifically and street-crossing behaviours. Whilst a review of dual-tasking was outside the scope of this review, it may be suitable for a future research.

3.2. All adults

3.2.1. Study characteristics

Table 1 displays the study characteristics of the five studies which included adults. This means that studies conducted analyses over and above age or without isolating findings to a specific age group. A total of 362 participants were involved in these studies, with age ranging from 20 years to 80 years of age. All articles were published since 2011, with three studies being conducted in France, and one in America and England. All studies examined pedestrian behaviours by utilising a pedestrian street crossing simulation task. These studies examined seven different street-crossing behaviours. Unsafe crossing street crossing decisions in four studies[1–3,5], with Geraghty et al. (2016)[5] further examining this in terms of near-side and far-side crossings. Each of the following were only examined once, start-up delay[5], auditory detection distance[4], direction determination[4] and unacceptable distance[4].

3.2.2. Pattern of relationships & meta-analysis

Findings related to cognitive function and street-crossing behaviours for all adults are presented in Table 2. All significant findings within the table represent a relationship between poorer cognitive function in a specific cognitive domain and poorer safety on a specific pedestrian behaviour measure. Across all cognitive domains, there were a total of 47 unique findings, with only nine significant (19 %). Bivariate or partial correlation coefficients were extracted directly from six studies[1,2,4,5], excluding Dommes et al. (2015a)[3] which included odds ratios. The overall relationship between cognitive function regardless of domain and street-crossing behaviours was found to be positive, weak, and significant, $r = 0.27$, 95 % CI [0.07, 0.45], $p = .009$, $k = 4$. Heterogeneity between studies was found to be moderate, $Q = 8.75$, $p = .033$, $I^2 = 65.69$, $\tau^2 = 0.03$. See Fig. 2 for the forest plot.

3.2.2.1. Attention and processing speed. There were 20 unique findings[1–5] relating to attention and processing speed, and street-crossing behaviours. Five out of the 20 findings (25 %) found a significant positive relationship between scores on attention and processing speed tests and street-crossing behaviours. The overall relationship was found to be significant, moderate, and positive, $r = 0.33$, 95 % CI [0.08, 0.54], $p = .010$, $k = 4$. Heterogeneity was found to be large and significant, $Q = 14.08$, $p = .003$, $I^2 = 78.70$, $\tau^2 = 0.06$. To examine the source of this heterogeneity, subdomains were analysed where possible.

The three subdomains of processing speed, divided attention and selective attention were examined. Eight findings[3-5] related to processing speed, with two different tests used, UFOV subtest 1 and the Pattern Comparison Test. Only two out of eight findings (25 %) found a significant relationship, with the overall relationship found to be weak and non-significant, $r = 0.12$, 95 % CI [−0.04, 0.27], $p = .154$, $k = 2$, $Q = 1.12$, $p = .290$, $I^2 = 10.80$, $\tau^2 = 0.002$. Five findings[3,5], all using the UFOV subtest 2, examined divided attention, with all reporting no relationship between divided attention and street-crossing behaviours. Due to insufficient studies, no meta-analysis was conducted for divided attention. For selective attention, there were seven findings[1–3,5] all using the UFOV subtest 3. Three out of the seven findings (42.9 %) found a significant relationship between selective attention and street-crossing behaviours. The overall relationship between selective attention and street-crossing behaviours was found to be significant, moderate, and positive,

Table 1
Summary of Study Characteristics for All Adults.

Author, Year (Country)	*N*	Age: M (SD)	% Female	Design	Cognitive Measure	Pedestrian Measure -Behaviour	Main Findings
[1]Dommes & Cavallo, 2011; (France)	Young adults: 20 Younger-old adults: 21 Older-old adults: 19	Young adults: 25.2 (3.4) Younger-old adults: 68.1 (2.7) Older-old adults: 76.7 (3.5)	Young adults: 50 % Younger-old adults: 57 % Older-old adults: 58 %	Cross-sectional	• Useful Field of View (UFOV Subtest 3-Selective Attention) • Spatial Stroop Task (Inhibition)	Stimulator-unsafe street crossing decisions	There was a significant positive relationship between both selective attention and inhibition, and unsafe street crossing decisions
[2]Dommes et al., 2013 (France)	Young adults: 16 Younger-old adults: 17 Older-old adults: 18	Young adults: 28.3 (4.3) Younger-old adults: 62.8 (2.4) Older-old adults: 76.9 (4.4)	Young adults: 50 % Younger-old adults: 59 % Older-old adults:56 %	Cross-sectional	• UFOV- subtest 3 (Selective Attention) • Test of Attentional Performance (TAP; Inhibition, Shifting, Updating)	Stimulator-unsafe street crossing decisions	There was a significant positive relationship between selective attention, inhibition and shifting, and unsafe street crossing decisions. There was no relationship between updating and unsafe crossing decisions
[3]Dommes et al., 2015a (France).	Young adults: 20 Younger-old adults: 25 Older-old adults: 33	Young adults: 22.2 (1.94) Younger-old adults: 67.8 (3.35) Older-old adults: 77.2 (4.4)	Young adults: 60 % Younger- old adults: 60 % Older- old adults: 69.7 %	Cross-sectional	• UFOV- subtest 1 (Processing Speed) • UFOV- subtest 2 (Divided Attention) • UFOV-subtest 3 (Selective Attention) • TAP (Shifting, Inhibiting, Updating subtests)	Simulator-unsafe street crossing decisions	Processing speed and selective attention were significant predictors of unsafe street crossing decisions. Divided attention, shifting, inhibiting, and updating were all non-significant predictors.
[4]Barton et al., 2016 (America)	Younger adults: 35 Older adults: 35	NR	Younger adults: 57 % Older adults: 51 %	Cross-sectional	• Pattern Comparison test, Contingency Naming test (Processing Speed)	Simulator- Pedestrian auditory detection distance, direction determination, unacceptable distance.	There was a significant positive correlation between speed of processing, unacceptable distance, and detection distance
[5]Geraghty et al., 2016 (England)	103 aged 45 years and over.	66.5 (9.89)	63 %	Cross-sectional	• UFOV- subtest 1 (Processing Speed) • UFOV- subtest 2 (Divided Attention) • UFOV-subtest 3 (Selective Attention) • Affective Go-No-Go Task (Shifting) • Stop-Signal Task (Inhibition) • Intra-Extra Dimensional Set Shift (Updating) • Spatial-Span Task (Working Memory) • Stockings of Cambridge (Spatial Planning)	Stimulator– unsafe street crossing decisions, unsafe near-side crossings, unsafe far-side crossings, start-up delay	There was a significant positive correlation between inhibition and unsafe crossing errors. There were trending significant positive relationships between inhibition and near-side unsafe decisions, and selective attention and far-side unsafe decisions. All other relationships were non-significant.

