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# Individual differences in visual search: A systematic review of the link between visual search performance and traits or abilities

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ABSTRACT

Visual search (VS) comprises a class of tasks that we typically perform several times during a day and requires intentionally scanning (with or without moving the eyes) the environment for a specific target (be it an object or a feature) among distractor stimuli. Experimental research in lab-based or real-world settings has offered insight into its underlying neurocognitive mechanisms from a nomothetic point of view. A lesser-known but rapidly growing body of quasi-experimental and correlational research has explored the link between individual differences and VS performance. This combines different research traditions and covers a wide range of individual differences in studies deploying a vast array of VS tasks. As such, it is a challenge to determine whether any associations highlighted in single studies are robust when considering the wider literature. However, clarifying such relationships systematically and comprehensively would help build more accurate models of VS, and it would highlight promising directions for future research. This systematic review provides an up to date and comprehensive synthesis of the existing literature investigating associations between common indices of performance in VS tasks and measures of individual differences mapped onto four categories of cognitive abilities (short-term working memory, fluid reasoning, visual processing and processing speed) and seven categories of traits (Big Five traits, trait anxiety and autistic traits). Consistent associations for both traits (in particular, conscientiousness, autistic traits and trait anxiety – the latter limited to emotional stimuli) and cognitive abilities (particularly visual processing) were identified. Overall, however, informativeness of future studies would benefit from checking and reporting the reliability of all measurement tools, applying multiplicity correction, using complementary techniques, study preregistration and testing why, rather than only if, a robust relation between certain individual differences and VS performance exists.



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## 1. Introduction

Requiring a target item to be detected among distractor items, visual search (VS) is a class of tasks in which we all engage several times each day. Looking for a friend in a crowd, browsing for a specific product in the supermarket, or looking for the car keys on a coffee table are familiar examples of VS tasks. An individual's survival and safety may also crucially depend on the efficiency of VS; for instance, by spotting the right signals when driving down an unknown road or scanning the environment to avoid a collision course with an angry dog approaching from 2 o'clock. Among the most recent versions of VS made possible by technological developments, we can list looking for icons on computer or mobile screens, and a range of specialised tasks with important societal consequences, such as the inspection of an airplane fuselage for cracks, the search for weapons in security images, or the search for abnormalities in medical images (Eckstein, 2011). Requiring the coordination of a variety of functions, some aspects of VS as carried out by humans can be hardly replicated by machines (Eckstein, 2011). Accurate knowledge of the individual differences that associate with successful performance in VS can help improve many performance-critical processes, such as medical and security screening, by enabling the identification of individuals with the potential to achieve effective performance (Parasuraman & Jiang, 2012), in addition to enriching basic models of cognitive and visual function as supported by interacting brain networks, by suggesting specific mechanisms that could contribute to search efficacy (Posner, 2014).

VS tasks can be of many types and greatly vary in complexity. They can range from multiple searches for a simple shape among randomly scattered or circularly arranged distractors on the display of a computer to prolonged searches for multiple potential targets in a complex scene. Typical laboratory-based tasks (as in classical VS; Wolfe, 2018) are simplified versions of real-world tasks and tend to be repetitive and with a high probability of a target present. These characteristics have enabled, via series of systematic manipulations, a thorough study of the basic mechanisms of VS, the identification of factors that guide attention and of their interactions. However, the challenges posed by typical real-world tasks differ in part from those posed by classical VS tasks. Indeed, real-world visual searches may be conducted on more complex scenes (be they natural or artificial, such as in medical or security screening), with multiple, unknown and/or infrequent targets (Wolfe, 2020). A comprehensive and realistic appreciation of VS must therefore take into account both lab-based and real-world tasks.

Performance in search tasks is typically measured in response or reaction time (RT) and accuracy but other informative indices can also be derived by taking into account specific conditions within a task, such as slope (i.e., the coefficient of a linear equation fitted to a plot of RTs by distractor numerosity; Wolfe, Alvarez, Rosenholtz, Kuzmova, & Sherman, 2011) and sensitivity to the signal (d′; i.e., a measure of signal detection ability, which can be calculated if the proportion of hits and false alarms is known; Stanislaw & Todorov, 1999; Verghese, 2001). In very general terms, faster correct RTs and/or higher accuracy, higher d′ and lower slopes are taken to indicate more successful search performance (though the emphasis may vary widely from the context, e.g., presence of a speed-accuracy tradeoff; or the task objectives, e.g., a small increase in accuracy is much more relevant than a small increase in RTs when searching for a tumour in an x-ray image). Whereas RTs and accuracy offer crude measures of performance across types of trial (e.g., with and without a target present) and are very frequently provided in the literature, slope and d′ can capture information on how much the presence of an increasing number of distractors affects an individual's performance, and on specific sensitivity to the presence of a target, by taking into account an individual's general tendency to respond positively or negatively (i.e., their response bias), respectively. Across the literature, slopes are generally reported when a manipulation of the number of distractors is included in the study design (Wolfe, 2018), and d′ if the authors have an interest in distinguishing perceptual from decision making components of search performance (Verghese, 2001). Thus, the choice to focus on one or the other index of performance and the theoretical interpretation given to variations across indices of performance depend crucially on the specific aims and on the theoretical framework of reference of a study (which will also determine the tasks or conditions of comparison, if any, included in the study design), and on the availability of converging evidence from different tasks and/or different fields (e.g., from neuroscience; Lavie & Dalton, 2014). In this exploratory review, which sets out to synthesise the existing literature in order to clarify whether any association has been documented robustly so far between VS performance and measures of individual differences, all of the four indices of performance mentioned above will be considered as outcomes of interest across studies.

Traditionally, searches have been divided in two main categories based on their sensitivity to the numerosity of distractors: parallel and serial searches (Treisman & Gelade, 1980). In parallel searches, the target is typically identified by a pop out feature and can be found by processing all items in parallel. Therefore, varying the number of distractors does not influence the speed of a successful search (i.e., in a plot of search speed by distractor numerosity, the slope is near zero). In serial searches, focused attention will be necessary in order to distinguish the target from the distractors. Therefore, the items need to be processed in succession (i.e., in a plot of search speed by distractor numerosity, the slope will be positive and different from zero). More recently however, it has been argued that such categorical distinction may not capture the complexity of VS, and tasks could be best described as lying on a continuum of efficiency, from very efficient to very inefficient (Wolfe, 1998, 2018). In this review, we still classify tasks as parallel or serial to provide a first step broad distinction (see Supplementary Table 1).

