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Active life–active mind? Associations between active travel and cognitive functions across the lifespan: a systematic review

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ABSTRACT

Particular types of physical activity (PA) hold the potential to enhance brain structure and functions across various age groups. *Active travel (AT)*, a non-motorised human-powered mode of transportation, might be a particularly important form of PA that may enhance neuropsychological development, benefit executive and visuospatial cognitive abilities, and contribute to preventing cognitive degeneration. Accordingly, this systematic review explores the associations between AT and cognitive outcomes in all age groups. Searches were conducted in five databases. Of 2401 initial hits, 11 studies met the inclusion criteria. The studies ranged from 36 to 2702 participants, examined diverse cognitive outcomes, and were predominantly with children or adolescents. No studies among adult ages 20- to 60-years were included, while only one study among older adults was included in the review. There was some evidence of positive associations between AT and spatial and reasoning abilities. Mixed results were identified between AT and executive functioning and processing speed, and no associations between AT and general intelligence. Limitations included reliance on self-reported AT, a focus mainly on school travel, and heterogeneity of cognition measures. Overall, this review reveals insufficient evidence for an association between AT and cognitive functions across the lifespan, underscoring the need for further investigation.

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Introduction

There is growing interest in the role of movement in brain function and cognition given the brain's role in intentional and unintentional movements via planning, commanding, evaluating, and enhancing specific movements and reactions, primarily within prefrontal cortex areas (Houk & Wise, 1995; Sarkodie-Gyan & Yu, 2023). Exercise may positively regulate synaptic functions (i.e. neurotransmission) (Hillman et al., 2008; Lubans et al., 2016; Voelcker-Rehage & Niemann, 2013), which can lead to molecular, cellular, behavioural, and systematic benefits for the brain, including better cognitive control and memory (Chaddock-Heyman et al., 2014; Sng et al., 2018; Varma et al., 2015, 2016). Combining locomotion with diversity and coordination challenges has been shown to further enhance the potential benefits on cognitive abilities, probably due to the involvement of sensory input (Bear et al., 2018; McArdle & Woodcock, 2014; McMorris, 2016; Purves et al., 2018). While cognitive functions evolve during childhood, most brain areas maintain their capacity for plasticity in response to various external and internal stimuli throughout one's entire life (Basso & Suzuki, 2017). Multiple theories and models try to explain mechanisms between exercise and cognition, considering mediating roles of physical and mental resources, health, age, gender, or exercise-specific parameters like skill acquisition (McMorris, 2021; McMorris et al., 2018; Smith, 2009; Spirduso et al., 2008; Tomporowski & Pesce, 2019). Hertzog et al. (2008) argues that the individual

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functions within a specific range of developmental possibilities are influenced by factors that come into play before early adulthood. They suggest varying developmental paths in life resulting in four distinct individual cognitive curves over a lifetime based on behavioural, environmental, and genetic factors, assuming the onset of maturity at the age of 20. They also emphasize that activities promoting a sense of control and mastery are self-reinforcing and are more likely to result in the development of a consistent and lasting lifestyle that can potentially boost cognition (Hertzog et al., 2008).

A systematic review of 84 RCTs published until 2017 (Gunnell et al., 2019) among healthy children, aged <18 years found that acute and chronic PA was associated with positive or at least not harmful effects on cognitive function, brain function, or brain structure. Other systematic reviews analysing the effects of PA on cognition solely in children (Álvarez-Bueno et al., 2017; Bidzan-Bluma & Lipowska, 2018; Hillman et al., 2019) and solely in adolescents (Esteban-Cornejo et al., 2015; Haverkamp et al., 2020), have also indicated PA benefits for cognition with the potential mediating role of type of activity and some psychological factors (i.e. self-esteem, depression). Positive associations have also been observed among adults. A comprehensive review by Jedrziewski et al. (2007) on PA and cognitive health, covering various publications in adults since 1999, suggests that there may be a reduced risk of cognitive decline with aerobic activity, engagement in PA may hold the greatest impact on executive function, and exercise sessions of at least 30 min may benefit cognitive health.

The societal shift towards more sustainable mobility has boosted the focus on cycling and walking to reach places in everyday life, known as *active travel (AT)*, which may be a potentially efficient way to keep the brain active and healthy. AT, also known as *active transport*, *active mobility*, or *active commuting*, encompasses all kinds of non-motorised, human-powered transportation and can be carried out by most people regardless of age, sex, or socioeconomic status depending on the distance to destinations (Foley et al., 2018; Van Dijk et al., 2014). Besides the most common modes of walking and cycling, AT can also include other modes of locomotion, such as inline skating, longboarding, or kick scootering (Cook et al., 2022), and is classified as moderate to vigorous aerobic PA (Shephard, 2008).

Given that mentally stimulating and self-reinforcing activities promote cognitive functioning (Diamond & Ling, 2016; Pesce, 2009), it can be assumed that AT could enhance brain health and cognitive function, with potentially greater effects due to context. Engaging in AT can require quickly processing visual information and distinguishing relevant from irrelevant details (e.g. swiftly identifying and interpreting traffic signs, pedestrians, and potential obstacles while biking in busy urban environments), spatial awareness to judge distances and avoid collisions, use of executive functions like decision-making and problem-solving, sustained attention and switching focus quickly, while holding multiple pieces of information in mind, such as traffic patterns and road signs for wayfinding (Staplin et al., 2003; Staplin & Lococo, 2003; Zink et al., 2016). These demands make AT in busy traffic a challenging and cognitively engaging skill and experience. As such, it is plausible that AT could challenge the brain in a way that benefits cognitive functions, such as executive (updating, inhibition, shifting) and visuospatial (perception, orientation, anticipation) abilities. To date, two systematic reviews have summarised the studies investigating the relationship between *active school travel (AST)* and cognition or academic achievement among children and adolescents (Phansikar et al., 2019; Ruiz-Hermosa et al., 2019). Phansikar et al. (2019) reported that five out of eight studies on cognitive abilities found positive associations with AST among children and adolescents, with better verbal fluency, numeric skills, reasoning, or executive functioning among girls, or mapping accuracy in both sexes. In their meta-analysis of four studies, Ruiz-Hermosa et al. (2019) found no associations between AST and cognitive performance (non-executive functions, core executive functions, metacognition).