Note. Tests of Attentional Performance (TAP), Useful Field of View (UFOV), Mini Mental Status Exam (MMSE), Trial Making Test Part A(TMT-A), Trial Making Test Part B (TMT-B), Clock Drawing Test (CDT), Rey-Osterreith Complex Figure Test copy version (CFT-Copy, CFT-Recall).

Table 2
Relationship between Cognitive Function and Pedestrian Behaviours by Cognitive Domains in all Adults Over and Above Age.

Cognitive domain	Cognitive test	Significant association $p < .05$	No association $p > .05$
Attention and Processing Speed			
Processing Speed	Pattern Comparison Test	Barton et al.[4], 2016- unacceptable distance	
			Barton et al.[4], 2016- detection distance Barton et al.[4], 2016- direction determination
	Useful Field of Vision (UFOV)- subtest 1	Dommes et al.[3], 2015a- unsafe street crossing decisions	
			Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Divided Attention	UFOV- subtest 2		Dommes et al.[3], 2015a- unsafe street crossing decisions Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Selective Attention	UFOV- subtest 3	Dommes & Cavallo, 2011[1], 2011- unsafe street crossing decisions Dommes et al.[2], 2013- unsafe street crossing decisions Dommes et al.[3], 2015a- unsafe street crossing decisions	
			Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Executive Function			
Inhibition	Tests of Attentional Performance (TAP) Inhibition subtest	Dommes et al.[2], 2013- unsafe street crossing decisions	
			Dommes et al.[3], 2015a- unsafe street crossing decisions
	Spatial Stroop Task	Dommes & Cavallo, 2011[1], 2011- unsafe street crossing decisions	
	Stop Signal Task (SST)	Geraghty et al.[5], 2016- unsafe road crossing decisions	
			Geraghty et al.[5], 2016- start-up delay Geraghty et al.[5], 2016- far side crossings Geraghty et al.[5], 2016- near-side crossings
Updating	TAP Updating subtest		Dommes et al.[2], 2013- unsafe street crossing decisions Dommes et al.[3], 2015a- unsafe street crossing decisions
	Intra-Extra Dimensional Set Shift		Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Shifting	TAP Shifting subtest	Dommes et al.[2], 2013- unsafe street crossing decisions	
			Dommes et al.[3], 2015a- unsafe street crossing decisions
	Affective Go-No-Go Task		Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Working Memory	Spatial Span Task		Geraghty5 et al., 2016- start-up delay

(*continued on next page*)

Table 2 (*continued*)

Cognitive domain	Cognitive test	Significant association $p < .05$	No association $p > .05$
Spatial Planning	Stockings of Cambridge		Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing Geraghty5 et al., 2016- start-up delay Geraghty5 et al., 2016- unsafe crossings Geraghty5 et al., 2016-near-side unsafe crossing Geraghty5 et al., 2016- far-side unsafe crossing
Cognitive Status		–	–
Memory		–	–
Visuospatial Skills		–	–

Note. Useful Field of View (UFOV), Tests of Attentional Performance (TAP), Stop Signal Task (SST). Across all cognitive domains, there were a total of 47 unique findings, with only nine significant (19 %).

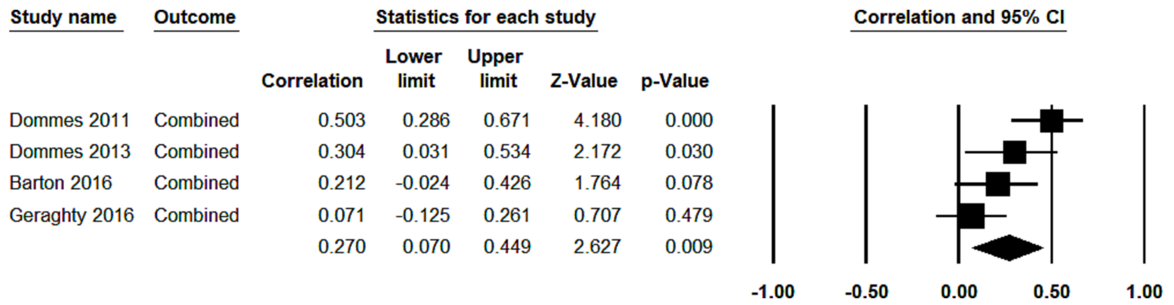

Fig. 2. Forest Plot for Overall Relationship Between Cognitive Function and Street-Crossing Behaviours In Adults. *Note.* A weak, positive significant relationship was found between poorer cognitive function across all domains and poorer safety on pedestrian behaviour measures.