Whatever the specific type of task and its challenges, it has progressively become clear that VS can be guided by a range of external and internal factors, such as bottom-up salience, top-down feature guidance, scene structure and meaning, the value of targets and distractors (according to the searcher), and a searcher's previous search history (e.g., Wolfe & Horowitz, 2017). All of these factors may combine into a priority map to guide search (Rust & Cohen, 2022; Wolfe &

Horowitz, 2017). Further, VS being intentional and goal-directed, both guiding representations (or templates) and target templates are thought to be active in working and long-term memory respectively. In other words, VS is known to recruit multiple cognitive processes beyond visual perception and attention (Nobre & Kastner, 2014; Wolfe, 2020).

Not surprisingly, VS has been the focus of much experimental psychology literature throughout the years, investigating the cognitive functions involved in such tasks and the external factors influencing success (e.g., Bravo & Nakayama, 1992; Woodman & Luck, 2003; Woodman, Vogel, & Luck, 2001). Further research in cognitive neuroscience has offered insight into the brain networks involved, highlighting a key role of frontal and parietal areas particularly in the right hemisphere (e.g., Ellison, Lane, & Schenk, 2007; Hodsoll, Mevorach, & Humphreys, 2009; Kristjánsson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007; Nobre, Coull, Walsh, & Frith, 2003; Rosenthal et al., 2006). Taken together, these studies have almost invariably adopted a nomothetic approach, and while offering invaluable insights into the underlying neural mechanisms, mental operations, and contextual factors that play a role in VS, they have rarely offered insights into individual differences.

In recent years, a renewed interest has been found in the role that individual differences play in human behaviour, perception, and cognition (e.g., Kanai & Rees, 2011; Schwarzkopf, Song, & Rees, 2011). Research investigating individual differences often offers correlational findings and does not allow for causal inferences (Altman & Krzywinski, 2015); however, such findings can be very informative both from a basic perspective and from an applied perspective. They can lead to the formulation of new basic research models and hypotheses. For instance, recent elegant research has allowed for a distinction between the role of perceptual and cognitive capacity across multiple VS tasks. Such a distinction was established initially by investigating individual differences across behavioural tasks (Eayrs & Lavie, 2018), and built upon by investigations linking specific brain areas with these distinct mechanisms (Eayrs & Lavie, 2019). They can also lead, via translational research, to the development of applications to real-world problems. Where robust associations are found, indeed, *ad hoc* tools can be developed to aid the prediction of individual performance in performance-critical roles, such as security screening (see Rusconi, Ferri, Viding, & Mitchener-Nissen, 2015, for an example). Thus, gaining an insight into the characteristics and qualities that make successful searchers could be highly beneficial to future research and applied endeavours; doing so may require a cognitive task or even a short questionnaire.

Within the individual differences literature, the considered latent factors often fall into the broad categories of intelligence/cognitive abilities and traits (Chamorro-Premuzic, Furnham, & Ackerman, 2006). Although there may be some conceptual overlaps between these categories (e.g., Schretlen, van der Hulst, Pearlson, & Gordon, 2010), they are often distinguishable by the different types of methods and measures used to describe them. Traits are characteristics associated with behaviour, thoughts, and feelings that are fairly stable (McCrae & Costa Jr, 1997), such as personality (McCrae & Costa, 2003), or autistic traits (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001), while cognitive abilities refer to mechanisms and resources for the mental processing required to understand and learn in a given domain (Carroll, 1993). Measurement of cognitive abilities is usually carried out by performance tasks, whereas questionnaires are typically used to measure traits (Herreen & Zajac, 2017).

### 1.1. *The reliability problem and variations in tasks used within the literature*

Arguably, the existing literature can be divided into studies seeking to investigate responses when experimental variables are manipulated and those studies measuring existing individual differences using behavioural tasks (Goodhew & Edwards, 2019). The methodological approaches taken in these two distinct categories of research differ; for instance, when considering the nomothetic approach, the variation that occurs between subjects is often considered a nuisance, with the within-subject variability being the focus of attention; on the other hand, by its very definition individual differences research turns its attention to inter-individual variations (Tulver, 2019). Importantly, tasks used to study variations occurring at the group level are not always ideal for investigating individual differences, often this is also the case for the data analysis decisions made; for instance, the critical performance measure used in hypotheses testing can have an impact on outcomes, that is, whether raw RTs or RTs calculated from different manipulations of the experimental paradigm are considered (Goodhew & Edwards, 2019). Furthermore, there is often also a variation in whether reliability is reported for questionnaires and behavioural tasks in experimental and individual differences research. This is a relevant issue, as the possibility to estimate a link between individual differences and behavioural measures is likely to be affected by the psychometric properties of the behavioural measures used. However, because many of these behavioural measures were originally developed for nomothetic research rather than for capturing individual differences (Hedge, Powell, & Sumner, 2018), their psychometric properties, including reliability, are often unknown. Our systematic review will highlight whether reliability measures are reported for the included studies. This will likely help improve the design and reporting standards of future studies. For instance, allowing an insight into whether any quantitative syntheses would be viable.

### 1.2. *Traits and VS*

Researchers interested in understanding individual behaviour have identified and investigated traits related to thoughts, feelings, and behaviours (McCrae & Costa Jr, 1997), which are relatively stable in adulthood (Hampson & Goldberg, 2006). Such traits – often referred to collectively as personality – have been investigated across cultures and age ranges. Personality has been investigated in the past for its role in visual outcomes; for instance, in visual perception, where certain personality traits have been linked with a preference for stimulating colours and/or stimulus complexity (Zuber & Ekehammar, 1988). Furthermore, an individual's experience of the world is influenced by what they choose to attend to

(Driver, 2001), and visual attention is influenced by stimulus-driven factors as well as characteristics of the individual (Swift, Wilson, & Peterson, 2020; Wolfe & Horowitz, 2017). With this in mind, research has highlighted the importance of considering the association between personality factors and visual attention, suggesting that the choice of visual signals attended to from the vast array of available signals may be related to traits (see Kaspar & König, 2012, for a discussion). Further, personality traits may be associated with attentional scope, which relates to an individual's proficiency at allocating attentional resources across a visual display (Swift et al., 2020). Thus, a link between individual differences in personality traits and VS abilities, which involves the ability to locate a target among distractors in a visual display, may be expected.

In the relevant literature, a wide range of traits has been investigated for different theoretical reasons, and the resulting picture is very fragmented; however, a scoping exercise carried out with broad search terms relating to personality and VS highlighted specific themes (see Supplementary Details available at https://osf.io/n6hzc for preliminary scoping review findings). The findings show the most frequent themes relate to the dimensions of the Big 5 (openness, conscientiousness, extraversion, agreeableness, and neuroticism), autistic traits, and trait anxiety. There are also solitary studies looking at other traits in the literature; however, given the requirement to synthesise the findings and the overarching aim of offering insight into the main body of individual differences literature, the Big 5, autistic traits, and trait anxiety have been chosen for inclusion in this review.