To date, existing reviews on AT and cognition are limited to few studies that employ diverse measurement tools, and predominantly focus on children and adolescents, with a particular emphasis on AST and academic achievement. It is important to gain a comprehensive understanding of how PA impacts cognitive functioning among all ages to inform more inclusive and effective policies and interventions. Additionally, given that these reviews included studies published up to early-mid 2019 (Phansikar et al., 2019; Ruiz-Hermosa et al., 2019), it is possible that newer studies have investigated the link between AT and cognition. To advance understanding, it is crucial to review all forms of AT beyond AST, explore associations with cognition in wider age groups, and investigate diverse cognitive outcomes. Hence, the aim of this review is to systematically explore existing literature on associations between AT and cognitive functions across the lifespan.

Materials and methods

The review was executed according to the PRISMA Statement (Page et al., 2021) and registered in PROSPERO [CRD42023407557] in March 2023.

Literature search

Five databases, including MEDLINE Complete, APA PsycINFO, SPORTDiscus, Environment Complete, and Embase were systematically searched using search terms related to the concepts of (1) active travel (e.g. active transport*, commut*, non-motorised, or bike*); and (2) cognition (e.g. cognitive abilit*, executive function*, or mental skill*). The terms were combined using the following strategies: (1 [TI, AB] OR 1 [Subject Headings]) AND (2 [TI, AB] OR 2 [Subject Headings]). The search terms in combination with database-specific filters were applied for EBSCO databases (MEDLINE Complete, APA PsycINFO, SPORTDiscus, and Environment Complete) and adapted for the Embase database. In addition, reference lists of included papers were hand-searched for eligible articles based on the snowball system. The reproducible search terms for all databases are presented in the supplementary material (see Appendix). The search was conducted by MH.

Eligibility criteria

The review encompassed diverse study types, excluding only case and qualitative studies to address difficulties in assessing internal validity. It focused on quantitative studies that reported statistical associations or the relationship between AT and cognitive functions at any age. The exposure of interest was any form of AT, such as walking, biking, or their combination. Studies were included if they met the criteria of involving the general population across the lifespan, including children, adolescents, adults, and older adults. For the outcome (dependent variable), any type or measure of cognitive function (i.e. executive, visuospatial, perceptive, or memory skills), measured using any tool, were eligible. Eligible studies had to be published in peer-reviewed journals, available in English or German, without any publication period restrictions.

Studies were excluded if they focused on participants with disabilities or specific health conditions (e.g. mental health conditions, overweight or obese, diabetic, injured), referred to AT in biological terms (i.e. the transport of molecules), or involved non-human participants. Studies measuring *active transport* in contexts unrelated to the research, such as biomedical studies were excluded. The review also excluded studies that only reported motorised AT (e.g. e-bikes, public transport) or other types of PA (e.g. leisure sports, occupational exercise). In addition, certain publication forms, such as books, non-peer-reviewed articles, theses, and conference papers, as well as studies not in English or German, were excluded.

Selection process

Literature search results were exported, filtered for duplicates, and imported to the software Covidence,[1] a web-based collaborative software platform designed to optimize the process of creating systematic and other literature reviews.

Data extraction

Data were extracted for synthesis by MH and EM and checked by AT. Demographics, methodological details, relevant exposure and outcome variables, and statistical results were catalogued in: author, year, and country; sample description (*n*, age, sex); study design; AT exposure (type, parameters, categories, measurements, validity/reliability); cognitive outcomes (type, parameters, categories, measurements); statistical methods (including covariates); main findings; and strengths and limitations.

Quality assessment

The Effective Public Health Practice Project (EPHPP) Quality Assessment Tool for Quantitative Studies (Thomas et al., 2004) was used to determine study quality. The risk of bias assessment was conducted by two reviewers (M.H. and E.M.). Assessment misalignments between the two reviewers were discussed until a consensus was reached. The final ratings are presented in Figure 2.

Results

Study selection

Of the 3514 records returned, 1113 duplicates were excluded, and 2401 articles were screened by title and abstract according to the eligibility criteria. Of the 31 studies that subsequently underwent full-text screening, 20 were excluded as the reported outcome ($n = 11$), exposure ($n = 6$), population ($n = 1$), study design ($n = 1$), or publication type ($n = 1$) were not eligible for inclusion. In total, 11 studies were selected for the final review process. Each abstract and full-text article was screened independently by MH and EM until a consensus was reached. See Figure 1 for the full flow diagram of reviewed studies.