Table 3
Quality Assessment STROBE.

	Introduction		Method									Results and Discussion				Score	Quality
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
All Adults																	
Dommes & Cavallo, 2011[1]	2	2	0	2	1	2	2	2	1	1	2	1	2	2	0	21	Poor
Dommes et al. (2013)[2]	2	1	0	2	1	2	2	2	1	1	2	1	2	2	0	24	Medium
Dommes et al. (2015a)[3]	2	2	2	2	1	2	2	2	1	1	2	1	2	2	0	24	Medium
Barton et al. (2016)[4]	2	2	2	1	2	2	2	1	1	2	2	2	2	2	2	27	High
Geraghty et al. (2016)[5]	2	2	2	2	2	2	2	2	1	2	2	2	1	2	2	28	High
Older Adults – With and Without Cognitive Impairment																	
Lin et al. (2013)[6]	2	2	2	2	1	2	2	2	1	1	2	1	2	2	2	25	Medium
Dommes et al. (2015b)[7]	2	2	2	2	1	2	2	2	2	1	1	2	2	2	2	25	Medium
Ford et al. (2017)[8]	2	2	2	2	0	2	2	2	2	2	1	2	2	2	2	26	High
Callisaya et al. (2017)[9]	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	28	High

Note. **Questions:** 1 = Is the scientific context clearly explained?, 2 = Are the objectives clearly stated?, 3 = Are the setting and relevant dates (periods of recruitment, exposure, follow-up and data collection) clearly explained?, 4 = Are inclusion and exclusion criteria and selection of participants clearly explained?, 5 = Is the sample size considered adequate?, 6 = Are the study outcomes clearly described?, 7 = Is the method used in the assessment clearly described?, 8 = Is the method for assessment valid?, 9 = Are the efforts to limit potential sources of bias reported?, 10 = Are the statistical methods clearly described?, 11 = Are the statistical methods appropriate?, 12 = Is drop-out during the study clearly described?, 13 = Are the characteristics of the subjects described?, 14 = Is there selective reporting of results?, 15 = Are study limitations discussed?.
Rating System: 0 = negative rating, 1 = mediocre rating, 2 = positive rating.
Total Score Criteria: ≤22 = poor quality, 23–25 = medium quality, ≥26 = high quality.
Methodological quality varied across the studies with the areas for most improvement being limits of potential bias and discussion of limitations.

$r = 0.39$, 95 % CI [0.10, 0.63], $p = .010$, $k = 3$, $Q = 10.11$, $p = .006$, $I^2 = 80.22$, $\tau^2 = 0.06$.

3.2.2.2. Executive functioning. There were 27 unique findings[1–3,5] relating to executive function, and street-crossing behaviours. Four out of the 27 findings (14.81 %) found a significant positive relationship between scores on executive function tests and street-crossing behaviours. The overall relationship was found to be significant, weak, and positive, $r = 0.24$, 95 % CI [0.01, 0.45], $p = .039$, $k = 3$. Heterogeneity was found to be moderate and non-significant, $Q = 5.61$, $p = .060$, $I^2 = 64.55$, $\tau^2 = 0.03$. To examine the source of this heterogeneity, subdomains were analysed where possible.

The five subdomains of inhibition, updating, shifting, working memory and spatial planning were examined. There were seven unique findings for inhibition across three tests, with a significant relationship found in three findings (42.9 %). The relationship between inhibition and street-crossing behaviours was found to be significant, weak, and positive, $r = 0.27$, 95 % CI [−0.09, 0.44], $p = .004$, $k = 3$, $Q = 3.68$, $p = .159$, $I^2 = 45.66$, $\tau^2 = 0.01$. For updating there were six unique findings[2,3,5] across two tests with all found to be non-significant. The relationship between updating and street-crossing behaviours was found to be non-significant, weak, and positive, $r = 0.13$, 95 % CI [−0.03, 0.28], $p = .117$, $k = 2$, $Q = 0.13$, $p = .719$, $I^2 = 0.00$, $\tau^2 = 0.00$. For shifting there were six unique findings[2,3,5] across two tests with only one found to have a significant relationship. The relationship between shifting and street-crossing behaviours was found to be non-significant, weak and positive, $r = 0.16$, 95 % CI [−0.10, 0.41], $p = .225$, $k = 2$, $Q = 2.43$, $p = .119$, $I^2 = 58.77$, $\tau^2 = 0.02$. For working memory there were four unique findings, all from the same study[5] measured using the spatial span task, with no relationship found between working memory and different street-crossing behaviours. For spatial planning there were four unique findings, all from the same study[5] measured using the Stockings of Cambridge task, with no relationship found between spatial planning and different street-crossing behaviours.

3.2.2.3. Other domains. No studies investigated the relationship between cognitive status, memory or visuospatial abilities, and street-crossing behaviours.

3.2.3. Quality assessment and publication bias

The amended STROBE quality assessment ratings are presented in Table 3. For all adults, there was one poor quality study, two medium quality studies and two high quality studies. All five studies utilised and described appropriate methods and utilised appropriate statistical analyses to answer their research questions. The most common area for improvement is in describing or making attempts to limit areas for potential bias, and in the discussion of the limitations of the study. When examining the pattern of findings, there was no evidence to suggest bias in the findings based on study quality. For example, for executive function, significant relationships were found in a poorly rated study[1], in a medium rated study[2] and in a highly rated study[3].