#### 1.2.1. *Personality*

Consensus has gradually emerged in the last 30 years around the existence of 5 broad traits (widely known as the Big Five; McCrae & Costa, 1987), to which most alternative models can be rather easily related (Goldberg, 1993). As these traits reflect characteristic patterns of behaviour, they are often considered for their association with behaviour and performance in specific situations, and more generally with various life outcomes, from the ability to cope during a pandemic (Volk, Brazil, Franklin-Luther, Dane, & Vaillancourt, 2021) to academic achievement (Chamorro-Premuzic & Furnham, 2003). These relatively stable characteristics may, therefore, also help identify which individuals could achieve better results in VS than others.

Looking closely at each dimension of the Big Five can offer an understanding of their potential links with VS task performance. For instance, those high in openness are thought to be more tolerant, open to experience, and able to bring perceptual experiences together (McCrae & Sutin, 2009). These searcher-specific factors may influence aspects of VS over and above stimuli-specific and task-specific factors. At a general level, an individual scoring high in openness may be more likely to engage in a novel task or may better deal with uncertainty when compared with individuals scoring low in openness; it could thus be expected that openness will be associated with aspects of learning and motivation to engage in tasks (Chamorro-Premuzic & Furnham, 2009). Such variations in personality may influence how individuals engage in a task and interact in their environment. For instance, a study on eye movements has shown variations in gazing behaviour based on personality traits including openness, with higher openness being associated with longer mean fixation durations and dwelling time, an outcome which may be driven by the open individual's tendency to process new information at a deep level (Rauthmann, Seubert, Sachse, & Furtner, 2012). Specific to visual attention, a study investigating the ability to distribute resources across a visual field using tasks measuring attentional scope flexibility, endogenous control, and global/local precedence, found individuals higher in openness were better at adapting and reallocating attentional resources (Swift et al., 2020), which may also benefit VS paradigms. For instance, individuals scoring high in openness may be more flexible in their re-allocation of attentional resources to broad or narrow visual fields, which may allow for adjustment to meet task demands in certain VS tasks, such as naturalistic VS where attention may be paid initially to an item in the display, such as an enemy soldier, but a threat is hidden in another discrete location.

Conscientiousness is characterised by the propensity to plan and be goal-directed (Roberts, Jackson, Fayard, Edmonds, & Meints, 2009), and has been shown to be associated with school academic outcomes when cognitive ability is controlled for (Noftle & Robins, 2007). Such findings are often attributed to an individual's effort and persistence (Noftle & Robins, 2007). Similarly, it has been suggested that these characteristics can also be beneficial in VS, with conscientious participants less likely to miss targets in a traditional VS task than participants scoring lower in conscientiousness (all participants were trained searchers), the notion being that conscientious individuals are more likely to sustain effort in such tasks (Biggs, Clark, & Mitroff, 2017). Furthermore, a link has been established between conscientiousness and the ability to attend to visual detail as measured by attentional scope tasks (Swift et al., 2020). The findings of this research support the idea that individuals high in conscientiousness are better at allocating attentional resources to narrow and broad details based on task aims than individuals low in conscientiousness, which may be a reflection of superior top-down control factors (Swift et al., 2020). Thus, it may follow that those individuals scoring high in conscientiousness may be more successful in VS; for instance, in relation to how likely they are to exhaust VS early.

On the other hand, evidence from a study investigating personality and VS suggests neuroticism could be linked with lower performance, especially in no target searches (Newton, Slade, Butler, & Murphy, 1992), which may reflect higher anxiety related to making decisions. Neuroticism has also been linked with affective disorders, and studies have shown variations in brain activity during the viewing of emotive stimuli based on scoring in neuroticism (e.g., Canli et al., 2001). VS can often involve searching for a threatening or emotive target, as such, those scoring high in neuroticism may have an altered response to emotive stimuli or be more distracted by emotionally relevant stimuli. For instance, there is evidence linking neuroticism with delayed responses when searching for target facial expressions (Sawada et al., 2016).

Agreeableness has been characterised by conformity and, in the NEO-PI, has facets which include trust, straightforwardness, altruism, compliance, modesty, and tender-mindedness (Costa Jr, McCrae, & Dye, 1991). Such factors suggest agreeableness has a social aspect. Research has also linked agreeableness with effortful control, with specific associations being shown with RTs on the Stroop test (inverse relationship) and measures of success in the Wisconsin Card Sorting Task (negative relationship with error rates; Jensen-Campbell et al., 2002); these results support links between agreeableness and cognitive functioning and, although VS differs substantially from the tasks from which this evidence comes, there are arguably still elements of self-regulation processes required in VS; for instance, with early response errors. However, studies on gaze patterns during the viewing of abstract animation found no association with the trait agreeableness (or conscientiousness), but did find variations based on the other Big Five traits, which the authors suggest may be down to a lack of a social element in the abstract task (Rauthmann et al., 2012). Thus, it may be that certain personality traits only influence VS outcomes depending on the nature of the stimuli.

Finally, extraversion has been investigated for its associations with vigilance as it has been suggested extraverts are low in arousal, a notion posited by Eysenck (1963), and as such show poorer sustained attention than introverts (Davies & Parasuraman, 1982). However, the evidence in terms of behavioural performance is mixed (see Matthews, Davies, & Lees, 1990). Sustained attention may be required in certain VS tasks and may be more important in roles involving performance-critical VS, such as those required in security and defence. Evidence from a study looking specifically at VS and not sustained attention, has shown slower responses by extroverts than introverts (Newton et al., 1992).

Taken together these findings on personality and VS are ambiguous and, in order to gain a clear insight into the individual characteristics (if any) that are consistently associated with successful search, a thorough, systematic screening of studies investigating personality traits is required. The Big Five model offers a common approach for researchers by which personality traits can be integrated, understood, and investigated (John, Naumann, & Soto, 2008). Thus, for the purpose of this research, data from studies investigating the Big Five will be considered alongside two further traits, which have a theoretical basis for their potential association with VS performance – trait anxiety and autistic traits.

#### 1.2.2. *Autistic traits and trait anxiety*

Although personality ranks highly in trait-related research, there are many more characteristics related to thoughts, feelings, and behaviours that have been considered for their association with outcomes of life, and specific traits have been highlighted for their presence in the VS literature, such as autistic traits (Baron-Cohen et al., 2001) and trait anxiety (Spielberger, Gonzalez-Reigosa, Martinez-Urrutia, Natalicio, & Natalicio, 1971); these are traits that may show some relation with major dimensions of the Big Five, but cannot be fully accounted by/or fully account for Big Five dimensions (e.g., Smits & Boeck, 2006; Wakabayashi, Baron-Cohen, & Wheelwright, 2006), and have specific tools developed for their measurement.