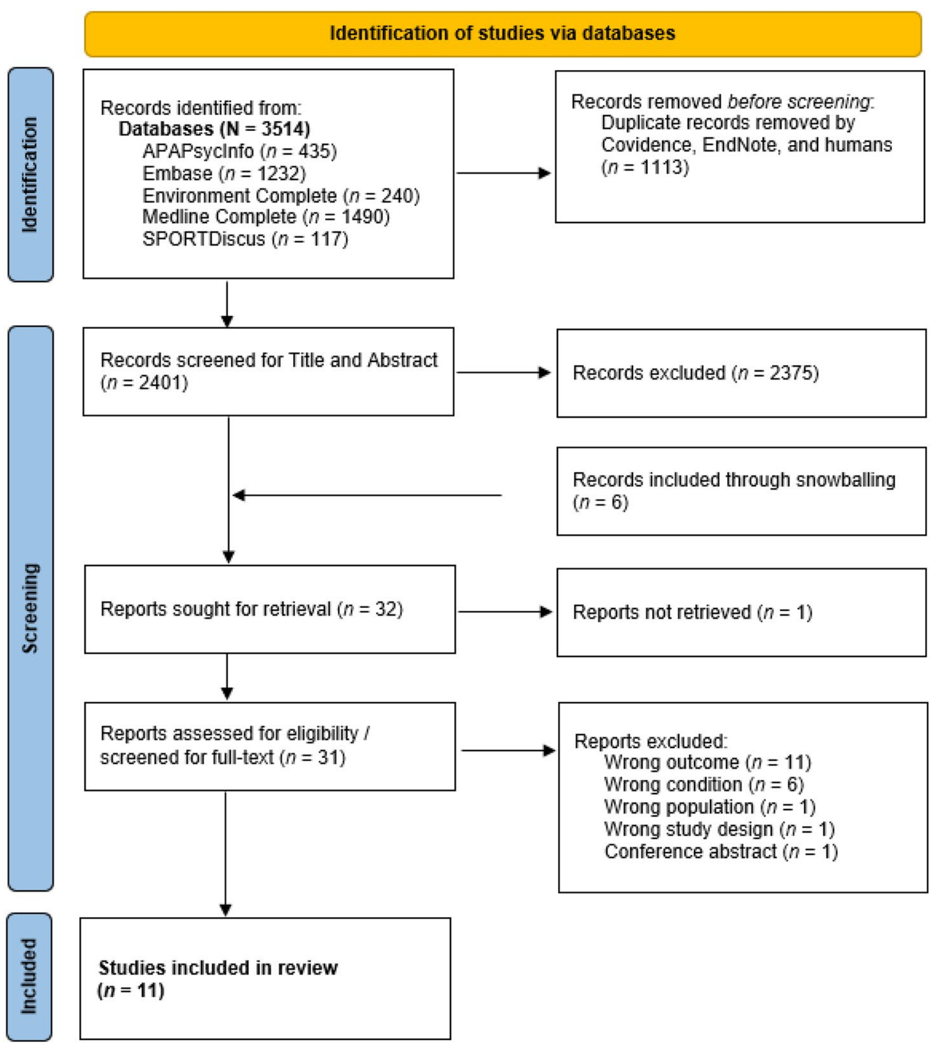

Figure 1. PRISMA 2020 flow diagram visualising the study search and selection process according to the PRISMA Statement (Page et al., 2021).

Study characteristics

The 11 studies were conducted in eight different countries (three in Spain, two in the USA, and one in Denmark, Taiwan, Sweden, Netherlands, Portugal, and Israel) and included 10,659 participants in total (sample sizes ranging from 36 to 2702 participants), generally equally distributed by sex (47–58% female), and aged between 4 and 77 years (Children: $n = 5049$ across six studies; Adolescents: $n = 2908$ across four studies; Adults: $n = 0$; Older adults: $n = 2702$ across one study). Ten of the 11 studies were cross-sectional (Appleyard, 2017; Domazet et al., 2016; Fang & Lin, 2017; Martínez-Gómez et al., 2011; Moran et al., 2017; Phansikar & Mullen, 2019; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018; Van Dijk et al., 2014; Westman et al., 2017), and one used a longitudinal design and reported both cross-sectional and longitudinal results (López-Vicente et al., 2016). See Table 1 for a detailed overview of all study characteristics.

The average study quality across all subcategories was moderate while the overall study quality was rated weak for three studies (Appleyard, 2017; Fang & Lin, 2017; Moran et al., 2017) and moderate for all others (Figure 2). All eleven studies scored a weak rating for the study design. The subcategories 'controlling for cofounders' and 'data collections methods' included the most ratings of high quality ($n = 11$), yet averagely does not surpass a medium level.

Active travel

All studies used self- or proxy report questionnaires to measure AT, with one exception: Van Dijk et al. (2014) used movement data between 7 am and 8:40 pm on weekdays measured by an ActivPal accelerometer to estimate the duration of AST. All of the studies with children and adolescents explicitly examined AST, whereas the study with older adults included AT to any destination (Phansikar & Mullen, 2019). Six studies explicitly measured only travel *to* school and two studies only examined travel for the day of the test.

The AT modes included in the studies ranged from active (walking, biking, inline skates, scooters) to passive (motorcycle, car, bus, subway, general public transport), as shown in Table 1. Table 2 presents an overview of the main AT outcome parameters and their distribution across the included studies. The exposure variables varied from being categorised by travel modes (Appleyard, 2017; Domazet et al., 2016; Martínez-Gómez et al., 2011; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018; Westman et al., 2017), to measures of frequency (Fang & Lin, 2017; Moran et al., 2017) and duration of AT (López-Vicente et al., 2016; Martínez-Gómez et al., 2011; Rodrigues et al., 2022; Van Dijk et al., 2014), and one examined meeting PA guidelines via METs-min/week of AT (Phansikar & Mullen, 2019). Nine studies collapsed frequency or duration into categories. Five studies included two categories, e.g. ≤15 *vs.* >15 min, active vs passive, or <4 days/week vs ≥4 days/week (Appleyard, 2017; Martínez-Gómez et al., 2011; Moran et al., 2017; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018), four included three categories (Domazet et al., 2016; Martínez-Gómez et al., 2011; Rodrigues et al., 2022; Westman et al., 2017), and two studies included four categories (López-Vicente et al., 2016; Phansikar & Mullen, 2019).

Only two studies that examined frequency or duration did not collapse the exposure variable. Fang and Lin (2017) examined the frequency/week of AST, while Van Dijk et al. (2014) computed the total duration (min/week) of AST based on ActivPAL data recorded between 7 and 8.40 am on weekdays.