Visual inspection of the funnel plot (see Fig. 3) for the overall analysis between cognitive function and street-crossing behaviours found no evidence of asymmetry. This was supported by a non-significant Egger's intercept = 8.29, $p = .219$. The Duval and Tweedie's trim and fill analysis demonstrated that no studies were required to be trimmed from either side of the funnel plot suggesting that there is no evidence of bias. The classic failsafe N found that 17 non-significant studies would be needed to bring this effect to the null. Given that only four studies were included in the analysis, and the high number of non-significant findings revealed through the systematic review, 17 non-significant studies is not impossible, suggesting the chance for bias.

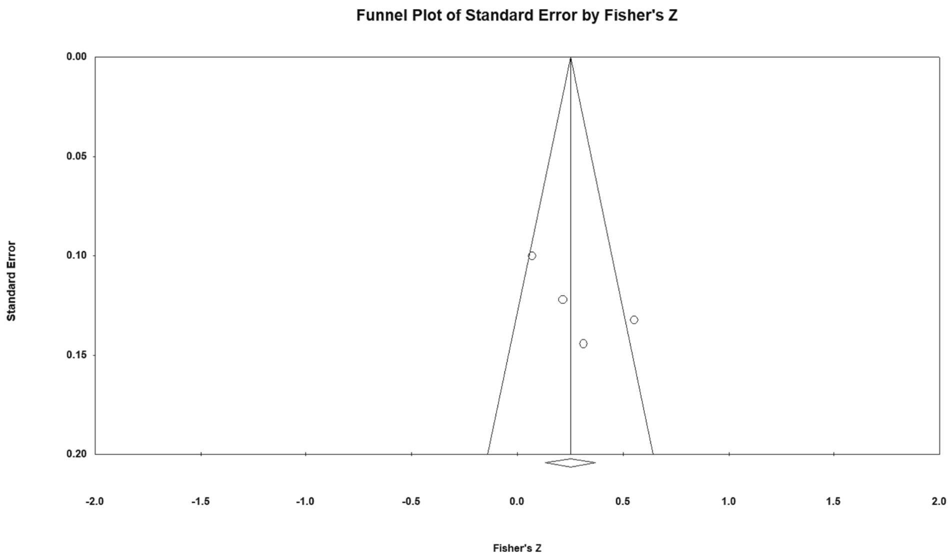

Fig. 3. Funnel Plot for the Overall Analysis Examining the Relationship Between Cognitive Function and Street-Crossing Behaviours. *Note.* No evidence of asymmetry found in the funnel plot suggesting no publication bias.

Table 4
Summary of Study Characteristics for Older Adults With and Without Cognitive Impairment.

Author, Year (Country)	*N*	Age: M (SD)	% Female	Design	Cognitive Measure	Pedestrian Measure -Behaviour	Main Findings
[6]Lin et al., 2013 (Taiwan)	PD: 31 Healthy older adults: 50	PD: 65.3 (8.1) Healthy older adults: 67.7 (5.4)	PD: 48.4 % Healthy older adults: 46 %	Cross-sectional	• MMSE (cognitive status) • UFOV-total (visuospatial)Rey-Osterreith Complex Figure Test copy version (CFT-Copy; visuospatial) • CFT-recall (memory) • Clock Drawing Test (CDT; visuospatial) • Benton Visual Form Discrimination (VFD; visuospatial) • TMT- A and TMT-B (executive function)	Stimulator-unsafe street crossing decisions	For PD Memory and visuospatial skills were significant unique predictors of unsafe road crossing decisions Regardless of cognitive statusVisuospatial skills, memory and executive function were all significant unique predictors of unsafe road crossing decisions. Only MMSE was non-significant
[7]Dommes et al., 2015b (France)	Mild Alzheimer's disease (AD): 25 Healthy older adults: 33	Mild AD: 76.8 (7.8) Healthy older adults: 76.4 (5.4)	Mild AD: 64 % Healthy older adults: 67 %	Cross-sectional	• UFOV- subtest 1 (Processing Speed) • UFOV- subtest 2 (Divided Attention) • UFOV- subtest 3 (Selective Attention) • TAP (Shifting, Inhibition, Updating, Behavioural Control subtests)	Simulator -unsafe street crossing decisions	There was a significant positive correlation between all subtests of the UFOV and the TAP (shifting) and unsafe street crossing decisions regardless of cognitive status
[8]Ford et al., 2017 (America)	Parkinson's disease (PD): 50 Healthy older adults: 25	PD: 62.54 (8.04) Healthy older adults: 61.88 (9.51)	PD: 42 % Healthy older adults: 48 %	Cross-sectional case-control observational study	• UFOV- Total	Simulator – Time to contact (TTC), number of hits and close calls	There was a significant negative correlation between UFOV-Total and TTC, Hits/Close calls amongst PD group There was no significant association between UFO-total and TTC, Hits/Close calls amongst older adults.
[9]Callisaya et al., 2017 (France)	Healthy older adults: 321 Mild cognitive impairment (MCI): 321 Mild dementia: 70 Moderate dementia: 38	Healthy older adults: 70.8 (3.5) MCI: 73.1 (5.1) Mild dementia: 80.1 (5.5) Moderate dementia: 82.9 (5.9)	Healthy older adults: 42 % MCI: 37 % Mild dementia: 65 % Moderate dementia: 68 %	Cross-sectional	• MMSE (Grouping into cognitive status diagnoses)	Stimulator-safe street crossing walking speed (i.e, faster, and preferred walking speed)	There was a significant relationship between poorer cognitive status and faster and preferred walking speed

Note: Tests of Attentional Performance (TAP), Useful Field of View (UFOV), Mini Mental Status Exam (MMSE), Trial Making Test Part A(TMT-A), Trial Making Test Part B (TMT-B), Clock Drawing Test (CDT), Rey-Osterreith Complex Figure Test copy version (CFT-Copy, CFT-Recall), Mild Cognitive Impairment (MCI), Parkinson's Disease (PD), Alzheimer's Disease (AD).