For instance, many studies have shown enhanced VS abilities and visuospatial processing in individuals with autism when compared to typically developing control groups (Happé, Briskman, & Frith, 2001; Happé & Frith, 2006; Joseph, Keehn, Connolly, Wolfe, & Horowitz, 2009; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001; but, see Muth, Hönekopp, & Falter, 2014, for examples of instances where findings have been mixed). Early researchers reported the tendency to focus on small details and changes in the environment in autistic children (e.g., Kanner, 1943) and further studies have posited the theory that autistic individuals often show a detail driven focus that leads to enhanced performance on tasks such as the Embedded Figures Test (EFT; Joliffe & Baron-Cohen, 1997). The EFT requires participants to locate a shape hidden in a larger display. This tendency has been termed by some researchers as weak central coherence, a focus on details at the expense of the bigger picture (e.g., Happé, 1999). A revised account of the theory (Happé & Frith, 2006) suggests that although local processing is the default of autistic individuals, global processing can still be carried out effectively (e.g., O'Riordan et al., 2001). Further theories have put forward alternative potential reasons driving enhanced performance outcomes on visual tasks (see Pellicano, 2012, for an interesting discussion of the central coherence theory); however, the underlying idea that autistic individuals differ from control groups in performance in visual functioning remains prevalent (although this has not always been seen in behavioural results on tests – see Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015, for results of a meta-analysis of local-global visual processing studies).

As autistic traits can be measured in the general population on a continuum, attention has been given to the relationship between autistic traits (measured by self-reporting tools, such as the Autism Quotient, AQ; Baron-Cohen et al., 2001) and visual-spatial tasks. A recent meta-analysis suggests that systematic variations in EFT performance, linked to autistic traits in the general population, are shown when extreme groups are considered, but not when autistic traits (as measured by the AQ) are investigated as a continuum (Cribb, Olaithe, Di Lorenzo, Dunlop, & Maybery, 2016). Similar investigations with VS tasks have also shown mixed results (Brock, Xu, & Brooks, 2011; Gregory & Plaisted-Grant, 2016; Rusconi, McCrory, & Viding, 2012). However, there is no recently published systematic review that we are aware of that considers performance in VS tasks for those in the general population based on autistic traits, rather than looking at visual-spatial tasks involving dis-embedding/local-global processing/field independence (Cribb et al., 2016), or looking specifically at individuals with a diagnosis of autism spectrum disorder (Muth et al., 2014; Van der Hallen et al., 2015).

One further trait receiving a great deal of attention in studies deploying VS tasks is trait anxiety. VS stimuli may have emotional relevance, and variations at the individual level may influence attention to certain emotive stimuli, such as threatening objects or faces. With this in mind, trait anxiety has been considered most frequently in search for threat, as evidence suggests that trait anxiety is associated with a bias for threatening information, which has been shown in behavioural measures (e.g., Moran & Moser, 2014), as well as activations in the amygdala during the processing of threat (e.g., Etkin et al., 2004; Ohrmann et al., 2007). Furthermore, distractibility has been found to accompany anxiety and studies have shown this is particularly evident when distractors or cues are threatening, with variations shown in performance outcomes (Moran & Moser, 2014) and physiological indices of attentional selection (e.g., Gaspar & McDonald, 2018) (evidence also links anxiety with higher distractibility even with non-threatening stimuli – e.g., Moser, Becker, & Moran, 2012). Other research has shown enhanced visual information processing in individuals with high trait anxiety when participants were required to find a target letter under an incrementing perceptual load. As trait anxiety level increased, the ability to detect the additional critical stimulus improved, with faster RTs and accurate sensitivity regardless of perceptual load, suggesting a potential enhancement of sensory processing and an alteration in visual perception in line with hypervigilance (Berggren, Blonievsky, & Derakshan, 2015). The authors did not include threat stimuli, so their results can be generalised and interpreted in VS without a contextualised situation; reviewing similar effects across the literature could benefit basic knowledge of VS.

### 1.3. Cognitive abilities and VS

Research into individual differences has also placed a large focus on intelligence as a key differentiator in human behaviour, with evidence suggesting that, although its stability depends on the age at which it is tested, intelligence is relatively stable in adulthood (see Rinaldi & Karmiloff-Smith, 2017, for a discussion). However, evidence also suggests intelligence is not unidimensional (see Schneider & Newman, 2015, for a discussion). Thus, studies have focused on individual cognitive abilities, rather than general intelligence, to understand variation in human behaviour, referring to models of intelligence driven by empirical research to understand how such abilities are related and structured. For instance, by categorising tasks in relation to broad or narrow cognitive abilities, such as in the Cattell-Horn-Carroll (CHC) model (McGrew, 2009). Such models have also allowed for cognitive tasks to be categorised based both on their psychometric relation to other tasks and the main cognitive abilities they are expected to measure. We will adopt here the CHC framework, as this model of intelligence has been studied widely and, in recent years, has been adopted across several fields for classifying and investigating cognitive abilities (McGrew & Wendling, 2010; Newton & McGrew, 2010; Schneider & McGrew, 2018). Taking a hierarchical approach, the model classifies cognitive abilities from an overarching general ability (Stratum III) down to the level of narrow abilities, which are clearly defined and can be measured using specific tasks (Stratum I) (Schneider & McGrew, 2012, pp. 99–144). As an evolving theory, the CHC model may still have improvements to come; however, currently, it appears to be a meaningful and empirically tested method of classifying and synthesising findings related to cognitive abilities across the literature (McGrew, 2009; Schneider & McGrew, 2018).