Cognitive functions

Cognitive outcomes were heterogeneous in terms of their different measurement instruments. Three studies investigated visuospatial skills (Appleyard, 2017; Fang & Lin, 2017; Moran et al., 2017) using a cognitive mapping exercise, which allows an environmental classification of paths, edges, districts, nodes, and landmarks (Lynch, 1975). However, all of those executed and evaluated the exercise differently. All other studies could be categorized according to the measured cognitive function rather than the measurement instrument as none of the studies used the same tool, neither within the same category nor within the same function, e.g. for working memory López-Vicente et al. (2016) used the *n*-back task whereas Rodrigues et al. (2022) used the Cognitive Telephone Screening Instrument (COGTEL).

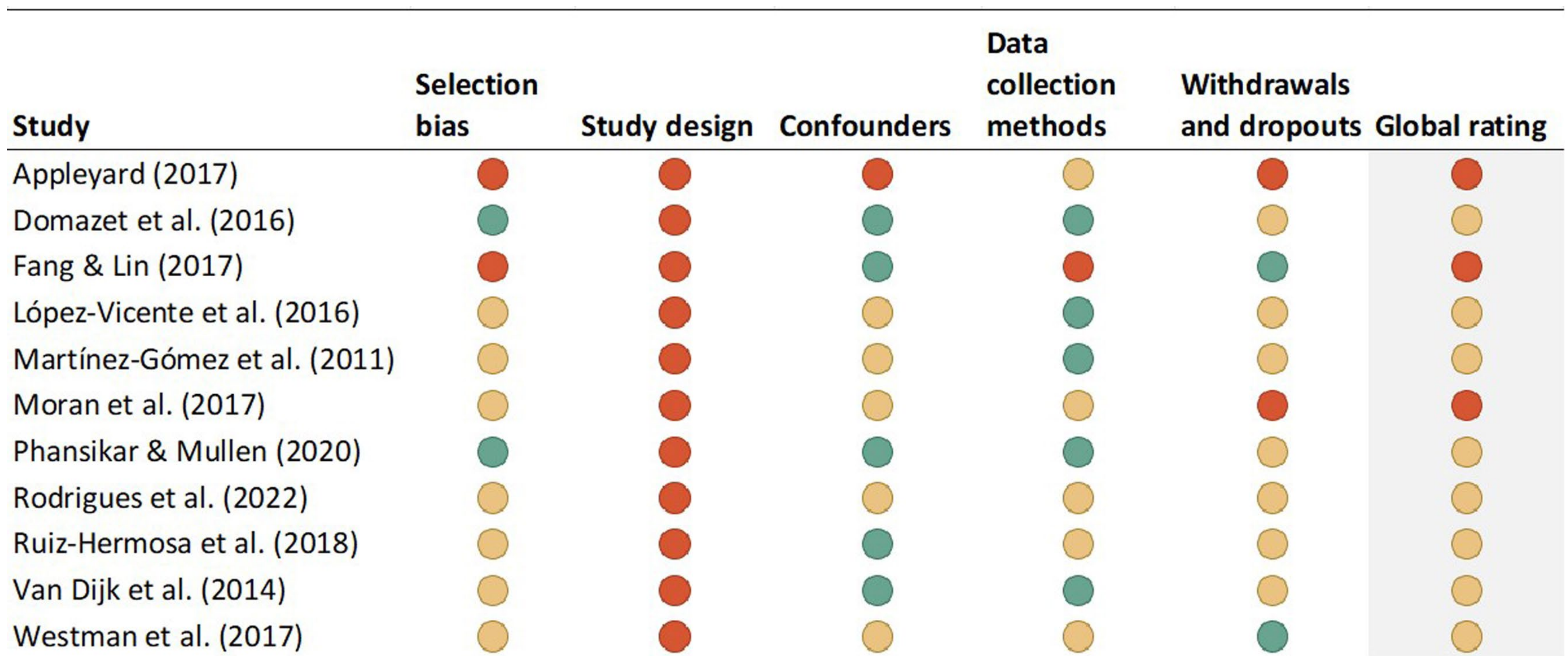

Figure 2. Summary of quality assessment results categorised in weak (red), moderate (yellow), and strong (green) according to the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool for Quantitative Studies (Thomas et al., 2004).

Table 1. Overview of the characteristics of all studies investigating the associations and effects of active travel and cognitive functions across the lifespan.