3.3. Older adults with and without cognitive impairment

3.3.1. Study characteristics

Table 4 displays the study characteristics of the four studies which isolated results to older adults, with or without cognitive impairment. There was a total of 895 older adults included across the studies. All studies included a sample of healthy older adults and older adults with a form of cognitive decline. Diagnoses for cognitive impairment included PD in two studies[6,8], mild Alzheimer's disease in one study[7] and in one study[9] a mixed sample of mild cognitive impairment, mild dementia and moderate dementia (form of dementia not specified). All four studies were conducted between 2013 and 2017, with two studies conducted in France, and one each in America and Taiwan. All studies examined pedestrian behaviours by utilising a pedestrian street crossing simulation task. Three different street-crossing behaviours were examined; unsafe street crossing decisions was examined by two studies[6,7], time to collisions in one study[8] and walking speed in one study[9].

Table 5

Relationship between Cognitive Function and Street-Crossing Behaviours by Cognitive Domains in Older Adults With and Without Cognitive Impairment.

	Cognitive test	Significant association $p < .05$	No association $p > .05$
Attention and Processing Speed			
Processing Speed	Useful Field of Vision (UFOV)- Subtest 1	Dommes et al.[7], 2015b- unsafe street crossing decisions – all	
Divided Attention	UFOV- Subtest 2	Dommes et al.[7], 2015b- unsafe street crossing decisions – all	
Selective Attention	UFOV- Subtest 3	Dommes et al.[7], 2015b- unsafe street crossing decisions – all	
Executive Functioning			
	Trial Making Task (TMT- B-A)	Lin et al.[6], 2013- unsafe street crossing decisions – all	
			Lin et al.[6], 2013-unsafe street crossing decisions- PD
Inhibiting	TAP subtest		Dommes et al.[7], 2015b- unsafe street crossing decisions – all
Updating	TAP subtest		Dommes et al.[7], 2015b- unsafe street crossing decision – all
Shifting	Test of Attentional Performance (TAP) subtest	Dommes et al.[7], 2015b- unsafe street crossing decisions – all	
Behavioural Control	TAP subtest		Dommes et al.[7], 2015b- unsafe street crossing decision – all
Cognitive Mental Status			
	Mini Mental State Exam (MMSE)	Callisaya et al.[9], 2017- fast walking speed- individuals with poorer stages of cognitive impairment Callisaya et al.[9], 2017- preferred walking speed- individuals with poorer stages of cognitive impairment	
			Lin et al.[6], 2013- unsafe street crossing decisions – all Lin et al.[6], 2013- unsafe crossing decisions- PD
Memory			
	CFT-recall	Lin et al.[6], 2013- unsafe street crossing decisions – all Lin et al.[6], 2013- unsafe street crossing decisions-PD	
Visuospatial Abilities			
	Benton Visual Form Discrimination (VFD)	Lin et al.[6], 2013- unsafe street crossing decisions – all	
		Lin et al.[6], 2013- unsafe street crossings decisions- PD	
	CFT-Copy	Lin et al.[6], 2013- unsafe street crossing decisions – all	
			Lin et al.[6], 2013- unsafe street crossing decisions- PD
	Clock Drawing test	Lin et al.[6], 2013- unsafe street crossing decisions – all Lin et al.[6], 2013- unsafe street crossing decisions-PD	
	UFOV-Total		Ford et al.[8], 2017- Time to Contact (TTC) – older adults Ford et al.[8], 2017- Hits and Close calls – older adults
		Ford et al.[8], 2017- Time to Contact (TTC)- PD Ford et al.[8], 2017- Hits/close calls- PD Lin et al.[6], 2013- unsafe street crossing decisions- PD Lin et al.[6], 2013- unsafe street crossing decisions – all	

Note: Useful Field of View (UFOV), Time-to-contact (TTC), Rey-Osterreith Complex Figure Test (CFT-copy, CFT-recall), Benton Visual Form Discrimination (VFD), Trial Making Task Part A and Part B(TMT-B-A), Tests of Attentional Performance (TAP), Mini Mental State Exam (MMSE). Across all domains there were a total of 26 unique findings, with 17 (65 %) of these significant.

3.3.2. Pattern of relationships

Findings related to cognitive function and street-crossing behaviours for older adults with and without cognitive function are presented in Table 5. All significant findings within the table represent a relationship between poorer cognitive function in a specific cognitive domain and poorer safety on a specific pedestrian behaviour measure. Across all domains there were a total of 26 unique findings, with 17 (65 %) of these significant. Due to Lin et al. (2013)[9] included odds ratios with corresponding 95 % CI's however these were adjusted in multiple logistic regression analyses and therefore were not included in the analysis, and Callisaya et al. (2017)[8] group of cognitive status into four distinct groupings, these studies were not able to be included in the meta-analyses. With these exclusions meta-analyses were unable to be conducted for older adults with and without cognitive impairment due to insufficient data.