The CHC model comprises 11 broad abilities including fluid reasoning (previously fluid intelligence), short-term working memory, learning efficiency, visual-spatial processing, auditory processing, comprehension-knowledge, domain-specific knowledge, reading and writing, quantitative knowledge, retrieval fluency, processing speed, reaction and decision speed, psychomotor speed, psychomotor abilities, olfactory abilities, tactile abilities, kinesthetic abilities, and emotional intelligence (Schneider & McGrew, 2017). To include all in the review would render the scope too broad and may result in great difficulty when synthesising the results. A preliminary scoping exercise revealed working memory and fluid intelligence to be the two cognitive abilities appearing the most frequently in the records returned (see Supplementary Details available at https://osf.io/n6hzc for more information) and many other individual differences appearing only once or twice in the literature. However, as this was based on a general search it is understood that several studies may not be returned unless more specific terminology is included in the search terms, but including specific terms at the scoping stage would lead to circular reasoning. Thus, the decision on cognitive abilities was made on frequency in the literature and theoretical reasoning. For instance, attentional abilities have been noted as crucial in VS, with the ability to maintain focus on goal-relevant stimuli being key for task success (e.g., Lavie, 2001, 2005), and selective attention will determine which items are attended to in a scene (Wolfe, 2020). With regards to the attention system, Petersen and Posner (2012) posited an alerting network relating to vigilance or sustained attention, an orienting network, and an executive function network (Petersen & Posner, 2012; Posner & Petersen, 1990). Looking more closely at executive functions it is clear that they are not homogenous and, therefore, are unlikely to be captured using one tool or even a select number of tools. For instance, Miyake et al. (2020) investigated the executive functions most posited in the relevant literature, breaking these down into switching, inhibition and updating. Further research has investigated these categories of executive functions in relation to the CHC, suggesting updating is covered by the broad ability short-term memory (specifically the narrow ability working memory capacity) (Jewsbury, Bowden, & Strauss, 2016). Furthermore, the same study found inhibition to be inseparable from a general speed factor; switching was found to be more diverse with some analyses showing switching to be different from a general speed factor, and other analyses suggesting switching was not separable, with results depending on the test used. The authors interpret their findings as switching being a narrow factor under general speed (Jewsbury et al., 2016). In terms of processes related to attention including orienting and alerting systems as proposed by Posner and Petersen (1990), which are often tested using the Attentional Network Test (ANT) (Fan, McCandliss, Sommer, Raz, & Posner, 2002), these will be categorised under processing speed (see Frischkorn, Schubert, & Hagemann, 2019; McGrew, 2006).

Finally, as the findings of the initial scoping review of personality highlighted autistic traits as having been frequently studied for their association with VS based on the notion that autistic individuals have a tendency for local processing, it would be prudent to include the cognitive ability of visual-spatial processing. This is the ability to manipulate images mentally and use such imagery to solve problems and includes the narrow ability of flexibility of closure, the ability to identify a known embedded figure/pattern in a more complex display. Performance on the EFT involves such an ability and, as EFT performance has also been used as a measure of tendency to attend to local detail (see Milne & Szczerbinski, 2009), including studies of this nature would offer a comprehensive synthesis of the main themes addressed by the literature.

Considering the idea of cognitive abilities and VS tasks, the expectation may be that performance in similar tasks should be highly correlated; for instance, individuals proficient at searching for an angry face among neutral faces may be expected to be good at another VS task, such as searching for a T amongst Ls. Yet, often search tasks are complicated and diverse; as the definition of VS is broad – *searching for a target among distractors* – such tasks can take many forms, and the similarity among VS tasks may not be as substantial as first expected. For instance, it has been found that searching for a threatening target (e.g., an angry face – the paradigm adopted in many studies investigating selective attention to threat), can activate different areas of the brain than search for a neutral target (see Öhman, 2005, for a discussion). As a result, variations in the cognitive mechanisms required between the two tasks, chosen for illustrative purposes from a huge array of VS tasks, may be expected.

However, there is a possibility that there are still sufficient similarities in the cognitive abilities required for these tasks, and research investigating these relationships can offer insight into key individual differences worthy of future investigation. This is particularly important, as recent research has turned its focus towards investigating whether a domain-general visual ability exists in the areas of visual perception (Tulver, 2019) and object recognition (Richler et al., 2019) with mixed results, specifically the latter study offered evidence in favour of a domain general object recognition ability when investigating performance across different tasks with different categories of object, whereas the former review considered studies adopting latent variable techniques investigating individual differences in visual ability and found little evidence to support a general visual ability. Indeed, it is likely that the large variation in visual tasks adopted in the literature, including the variation in task difficulty, cognitive requirements, environmental settings and motivational factors, may drive variations in performance outcomes between tasks more than the basic visual aspects impact similarities in performance. Thus, understanding the cognitive abilities that maintain their association across VS paradigms is arguably, currently, as important as understanding how different search paradigms are related to different cognitive abilities. In turning attention to key cognitive abilities and their definitions, their potential association with VS performance is made clearer.

Short-term memory is a broad ability concerned with retaining and using information in active attention and includes narrow abilities such as working memory capacity (Schneider & McGrew, 2017). Working memory has been investigated for its role in guiding attention during VS (Woodman & Chun, 2006). As VS involves detecting a target object among distractors, it has been suggested that the role of working memory may include tracking rejected distractors to prevent having to re-assess them as well as holding a template of the target in memory. Experimental studies have sought to understand the working memory requirement by manipulating search factors, such as object location (relocating every 111 msec) and found no change in efficiency in those conditions when compared with static object locations, suggesting location information is not held in working memory during search (Horowitz & Wolfe, 1998). Further studies, investigating the nature of working memory requirements in VS have utilised the dual-task paradigm (carrying out another concurrent task requiring working memory while undertaking a VS task). Findings from key studies of this nature have found that maintaining spatial representations in working memory hinders VS efficiency (Woodman & Luck, 2004), but found no impairment of VS efficiency when object representations were held in visual working memory (Woodman et al., 2001). Further evidence suggests the role of working memory may be largely based on the nature of the stimuli, including target-distractor similarity (Williams & Drew, 2020). Taking these findings together, one may expect working memory capacity to be linked with VS performance. Research investigating individual differences in working memory has shown working memory capacity to be a predictor of performance when searching for rare targets (Peltier & Becker, 2017a; Schwark, Sandry, & Dolgov, 2013). However, findings from other VS studies are not so clear as to the association between working memory and VS performance (Kane, Poole, Tuholski, & Engle, 2006; Sobel, Gerrie, Poole, & Kane, 2007).

Further cognitive abilities, such as processing speed have been linked to the ability to successfully carry out simple and repetitive cognitive tasks quickly (Schneider & McGrew, 2017). Theoretically, faster processing speed may be associated with enhanced VS abilities, with more difficult VS requiring more processing. Thus, individuals with a faster processing speed may excel at these tasks. However, a recent study comparing the similarities and differences of the cognitive abilities required for a traditional VS task and an x-ray security screening task looked specifically at the associations between performance in these VS tasks with processing speed, visual processing, and working memory performance (Hättenschwiler, Merks, Sterchi, & Schwaninger, 2019). Interestingly, the results showed that different aspects of the cognitive abilities were associated with performance in the different tasks. For instance, processing speed correlated with sensitivity to the signal in the simulated baggage screening task, but not with performance measures in the traditional VS task. However, visual processing performance, which is the ability to solve problems using mental imagery (Schneider & McGrew, 2017), correlated positively with performance measures in both tasks, although there was little overlap between the cognitive abilities required to carry out the tasks. Some cognitive abilities may thus be more likely than others to hold across VS paradigms.