Author (year) Country Design	Sample (*n*, age, sex)	AT exposure	Cognitive outcome	Statistical method	Associations	Quality
Appleyard (2017) USA Cross-sectional	Children *n* = 36 *Schools:* 2 *Age:* 9–10 years *Female:* 58.3%	Usual travel mode *to* school [categories: active (bike, walking); passive (car)]	Visuospatial skills (cognitive mapping of neighbourhood between home and school)	Comparison of maps (no statistics reported)	Children who were driven to school drew less comprehensive maps	Weak
Domazet et al. (2016) Denmark Cross-sectional	Adolescents *n* = 561 *Schools:* 14 (5 regions) *Grades:* 6–7 *Age:* 12–14 years *Female:* 52.6%	Travel mode *to* school on test day (categories: car/public transport; walk; cycle)	Inhibitory control (modified Erikson Flanker Task): • Interference score–accuracy • Interference score–reaction time	Mixed model regression (adjusted)	No significant associations	Moderate
Fang and Lin (2017) Taiwan Cross-sectional	Children *n* = 521 *Schools:* 1 *Grades:* 1–6 *Age:* 7–12 years *Female:* 50.1%	Frequency of AST (walking or biking) in last week (times/week)	Visuospatial skills (cognitive map of area along home-school route): • Richness: landmark, path, place, object • Route orientation • Route structure • Aggregation	Ordinal least squares linear regression (adjusted) *PA adjusted*	Positive associations with route orientation and aggregation Negative association with route structure	Weak
López-Vicente et al. (2016) Spain Longitudinal	Children *n* = 2897 *Schools:* 39 (2 cities) *Grades:* 2–4 *Age:* 7–10 years *Female:* 49.7%	Duration (min/trip) of AST *to* school (categories: passive mode, 1–25 min, 25–50 min, >50 min)	Working memory (2- and 3-back): • Hit reaction time • Overall accuracy • Detection Attention (attentional network task): • Accuracy • Response time (median, *SD*)	Linear mixed effects model (adjusted)	Higher 3-back scores (*d'*) at baseline among those with >50 min of AT to school compared to passive transport	Moderate
Martínez-Gómez et al. (2011) Spain Cross-sectional	Adolescents *n* = 1700 *Schools:* N/A (5 cities) *Age:* 13–18.5 years *Female:* 52.5%	Usual AST mode *to* school [categories: AST (walk/bike); non-AST (car, bus, subway, motorcycle)] Usual AST duration (min/trip *to* school) (categories: non-AST; ≤15 min AST; >15 min AST)	Cognitive abilities [SRA test of educational ability (in Spanish)]: • Verbal ability • Numeric ability • Reasoning ability • Cognitive performance (sum)	Analysis of covariance by sex (adjusted)	Girls engaged in AST had higher scores for each cognitive outcome compared to non-AST Girls with >15 min AST had higher scores for each cognitive outcome compared to non-AST Girls with >15 min AST had higher scores for numeric ability, reasoning ability and overall cognitive performance compared to <15 min AST Girls with <15 min AST had higher verbal ability and overall cognitive performance scores compared to non-AST	Moderate
Moran et al. (2017) Israel Cross-sectional	Children *n* = 92 *Schools:* 4 *Grades:* 5–6 *Age:* 10–12 years	Frequency of walking to school (categories: <4 days/week *vs.* ≥4 days/week)	Visuospatial skills (cognitive map of area along home-school route): • Accuracy (route and structure) • Richness (diversity and level of detail)	Chi-square multivariable linear regression (adjusted)	Accuracy scores higher among those that walked to school ≥4 times/week Positive association between frequency of walking (days/week) and accuracy score	Weak

(*Continued*)

Table 1. Continued.

Author (year) Country Design	Sample (*n*, age, sex)	AT exposure	Cognitive outcome	Statistical method	Associations	Quality
Phansikar and Mullen (2019) USA Cross-sectional	Older adults *n* = 2702 *Age:* ≥60 years (*M* = 70.0) *Female:* 51.6%	Meeting physical activity guidelines *via* usual AT (categories: not meeting GL; meeting GL *via* AT only; meeting GL *via* LTPA only; meeting GL *via* both AT and LTPA)	Processing speed (Digit Symbol Substitution Test) Verbal ability (Animal Fluency Test) Memory–delayed recall (Consortium to Establish a Registry for Alzheimer's Disease (CERA) World Learning subtest)	Analysis of covariance (adjusted) *PA adjusted*	No significant associations for meeting GL *via* AT only Processing speed and verbal ability were higher among those that met the GL *via* AT and LTPA compared to the inactive	Moderate
Rodrigues et al., 2022 Portugal Cross-sectional	Adolescents *n* = 370 *Schools:* 5 *Age:* 11–20 years *Female:* 54.1%	Usual AST mode [categories: AST (walk, bike) *vs.* non-AST (car, bus, motorcycle)] Usual AST duration (min/trip) (categories: non-AST; ≤30 min AST; >30 min AST)	Memory (COGTEL) • Prospective memory • Verbal short-term memory • Verbal long-term memory • Working memory Cognitive ability (COGTEL) • Verbal fluency • Inductive reasoning Total cognitive (weighted sum) score (COGTEL)	Multivariate analysis of covariance Multiple linear regression *PA adjustment*	Higher total cognitive score among those engaging in AST compared to non-AST Higher working memory (no adjustment), inductive reasoning and total cognitive scores among those with >30 min AST compared to non-AST	Moderate
Ruiz-Hermosa et al. (2018) Spain Cross-sectional	Children *n* = 1159 *Schools:* 21 *Age:* 4–7 years *Female:* 48.3%	Usual AST mode *to* school (AST: walking, biking; non-ACS: car, motorcycle, bus). No students biked to school.	*3–6 years (pre-school)* Cognitive ability (BADyG I): Verbal general intelligence General non-verbal intelligence General intelligence (sum) *6–8 years (primary education)* Cognitive ability (BADyG E1): Verbal factor (verbal comprehension) Numerical factor (numerical problems) Reasoning: logical reasoning Visuospatial skills (BADyG E1): Ability to make spatial turns General intelligence score (BADyG E1)	Analysis of covariance by sex (adjusted) *Fitness adjusted*	No significant associations	Moderate
Van Dijk et al. (2014) Netherlands Cross-sectional	Adolescents *n* = 270 *Schools:* 1 *Grades:* 7, 9 *Age: M* = 13.4, *SD* = 1.28 *Female:* 47.0%	Total duration (min/week) of habitual AST (device-assessed moving time)	Inhibition/attention (d2 test of attention): overall performance score Information-processing speed (SDMT)	Multiple linear regression *PA adjusted*	Positive association between duration of AST and attention among girls only	Moderate
Westman et al. (2017) Sweden Cross-sectional	Children *n* = 345 *Schools:* 5 *Grades:* 4, 6, 8 *Age:* 10–15 years *Female:* 48.0%	Travel mode *to* school on test day (categories: car; active (walk, cycle, inline skates, scooters); school bus/public transport)	Verbal fluency (word fluency task)	Analysis of variance (3 × 2 × 3: grade × sex × mode)	Positive associations between AST >15 min and verbal fluency performance compared to ≤15 min No main effect for mode of travel	Moderate

Table 2. Overview of the AT outcome parameters across the included studies.