3.3.2.1. Attention and processing speed. Attention and processing speed was examined in a single study[7] with three findings. Dommes et al. (2015b) examined processing speed, divided attention and selective attention using the UFOV subtests 1–3. Dommes et al. combined results for both older adults with and without Alzheimer's disease. For all three subtests (100 % of findings) a significant positive relationship was found between all tests such that poorer performance on the tests was associated with more unsafe road crossing decisions.

3.3.2.2. Executive functioning. Executive function was examined by two studies[6,7], with six findings. Two different tests were used, the Trail Making Tests which examined overall executive function, and the Test of Attentional Performance (TAP) which has different subtests examining domains of executive function (inhibiting, updating, shifting, behavioural control). A significant positive relationship between executive function and street-crossing behaviours was found in only two (33.3 %) of the findings regardless of cognitive impairment.

3.3.2.3. Cognitive Mental status. Cognitive mental status was examined using the Mini-Mental State Examination (MMSE) in two studies[6,9] with four findings. A significant positive association was found between cognitive mental status and pedestrian safety in two of the findings (50 %), with both significant findings from Callisaya et al. (2017)[9] and the two non-significant findings from the study by Lin et al. (2013)[6]. Callisaya et al.[9] found that poorer cognitive status according to the MMSE was associated with slower walking speeds.

3.3.2.4. Memory. Memory was only examined by a single study[6] using the Rey Complex Figure (CFT) Recall task, with two findings, one for individuals with PD and one for healthy older adults. For both groups (100 %) a significant relationship was found such that poorer memory was associated with more unsafe crossing decisions.

3.3.2.5. Visuospatial abilities. Visuospatial ability was examined in two studies[6,8] with 12 unique findings. A significant relationship with poorer visuospatial ability being associated with poorer street-crossing behaviours was found for nine of the 12 findings (75 %) Both studies isolated results for individuals with PD with a significant relationship between poorer visuospatial ability and poorer safety was found in five out of six findings (83 %).

3.3.3. Quality assessment

The amended STROBE quality assessment ratings are presented in Table 3. For older adults, there were two medium quality studies and two high quality studies. All four studies clearly outlined their inclusion criteria and utilised and described appropriate methods to answer their research questions. The most common area for improvement is in ensuring that the sample size was sufficient for the analyses, and as such meant that the analyses were not necessarily the most appropriate given the sample. When examining the pattern of findings, there was no evidence to suggest bias in the findings based on study quality. For example, when examining visuospatial abilities, both the medium[6] and high[8] quality studies found significant and non-significant relationships between visuospatial abilities and street-crossing behaviours.

4. Discussion

This review was the first to synthesize the existing literature on the relationship between cognitive function, across different cognitive domains and its relationship with street-crossing behaviours in adults. There has been limited research to date on the role of cognitive function as a predictor of pedestrian safety, with a lack of theoretical framework underlying the interplay between cognitive function and street-crossing behaviours. As pedestrians are vulnerable road users, it is important to understand the cognitive factors that might be associated with their increased risk of being in road crashes. Nine studies were included in the review, five which examined all adults, and four which included older adults with and without cognitive impairment. The results for these groups will be discussed separately below.

4.1. All adults

Five studies examined the relationship between cognitive functioning and street-crossing behaviours for adults. Across all domains a significant weak to moderate positive relationship was found between overall cognitive function and street-crossing behaviours. Whilst this is a small effect size, this is consistent with effect sizes in research into the relationship between cognitive function and driving performance across the lifespan (Ledger et al., 2019a; Ledger et al., 2019b). This finding provides preliminary support for the notion that cognitive function across some of the domains outlined in the IPM might predict street-crossing behaviours as well as driving safety. This is a tentative statement however as not all studies were able to be included in the meta-analysis. Similarly, due to the overall small number of studies included in the review there is a need for more research, in particular to include all of the domains outlined in the IPM (no studies have examined visuospatial skills or memory) before more definitive conclusions are made. The current finding however warrants this research. There is benefit in continuing this research to determine whether a single theory, such as the IPM, explains how cognitive function influences both driving and pedestrian safety. If there is a single model which explains both behaviours, it would provide a potential mechanism for which we can focus on through training. For example, if we knew that inhibition was It would also provide a potential mechanism by which greater safety gains could be made for both populations simultaneously. If we for which training of cognitive skills rather than just driver safety or pedestrian safety.

This review highlights that whilst we find this overall effect, some cognitive skills may be more related to street-crossing behaviours than others. When examining all studies in attention and processing speed the overall effect size was moderate and significant, but the effect size for processing speed specifically was weak and non-significant whilst the relationship for selective attention was moderate and significant. This finding is in line with the IPM that attention skills, in particular selective attention, are crucial for individuals' when identifying hazards in complex traffic environments (Uc & Rizzo, 2008). Of note, most of the tests that were used for attentional abilities (UFOV) were examining attention in the context of a visuospatial environment. This suggests that visuospatial attention could be an important skill for pedestrians when making street-crossing decisions. The ability to make a definitive conclusion about the role of visuospatial skills is limited however due to the lack of studies examining it. Future research should therefore specifically investigate visuospatial abilities as an individual domain across all ages to further understand its importance.