Furthermore, previous research has established a link between visual processing performance and performance in an x-ray screening security task, which may be expected as, in x-ray screening, objects are shown in various rotations, and are required to be removed from a more complex background. For instance, links have been established between performance in a visual task requiring dis-embedding and performance on an x-ray screening task (Wagner et al., 2020) and further evidence highlights links between mental rotation tasks and figure-ground segregation tasks and x-ray screening performance (Hardmeier & Schwaninger, 2008). However, at present, it is uncertain how substantial the evidence is for an association between visual processing performance and general VS performance.

Fluid reasoning, previously named fluid intelligence, is considered the ability to solve problems that cannot be solved with previous learning (Schneider & McGrew, 2017) and can be measured by tests such as visuospatial reasoning tasks (Shokri-Kojori & Krawczyk, 2018). Interestingly, fluid intelligence has been linked with eye movement behaviour, including fixation duration, during a comparative addition/deletion VS task with individuals with lower fluid intelligence spending more time processing objects than individuals with higher fluid intelligence (Abdi Sargezeh, Ayatollahi, & Daliri, 2019). Furthermore, previous evidence links performance in the Raven's Progressive Matrices, a task often used to measure fluid reasoning, with an index of performance in VS applied to security x-ray images (e.g., sensitivity to the signal; Hardmeier & Schwaninger, 2008; Hättenschwiler et al., 2019) and Raven's Progressive Matrices performance with indices of performance in a classical VS task (e.g., speed and sensitivity to the signal; Hättenschwiler et al., 2019).

Taken together, the literature on individual differences and VS is diverse and offers some suggestions that certain individual differences may impact search strategies and, in turn, have an association with search success. The literature on personality highlights its links with key outcomes and suggests the possibility that individuals with high/low scores on certain trait measures may be more adept at VS tasks; the idea of an association between self-reported variations in usual behaviour and outcomes on a cognitive task, however, may be less intuitive than the association between VS performance and performance in other cognitive tasks. Nonetheless, if such associations between traits and VS performance hold, then from an applied perspective issuing a questionnaire could be quick yet prove highly beneficial for recruitment and selection. On the other hand, variations in cognitive functions and abilities have also been shown to be linked with the heterogeneity between individuals in VS outcomes. Thus, it may be more promising to investigate variations by focussing on the use of cognitive tasks related to the specified cognitive abilities (see Study Materials at https://osf.io/qdj52/ for a list of key cognitive abilities based on the CHC model and the information extracted on the cognitive tasks used to measure these abilities; Schneider & McGrew, 2017).

## 2. Rationale and study aims

VS is a key requirement in everyday life and remains an important focus of scientific research. Individuals are often required to locate a target within a visual scene containing distracting objects, sometimes such tasks are undertaken in situations where the stakes are high; for instance, when searching for a tumour using x-ray technology, or for a hostile conspecific on a crowded battlefield. As with many cognitive tasks, individuals in the general population differ widely in their abilities to perform VS tasks (see Rusconi et al., 2012, for an example). Much of the research investigating associations between measures of individual differences and visual performance can be categorised under the heading of differential psychology (Eayrs & Lavie, 2018; Gerstenberg, 2012), while other studies are arguably a type of hybrid research, where experimental manipulations are combined with investigations into individual differences (e.g., Damjanovic, Williot, & Blanchette, 2020; Wagner et al., 2020). The latter appears to be growing in popularity (Goodhew & Edwards, 2019). As such, there is growing literature on the relationships between individual differences, in terms of traits and cognitive abilities, and VS performance; however, to date there is no review that we are aware of, that offers insight into the relationships between individual differences and VS. Such a study would add to the literature by highlighting whether the most promising areas of future research are related to cognitive abilities or traits, and potentially highlighting specific factors worthy of future study for both basic and applied scientific endeavours.

One aim of this research is to systematically investigate the existing evidence on associations between VS performance and a targeted selection of self-reported traits (autistic traits, trait anxiety, and the Big Five; see section 1.2). A parallel aim is to systematically investigate the existing evidence on associations between VS performance and a targeted selection of cognitive abilities (fluid reasoning, short-term memory, processing speed, and visual processing; see section 1.3).

Last but not least, this work is urgent and necessary to size up and highlight potential issues resulting from past and current standard practices (e.g., lack of psychometric information, and insufficient power; Hedge et al., 2018; Parsons, Kruijt, & Fox, 2019), which might undermine research endeavours, push back the creation of a robust body of knowledge in the field and weaken its applicative potential.

### 2.1. *Objectives*

The primary objectives of this study are therefore to:

1. Synthesise the evidence from the literature investigating associations between performance in VS (as measured by any of the following indices: RTs, accuracy, d′ or slope) and measures of individual differences belonging to one of four categories of cognitive abilities (fluid reasoning, short-term memory, processing speed and visual processing) or one of seven categories of traits (Big Five traits, trait anxiety and autistic traits).
2. Check and describe the reliability problem in the selected literature (see section 1.1; in what proportion of studies is reliability information available and considered?).
3. Discuss whether any/which of the selected cognitive abilities or traits appears to have a robust association to one or more indices of VS performance.

In doing so, further insight may be gained into the underlying mechanisms required for general VS, by identifying potential cognitive factors behind inter-individual variability in performance. Notably, inter-individual variability has often been considered as noise in nomothetic studies, which still represent the major building blocks of most theoretical frameworks (Kanai & Rees, 2011). Further insight could be gained on the specific measurement tools or tasks that benefit and inform the selection of visual searchers in real-world scenarios, such as security or medical screening, based on individual predispositions. Indeed, translational and applied researchers will find guidance on the associations between key traits or cognitive abilities and VS performance that may be best pursued and tested with job-specific materials and/or real-world contexts. Finally, this systematic endeavour will enable a first summary evaluation on the robustness of the evidence based on reporting practices (i.e., whether information on the reliability of all measures is available and considered) in the relevant literature.

## 3. Methods

This systematic review adheres to the approved Stage 1 procedure (https://osf.io/n6hzc), is guided by the PRISMA protocol and follows the PRISMA flow diagram (see Fig. 1a and b; Page et al., 2021), with detailed reasons for the exclusion of studies removed at the stage of reading the full article. Study and Supplementary Materials are also provided at the following link: https://osf.io/qdj52/.

***Transparency statement:*** We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, and all manipulations in the study.

### 3.1. *Study search terms*

The search aimed to capture all studies relevant to the targeted population (adult, non-clinical), context (laboratory based studies or, where naturalistic search is investigated, studies in highly controlled experimental settings), measure (VS performance and its associations with performance in a task that can be related to the following cognitive abilities: fluid reasoning, processing speed, short-term memory, and visual processing, or related to scoring in a tool measuring autistic traits, Big Five personality traits, or trait anxiety), and outcome (RTs, accuracy, d′, or slope).