	Mode of AT		
Parameter	Walk	Bike	Combined walking and biking
Mode	Domazet et al.[a,b] Ruiz-Hermosa et al.[a,c]	Domazet et al.[a,b]	Appleyard[a,c] Martínez-Gómez et al.[a,c] Rodrigues et al.[c] Westman et al.[a,b,d]
Frequency			
Trips/week			Fang and Lin[e]
Categories	Moran et al.[a]		
Duration per trip			
Categories			López-Vicente et al.[a] Martínez-Gómez et al.[a,c] Rodrigues et al.[c]
Volume/dose			
Min/week			Van Dijk[f,g]
Categories			Phansikar and Mullen[c,h]

[a]Travel *to* school only.
[b]Travel on test day only.
[c]Usual/habitual travel behaviour.
[d]Includes inline skates and scooters, in addition to walking and biking.
[e]Travel in last week.
[f]Travel *to* school extrapolated to total duration per week, including travel from school.
[g]Based on moving time (activPAL).
[h]Based on trips of ≥10 min.

The following cognitive functions were measured: visuospatial skills (Appleyard, 2017; Fang & Lin, 2017; Moran et al., 2017), inhibition (Domazet et al., 2016; Van Dijk et al., 2014), working memory (López-Vicente et al., 2016; Rodrigues et al., 2022), attention (López-Vicente et al., 2016; Van Dijk et al., 2014), processing speed (Phansikar & Mullen, 2019; Van Dijk et al., 2014), reasoning abilities (Martínez-Gómez et al., 2011; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018), verbal abilities (Martínez-Gómez et al., 2011; Phansikar & Mullen, 2019; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018; Westman et al., 2017), and numeric abilities (Martínez-Gómez et al., 2011; Ruiz-Hermosa et al., 2018). An overview of parameters, measurement tools, and assessments can be found in Table 1.

Associations

Overall, evidence of associations was mixed with about half of the studies reporting some positive and the remaining reporting no associations between AT and cognition.

Visuospatial skills

Appleyard (2017) used a more unique coding highlighting different neighbourhood parameters, e.g. volume and speed of AT and the sufficiency of walking and bicycling infrastructure. He reported that children who actively travelled to school drew more sophisticated and comprehensive maps than those who are mostly driven. However, no effect sizes or values were presented.

Fang and Lin (2017) specifically oriented their coding on Lynch (1975) and found positive associations between the frequency of AST and visuospatial skills [route orientation ($\beta = .03$), and route aggregation ($\beta = .25$)] but negative associations with route structure ($\beta = -.04$). Landmark, paths, places, and object richness were not significant.

Lastly, Moran et al. (2017) found positive associations between the frequency of AST and accuracy, and orientation and structure summary scores ($\beta = .20$) derived from cognitive maps, but not for richness.

In addition to those three cognitive mapping studies, Ruiz-Hermosa et al. (2018) measured a spatial factor with two tests (spatial rotations with geometric figures and inductive conclusions) within the Battery of General and Differential Aptitudes for Children (BADyG I and E1), but no associations with AST were found.

Executive functions

Inhibition: There were associations observed between walking or biking to school on a given day and inhibitory control outcomes, in contrast to those who travelled by car or public transport (Domazet et al., 2016). Similarly, the findings of Van Dijk et al. (2014) suggest that the duration of AST is positively associated with response inhibition, but in adolescent girls only ($\beta = .17$).

Working memory: Active travel for >50 min was positively associated with better 3-back scores at baseline compared to passive commuting (López-Vicente et al., 2016). However, no further associations between working memory parameters and AST were found. These outcomes were supported by the findings of Rodrigues et al. (2022), who used an interview-based cognitive screening tool [including the backward digit-span test (range 0–12 points)] among adolescents and found AST to be positively associated among those engaging in ≥30 min of AST ($\beta = .13$) compared to non-AST.

Attention: There were no differences in attention (inattentiveness) scores, measured by the Attentional Network Task, between categories of duration of AST among children (López-Vicente et al., 2016). However, Van Dijk et al. (2014) identified a significant interaction between AST and sex as the duration of AST was positively associated with attention (d2 Test of attention performance) in adolescent girls ($\beta = .17$), but not in boys.

Processing speed: Among older adults (60+ years), meeting PA guidelines only via engagement in AT was not significantly associated with processing speed compared to those classified as insufficiently active (Phansikar & Mullen, 2019). However, those meeting the guidelines via a combination of leisure-time physical activity and AT had higher processing speed scores compared to those who were insufficiently active. Among children, Van Dijk et al. (2014) also found no associations between AST and information-processing speed.

Reasoning abilities

Using the SRA Test of Educational Ability, Martínez-Gómez et al. (2011) found that adolescent girls who actively commuted to/from school for >15 min had significantly better reasoning ability scores than girls with ≤15 min of AST (score +1.90; 95% CI, 0.61–3.19) or non-AST (score +2.19; 95% CI, 0.81–3.57). There were no significant associations in boys.

Similarly, using the Cognitive Telephone Screening Instrument (COGTEL) with face-to-face interviews, Rodrigues et al. (2022) found AST to be positively associated with inductive reasoning abilities ($\beta = .134$) in favour of >30 min of daily AST ($M = 4.44$, $SD \pm 2.05$) compared to non-AST ($M = 3.19$, $SD \pm 2.01$) among adolescents. Nevertheless, among primary school children, walking to school was not significantly associated with logical reasoning, measured by the BADyG I and E1 test battery (Ruiz-Hermosa et al., 2018).