This same pattern was found for findings relating to executive function. Results demonstrated a weak significant relationship between executive functioning skills and street-crossing behaviours which is again consistent with prior research into driving across the lifespan (Ledger et al., 2019a; Ledger et al., 2019b). This relationship however appears to be largely driven by the relationship between inhibition and safety which was significant and weak to moderate, whereas the relationships for updating and shifting were both found to be weak and non-significant. The IPM postulates that executive functioning skills are integral for planning and enacting decisions related to street crossing. Whilst the relationship between inhibition and safety adheres to this framework, the lack of relationship between the skills of updating and shifting are unexpected. A detailed section on executive function is below.

The small number of studies reviewed in this population group reflects the sparsity of past research examining the relationship between cognitive functioning and street-crossing behaviours in adults. No studies have isolated findings for younger adults and middle-aged adults, this limits our understanding of how cognitive maturation processes may potentially impact their street-crossing behaviours. This is problematic as Holland and Hill (2007) argue that cognitive maturation processes may place different age groups at increased risk of making poorer street crossing decisions. Therefore, it is important that future research isolate findings by age groups to thoroughly understand how cognitive abilities impact on street-crossing behaviours for each age group individually, as well as across the lifespan.

4.2. Older adults with and without cognitive impairment

There were only four studies which isolated the results between cognitive function and street-crossing behaviours for older adults with and without cognitive impairment. As with the findings related to all adults, the following statements are tentative in nature due to the limited number of studies included in the review. Whilst a meta-analysis could not be performed, a significant relationship was found between cognitive function and street-crossing behaviours in almost two thirds of the findings for older adults regardless of cognitive impairment. Compared to the 19 % of significant findings found for all adults, the 63 % of findings for this group is much higher. This aligns with the known impact that age-related decline in cognitive function in older adults has on driving performance (Depestele et al., 2020). This finding suggests that cognitive function is an equally important predictor of safety for older pedestrians. This highlights the need to take into consideration cognitive functioning when developing strategies, such as training programs, to keep older pedestrians safe.

As with all adults, there is tentative support for the application of the IPM to understanding street-crossing behaviours in older adults. Similarly, this finding appears to be domain dependent. The findings related to attention and memory were consistent, however these were both from a single study each so need to be interpreted with caution. There were mixed results for visuospatial abilities, based on the type of street-crossing behaviour examined. For instance, poorer visuospatial abilities did not significantly predict hits/close calls as well as time to collision (Ford et al., 2017) but did predict unsafe street crossing decisions (Lin et al., 2013). Whilst most research has focused on unsafe road crossing decisions, there are numerous other street-crossing behaviours which remain important. The mixed findings for visuospatial skills suggest that the relationship between cognitive function and safety could be dependent on the behaviour being measured. Thus, it is important that future research examines a range of street-crossing behaviours to understand how they may be associated with different cognitive processes. Consistent with findings for all adults, across most studies, executive functioning was not a significant predictor of street-crossing behaviours and will be discussed below.

The limited number of studies specifically examining this vulnerable age group is of significant concern given that older adults experience age-related decline in cognitive function and are therefore more likely to do a significant portion of their commuting as pedestrians due to reduced driving abilities (Doulabi et al., 2021). Given that past research has highlighted that poorer cognitive functioning negatively impacts on driving safety behaviours amongst older adults (Depestele et al., 2020), more research is needed on how cognitive functioning affects street-crossing behaviours in this age group.

It should be noted that that due to the limited number of studies, the different diagnostic groups (PD, AD, MCI, and dementia) were combined despite the conditions having diverse neuropathology and resulting impact on cognitive function. Unfortunately, this limits our understanding of the nuance in relationships for these different disorders. Research into drivers with cognitive impairments has highlighted the importance of isolating findings for different dementia aetiologies (Piersma et al., 2016). Irrespective, the findings highlight that decline because of cognitive impairment is also likely to lead to impact on street-crossing behaviours. Given that individuals with neurodegenerative diseases tend to cease driving earlier than older adults and are thus more likely to represent a larger pedestrian group (Jacobs et al., 2017), future research in this population is critical so to develop more targeted pedestrian safety strategies.

4.3. Executive functioning

There were mixed findings relating executive function to street-crossing behaviours both within and across population groups. Predominately, results highlighted non-significant relationships between street-crossing behaviours and domains of executive functioning including shifting, updating, inhibition and working memory. This was unexpected given that the IPM contends that executive functioning is crucial for driving safety behaviours, and it was thus plausible that executive functioning would similarly be a key component of street-crossing behaviours. This unexpected finding could be because the measures used in the studies were not sensitive enough to elucidate the true relationship between executive function and pedestrian behaviours. The non-significant finding were across several executive function tests (i.e, TAP, TMT-B-A, Stop Signal Task), and different street-crossing behaviours (i.e, unsafe street crossing decisions, start-up delay, far-side crossings). It could be that either the cognitive tests were not sufficient at capturing the components of executive function relevant for pedestrian decision making, or that executive function is not related to the pedestrian behaviours measured. Executive function is a higher order processing skill, perhaps it simply only becomes more relevant to pedestrians when the task becomes more complex (like how driving is an incredibly complex task; Moran et al., 2020), such as when the pedestrian is also distracted by using their phone for example.

Given the theoretical argument for the role of executive functioning in street-crossing behaviours, further research is needed to determine the exact nature of this relationship. Suggestions for future research include increasing the complexity of pedestrian behaviour tasks to examine the above stated hypothesis. Furthermore, to determine whether there are limitations with the type of executive function tests used, research should compare multiple executive function tests within a single study. Finally, it would be important to understand whether the relationship between executive function and pedestrian behaviours depends on the developmental trajectory of executive function, studies should isolate findings for younger, middle-aged, and older adults.