To capture relevant studies searches were carried out on PubMed, Scopus, Web of Science, and Google Scholar, and the following search terms were used:

> *Traits*: ("big five" OR "open*" OR "conscientious*" OR "extraver*" OR "agreeable*" OR "neurotic*" OR "autis*" OR “trait anxiety”) AND ("visual search" OR "target detection" OR "threat detection")
> *Cognitive abilities:* ("cognitive abilit*" OR "intelligence" OR "human abilit*" OR “short-term memory” OR "working memory" OR "fluid reasoning" OR "processing speed" OR “visual spatial process*” OR “visuospatial process*” OR “visual process*” OR “executive function” OR “attention” AND ("visual search" OR "target detection" OR "threat detection"))

References of included studies, found from searching the above terms, were checked for any other eligible studies.

### 3.2. *Eligibility criteria*

A study was included in the systematic review if it met the following criteria:

1) The study must be published during or after 1985 (being a key year for a resurgence in studies related to the Big Five taxonomy and tools to measure these traits (e.g., McCrae & Costa, 1985).
2) The study must use original data.
3) The study must use an adult, healthy, human sample.
4) The study must be published in a peer-reviewed journal.
5) The study must be written in English.
6) The study must utilise a self-reporting tool for measurement of the traits Big Five, autism traits, or trait anxiety, or an experimental task measuring the specific cognitive abilities fluid reasoning, short-term memory, visual-spatial processing, or processing speed (as defined in the CHC model; see Schneider & McGrew, 2017 for definitions).
7) The study must link scores or performance measures from (6) to performance measures in a VS task using a correlation, regression analysis, or factor structure.
8) The study must report *p*-values of the analyses of interest, and this is reported in Supplementary Table 1 to determine significance along with effect size. Where no *p*-value had been reported but the authors state the result was significant/not significant the study would be included in the systematic review with a note in Supplementary Table 1. Where the *p-value* had not been stated in a study and no further information given then the relevant author would be contacted, and the data requested. A 2-week period would be given from the date of request and where no response had been received the study/relevant effect size would not be included. Where a response suggesting data would be sent later had been received, a further 2-week waiting period would be given. Where data had not been sent within this timeframe, the study would not be included. Relevant information regarding inclusion requests (if any) would be logged and made available.

The inclusion criteria were applied by two reviewers with disagreements being resolved by the most senior author. The agreement between the two initial reviewers was calculated using Cohen's kappa, and corresponded to .930 for traits and .947 for cognitive abilities (indicating 99.95% and 99.93% agreement respectively).

### 3.3. *Risk of bias and quality assessment*

There is a potential risk of adopting an incomplete search strategy and from publication bias. However, to reduce this issue alternative terms have been included for VS, such as threat detection. Furthermore, by ensuring reference lists of all included studies are checked for relevant studies the risk appears low. Studies were assessed by two researchers using the cross-sectional studies critical appraisal tool (Moola et al., 2020) (Supplementary Materials available at https://osf.io/qdj52/ (Study Materials)), with any disagreements being decided by the most senior author. Studies were given a quality score, with 0–3 being low quality, 4–6 being moderate and 7+ being high quality. However, to adapt the tool to this systematic review, question 3. “Was the exposure measured in a valid and reliable way?” was reworded to “Was the individual difference measured in a valid and reliable way?” and 4. “Were objective, standard criteria used for measurement of the condition?" was reworded to "Was visual search performance measured in a valid and reliable way?".

### 3.4. *Key classifications and definitions*

Tasks adopted in eligible studies were classified based on the broad definitions of the relevant cognitive abilities, as defined in the CHC model (see Schneider & McGrew, 2017 for a breakdown of all abilities and definitions).

For the purposes of this research, the following definitions apply:

*Autistic traits*: personality traits related to autism in non-clinical populations (i.e., autism-like traits), which may include social and communication impairments and

(a)

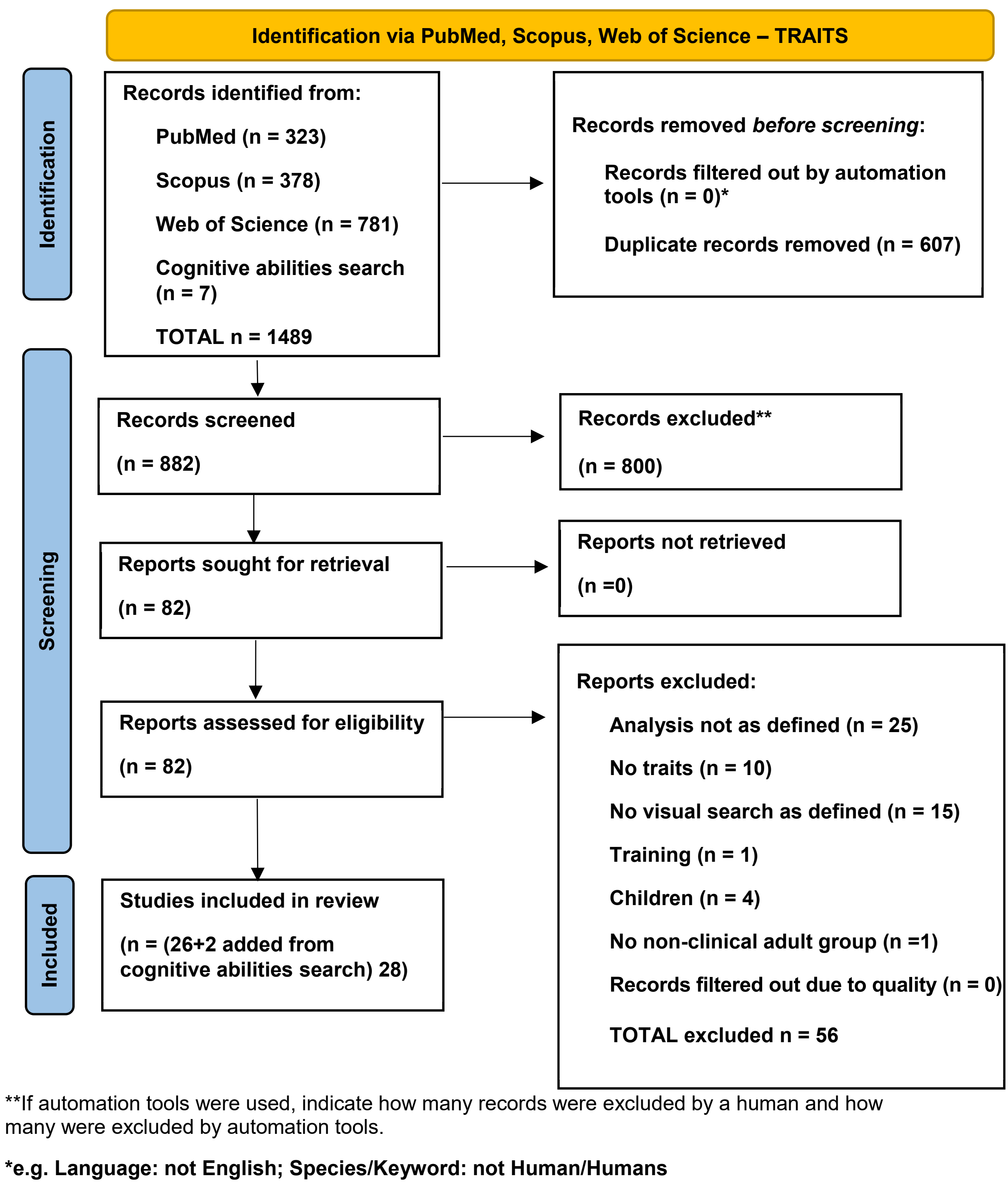


**Fig. 1** – **PRISMA 2020 flow diagram for the traits (a) and the cognitive abilities (b) part of the review.**

(b)