Verbal abilities

Verbal abilities were measured in five studies with five different measurement tools. Three studies found no associations (Phansikar & Mullen, 2019; Rodrigues et al., 2022; Ruiz-Hermosa et al., 2018) and two found positive associations (Martínez-Gómez et al., 2011; Westman et al., 2017). Only Westman et al. (2017) gathered their data not within a global test battery but isolated with the Word Fluency Task. In their study, travel mode was not associated with the verbal performance (number of produced words). In contrast, Martínez-Gómez et al. (2011) found higher verbal ability scores among girls who did any AST, some AST (<15 min) and >15 min compared to girls not using AT at all (score +2.75; 95% CI, 1.18–4.32).

Numeric abilities

Martínez-Gómez et al. (2011) found significant positive associations between participating in any AST for >15 min compared to ≤15 min (score +1.28; 95% CI, 0.13–2.43) and those that did non-AST (score +1.94; 95% CI, 0.71–3.17) among girls, but not boys. In contrast, Ruiz-Hermosa et al. (2018) did not find an association between AST and numeric abilities.

Summary scores

Martínez-Gómez et al. (2011) found higher overall cognitive performance scores (sum of verbal, numeric, and reasoning abilities) among girls engaging in AST, especially in favour of >15 min compared to both ≥15 min and non-AST, but no associations among boys.

Ruiz-Hermosa et al. (2018) computed a general intelligence score consisting of each variable included in their test batteries (BADyG I and E1). Respectively per age group, no associations between children actively walking to school and general intelligence were found.

Lastly, Phansikar and Mullen (2019) also generated a total cognitive score across their test battery (COGTEL) among adolescents. Results showed higher scores in AST compared to non-AST adolescents, primarily in favour of >30 min.

Discussion

Active travel *(AT)* refers to specific types of locomotion (walking, biking, inline skating, etc.) and can be operationalised or described in terms of dose (intensity, duration, frequency) and the context (independent/dependent, group/alone, winter/summer, urban/suburban, etc.) of actively traveling from A to B. The review identified few studies that have examined relationships between AT and cognitive functions. Most AT measures in the review primarily addressed AST. Additionally, many studies focused solely on travel mode, frequency, or duration. The studies were mainly conducted among children or adolescents and measured a range of cognitive parameters, including visuospatial skills, executive functions, processing speed, and reasoning, verbal, and numeric abilities. However, considering the scarcity of studies within this review, the diverse range of approaches to operationalising the AT exposure, and varying outcomes employed in each study, there is limited basis for direct comparisons. Hence, it appears to be more about identifying a broad pattern in general.

Key findings from this review encompass various cognitive domains (see Table 1): Spatial knowledge was examined through cognitive mapping exercises, revealing that adolescents using AT exhibited better spatial cognition, yet effect sizes were not always provided. Findings related to executive functions were mixed. Some associations were observed between AT and inhibition, working memory, attention, and executive functions among girls, but not in boys. Inductive and logical reasoning were positively associated with AT, with some evidence suggesting relationships particularly in girls and with AST of >15 min. Processing speed displayed limited associations with AT and verbal abilities yielded mixed outcomes. Numeric abilities were generally higher in boys but positively linked to AT among girls only.

Measured with cognitive mapping exercises, findings supported the notion that when people actively travel from point A to point B, they engage in both cognitive interaction with their environment and physical activation of their bodies given these participants were able to represent more objects and had higher route orientation and structure accuracies. These outcomes resemble processes found in open-skill sports (Guo et al., 2021; Pačesová et al., 2020). Much like within the ongoing discussions regarding the relationship between open- versus closed-skill exercises and cognition (Chueh et al., 2017; Gu et al., 2019), PA-levels may serve as the foundation, while the degree of cognitive load or challenge may determine cognitive advantages (Gökçe et al., 2021). However, it has been suggested that neither PA nor cognitive engagement should reach a threshold of overwhelming, as this can lead to adverse effects (Decroix et al., 2016; Dupuy et al., 2010). One study that examined associations between AT and the ability to make spatial turns (Ruiz-Hermosa et al., 2018) did not find any association. Contrary to mental and physical overload, as all children who used AST in that study commuted by foot and most children had a commute of ≤15 min, these results could be due to physical and mental underload. Following on from that, it may be that children who actively travel independently, without adult supervision, experience cognitive benefits due to higher cognitive loads as navigating on their own requires developing a mental map, enhancing spatial awareness, and making quick decisions fostering cognitive growth (Appleyard, 2017). Moreover, independent travel can promote a sense of responsibility and self-confidence, contributing to the development of a resilient and adaptable mindset (Fang & Lin, 2017; Westman et al., 2020).

It is possible that the length of the route to school may impact the extent of exposure and cognitive benefits. Moran et al. (2017), for example, found the strongest predictors of the associations between AST and orientation and structure summary to be the *route's length*, followed by *AT mode* and *gender*. Similarly, Fang and Lin (2017) also suggest that longer distances may increase opportunities to interact with the environment, which could benefit children's spatial cognition. Their study did not reject this, but shorter travel duration was associated with a higher subjective travel experience and more positive emotions. Cycling enables AT over longer distances, allowing greater exposure, and is considered both pleasant and arousing, as opposed to other modes (Gatersleben & Uzzell, 2007). However, in countries where AT is less common, such as Spain or the United States (Rodríguez-López et al., 2017), the probability of cycling decreases with longer distances, whereas in countries where AT is common, like the Netherlands or Denmark, a longer distance was associated with an increase in cycling (Dessing et al., 2014; Heinen et al., 2011). In this review, only two studies computed dose of total AT over a week (Phansikar & Mullen, 2019; Van Dijk et al., 2014), even though quantifying AT is essential to understand the mechanisms of action to assess health impacts and evaluate the environmental, safety, and economic implications of PA. Future research should consider both dose and distance when studying AT to allow examinations of thresholds at which cognitive benefits peak. In addition, distance thresholds that arouse but not overwhelm, and types of environmental conditions enroute, should also be explored to better understand AT-cognition relationships.