4.4. Limitations and directions for future research

Findings of this systematic review should also consider that there were a few methodological limitations, both of previous research and the review itself. Firstly, the research in this field has appeared to stall, with no studies that met inclusion criteria having been published since 2017. This is particularly problematic given that this review examined the relationship between cognitive function and pedestrian safety in older adults. Given that many countries are facing an ageing population more older adults will be traversing the roadway system on foot, so understanding how their declining cognitive skills might be affecting their safety as pedestrians is important. It is hoped that this review will reignite research into this important area by providing direction for further work. Similarly, the lack of recent work in this space has a limiting effect on the conclusions of this review. Only nine studies met inclusion criteria, and these were further sub-divided in two population groups which inhibits confidence that the pattern of results would hold if more research was done. This however does not detract from the necessity of this review. Understanding the relationship between cognitive function and pedestrian behaviours in adults is important because there is currently a lack of a theoretical framework for how cognitive function impacts on pedestrian safety. If we are to design safer roadway systems for pedestrians and training programs to improve the safety for this vulnerable population, we need to better understand the skills that are necessary for safe roadway navigation. It is hoped that by highlighting these issues through this review this will act as a catalyst for more research in this space, even if that further research changes the pattern of findings evidenced here within.

A significant limitation across the literature was the considerable variability in how street-crossing behaviours were measured. Whilst simulators were used in all studies, there was diversity in not only the simulated scenarios but also the range of dependent variables (i.e, unacceptable distance, unsafe street crossing decisions and start-up delay), which may cloud the identified relationships between cognitive domains and street-crossing behaviours. Consensus on the most important pedestrian behaviours and how to best operationalise these behaviours is needed across the literature. Once this is achieved, more laboratory-based studies which measure this range of behaviours critical to being a safe pedestrian are needed. If multiple outcomes are examined within the same cohort of participants it will give a better understanding of how cognitive function impacts on different behaviours.

It is important to note that this review was limited in scope as it is did not examine the evidence pertaining to cognitive function and pedestrian behaviour in children. Unlike adults whereby cognitive function remains relatively stable throughout middle adulthood, children experience rapid cognitive development with drastic changes in cognitive function evident between different ages/stages (Bjorklund, 2022). Given this, we determined that a more thorough and nuanced review focused specifically on children across the different stages of development would be more meaningful than one combined with adults. The named research team is currently investigating the relationship between cognitive function and pedestrian safety in children.

The review itself was also limited as unpublished studies and grey literature were not included. This may have led to the exclusion of findings that may have altered the conclusions of the review. Given the small number of studies, and the high proportion of non-significant result across the studies, it is possible that this field of research suffers from a file drawer problem. Whilst there was no evidence of publication bias, this potential file drawer problem has implications for the effect sizes represented within the paper.

There is benefit in continuing this research to determine whether a single theory, such as the IPM, explains how cognitive function influences both driving and pedestrian safety. If there is a single model which explains both behaviours, it would provide a focus for training. Currently training programs are designed to target only a single problem, i.e, hazard perception performance in drivers or street-crossing behaviours in pedestrians, with no studies to date (to the authors knowledge) examining transferability of training across different road user behaviours. However, if we knew that inhibition was a core skill for both drivers and pedestrians, targeting improving this cognitive skill through training could result in net-safety benefits in both behaviours simultaneously. We first need to determine through more research into this area if there is increasing support for the preliminary findings related to the applicability of the IPM for pedestrians outlined in this review. If so, future research should examine the potential of including cognitive training within other road safety interventions as well as the transfer effect across different road user behaviours.

5. Implications and conclusions

The current paper was the first to synthesize the literature on the relationship between cognitive functioning and street-crossing behaviours in adults, as well as older adults with and without cognitive impairment. Findings from this review highlighted that impaired selective attention and inhibition were the strongest predictors of higher levels of unsafe pedestrian street-crossing behaviours such as riskier street crossing decisions across all adults as well as older adults with and without cognitive impairment.

This review highlighted the overwhelming lack of research that has looked at these relationships, and that this research has stalled with no new papers published within the last six years. Doing more laboratory-based studies which examine the relationship between cognitive function and street-crossing behaviours is critical to the development of a solid theoretical framework. The development of this framework is necessary to determine best practice in terms of roadway design, and education and training programs. Safe-systems research based on modelling to determine roadway design is increasing in the road-safety space, and this modelling depends on an understanding of the individual characteristics which affect street-crossing decisions of pedestrians. Furthermore, understanding these relationships are particularly important for the older adult population who are more likely to move away from driving to traversing the roadway as pedestrians as their main transportation option. If we better understand the role of cognitive decline in street-crossing, we could use this information to develop large scale educational campaigns. These campaigns can equip older adults with information regarding the deficits they may be experiencing and through awareness help them regulate their own behaviours when crossing the street. Similarly, if we understand that pedestrians are more likely to make attentional based errors in street-crossing we can mitigate against these issues by developing training programs which are focused at improving the cognitive skill of attention. These types of training programs could be offered to older adults when they interact with driving licencing agencies and medical practitioners as they transition to driving cessation. Together, this can help reduce the number of adult and older adult pedestrian fatalities caused by cognitive errors when using street-crossing behaviours.

CRediT authorship contribution statement

Natasha Valos: Conceptualization, Methodology, Data curation, Writing – original draft. **Joanne M. Bennett:** Supervision, Conceptualization, Methodology, Formal analysis, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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