Only two of the studies included in the review specifically examined sex differences (Martínez-Gómez et al., 2011; Van Dijk et al., 2014). One found positive associations with verbal, numeric, and reasoning abilities, and the other one with attention, both among girls only, which corresponds to previous studies investigating PA in girls (Hillman et al., 2008). For example, a review by Esteban-Cornejo et al. (2015) concluded positive associations between vigorous PA (align with AT) and cognitive performance, also mainly in girls. In contrast, a meta-analysis of long-term effects of PA on cognition found less effects of exercise on cognition in adolescent females compared to males but limited their findings by methodological differences, dichotomization, cofounding variables, and dose differences (Ludyga et al., 2020). However, Van Dijk et al. (2014) ascribe the positive associations of AT and cognitive functions among girls to the beneficial effects of PA—especially in girls—on depressive symptoms and psychological well-being. Among children and adolescents, PA has been shown to be negatively associated with depressive symptoms (Biddle et al., 2019), while depressive symptoms tend to be negatively associated with cognitive performance across all ages (Hartlage et al., 1993). However, there is both older and more current research contrasting this hypothesis by finding no relationship between depressive symptoms and cognitive outcomes both in children (McGee et al., 1986) and elderly people (Gale et al., 2012). Another explanation for gender differences in cognitive outcomes may be sex hormones, with testosterone thought to enhance visuospatial skills with current research mainly investigating mental rotation (Kheloui et al., 2021) and oestrogen enhancing learning and memory skills by enhanced hippocampus structure and function (Daniel, 2006). Nevertheless, the examination of the relationship between cognitive gender disparities and sex hormones is infrequently explored and, as a result, should be approached with caution.

According to Hertzog et al. (2008), the individual cognitive functions within a specific range of developmental possibilities are influenced by factors that come into play before early adulthood with varying developmental paths in life resulting in individual cognitive curves over time. Positive outcomes were noted in five out of six studies among children and in three out of four studies among adolescents, although significant correlations were rare. Although it is generally considered that older adults stand to gain substantial advantages from PA (Jedrziewski et al., 2007; Ludyga et al., 2020), 20–60-year-olds were not included in any of the eleven studies in this review, and only one study included in this review focused on older adults and found no associations (Phansikar & Mullen, 2019).

As Erickson et al. (2022) very recently summarized the importance and effective role of PA in maintaining and optimising cognitive functions in late life, the missing associations are considered as outliers. However, Phansikar and Mullen (2019) considered AT in relation to PA guidelines for older adults. Future work should examine dose and also control for PA to tease out associations specifically with AT.

Strengths and limitations

The studies demonstrate considerable strengths, such as substantial sample sizes enhancing statistical power and generalizability, additional measurements of parameters like intensity, duration, and frequency of AT, and uses of advanced technology (e.g. accelerometers for AT measurement or GPS to score cognitive maps against reality). Available control of confounding variables and diverse participant groups contributed to methodological robustness.

However, the limitations outweigh the strengths. In this nascent research field characterized by discovery, data gaps, and ambiguous exploratory methods are apparent. Existing studies are challenged by a lack of detail and diversity in how AT is categorized or operationalised. Measurement tools were mainly based on self- or proxy-report questionnaires with potential bias and investigated walking and/or cycling only. Often, walking and cycling were combined as one category, but stronger effects are expected for cycling due to the greater physical effort and higher cognitive load it entails. Many studies relied on mode only and those that included frequency and duration often collapsed the variable into categories that were not able to be directly compared (see Tables 1 and 2), strongly limiting between-study comparisons. In addition, the studies were primarily limited to AST, but AT to other destinations may also be important and contribute to the overall AT dose. In addition, contextual factors, such as travel unaccompanied by an adult or in an environment that demands a higher cognitive load, may play a crucial role in safety as well. Furthermore, bidirectional causality cannot be definitively established in a cross-sectional study, and the exclusion of certain variables (e.g. overall PA) may impact the comprehensive understanding of the subject, making it challenging to determine whether AT influences cognitive abilities, cognitive abilities influence AT, both relationships exist concurrently without a clear causal direction, and whether the relationship is independent of general PA. Lastly, the study populations are primarily restricted to children and adolescents with only one study investigating older adults and a notable lack of representation for the middle-aged population, specifically those aged between 20 and 60.

Acknowledging these strengths and limitations, the studies included in this review lay a foundation for further empirical advancements highlighting the need for and huge potential of exploring the relationship between active travel and cognitive functions further.

Conclusion

This review aimed to explore associations between AT and cognitive functions. Mainly focused on children or adolescents and their school travel, the review found insufficient evidence supporting associations, underpinned by much variation in study design, exposure, and outcome variables. This variability limits our ability to draw definitive conclusions about the impact of AT on cognitive function. Although the evidence is limited, there are indications that longer AST commuting may be linked to certain cognitive outcomes.

So, active life–active mind? While the inclination suggests a connection between an active lifestyle incorporating AT into daily routines and cognitive enhancements, more extensive research is required. Future studies should include adults and older adults, consider the dose of AT, include AT to additional destinations, separate walking and biking, and explore potential moderating effects of age, sex, and the impact on associations of the context in which AT takes place.

Note

1. Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia. Available at www.covidence.org.

Authors contributions

Conceptualization: M.H. and S.T. jointly formulated the review's foundational ideas and theoretical framework. Methodology: M.H. executed the literature search. M.H. and E.M. independently screened all articles until full consensus was reached for the final selection. Data analysis: M.H., E.M., and A.T. worked together on data extraction and analysis, ensuring a comprehensive examination of the evidence. Writing—original draft: M.H. and A.T. led the creation of the initial manuscript, synthesizing conceptual and methodological elements. Writing—review and editing: M.H., A.T., E.M., and S.T. collectively reviewed and edited the manuscript for clarity, coherence, and overall quality.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study. The dataset that support the findings of this review are available on request from the corresponding author, M.H.

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