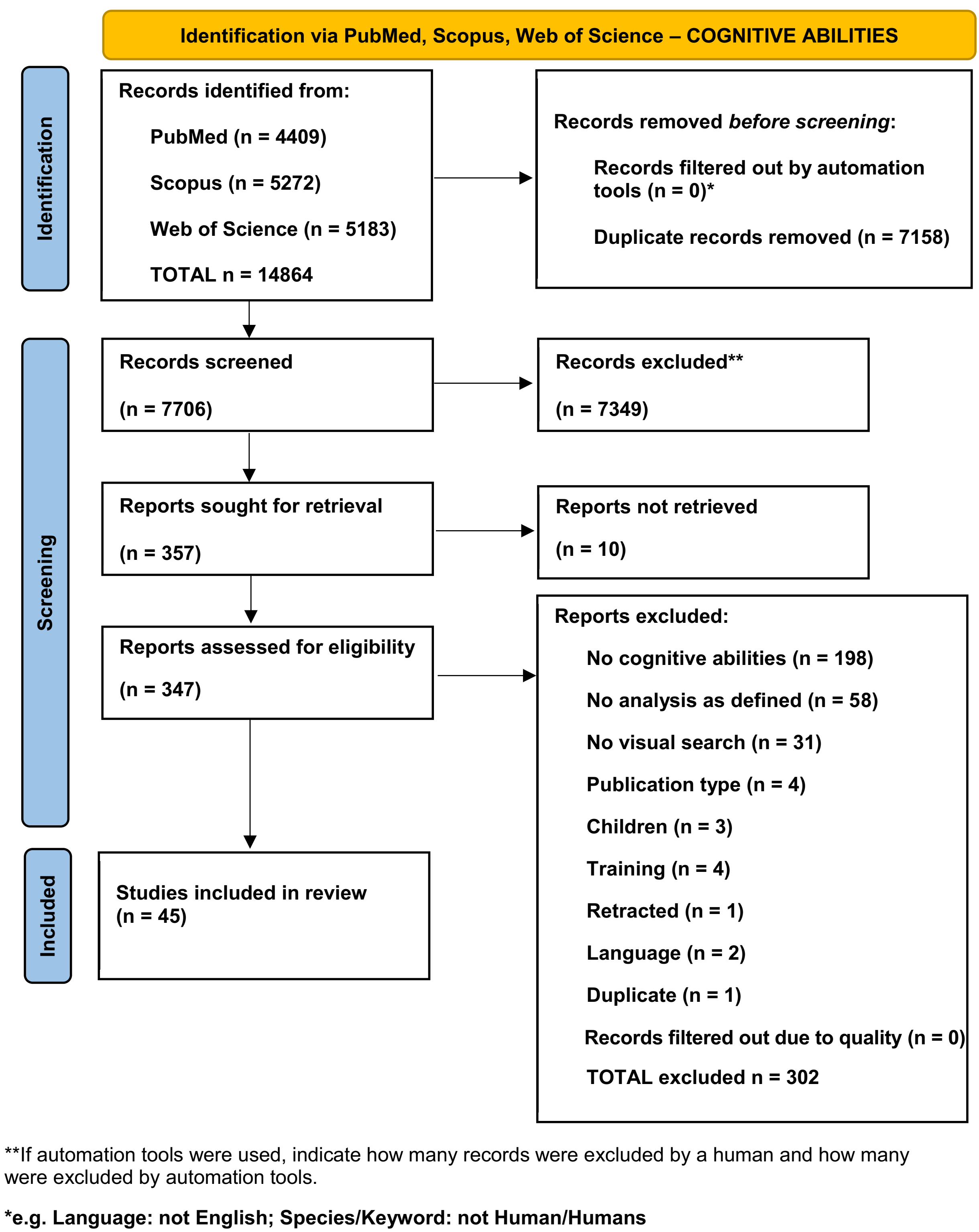


Fig. 1 – (*continued*).

restrictive and repetitive behaviours, measured using tools including, but not limited to, the Autism Quotient (Baron-Cohen et al., 2001), and the Social Responsiveness Scale (Constantino & Gruber, 2012).

*Trait anxiety*: The proneness of an individual to manifest anxiety states (Spielberger, 2010), measured using tools including the trait version of the State-Trait Anxiety Inventory (Spielberger et al., 1971). For this research, this relates to non-clinical populations.

*Big Five*: personality traits including Agreeableness, Conscientiousness, Extraversion, Neuroticism, and Openness, often measured using tools including, but not limited to, NEO Personality Inventory – Revised (Costa & McCrae, 1992), NEO-Five-Factor Inventory, and the Big Five Inventory.

*Fluid reasoning*: the ability to solve novel problems using controlled procedures (Schneider & McGrew, 2017).

*Processing speed*: the ability to perform repetitive and simple cognitive tasks using controlled attention (Schneider & McGrew, 2017).

*Short-term memory*: The ability to keep and manipulate information in attention (Schneider & McGrew, 2017).

*Visual-spatial processing*: The ability to solve problems using mental imagery (Schneider & McGrew, 2017).

*VS task*: a visual task where the purpose is to find a target among distractors; such tasks include yes/no target search paradigms and target location tasks (where the participant must highlight where the target is located). The target may be shown specifically to the participants before the task, or displayed at the same time as the search, or specific instructions may be given *before the* task beginning regarding the nature of the target; for instance, a participant may be told to respond based on whether “a gun” or “a T” appears in any of the images, or to search for differences between scenes/images. For the purposes of this research, targets may be of a threatening or non-threatening nature. Moreover, paradigms where targets and distractors are moving (e.g., motion detection) were not included. Distractors or scenes should be presented concomitantly with the target object(s) and not in a serial manner, such as in rapid serial visual processing paradigms.

*Performance Measure*: for the purposes of this research, performance relates to a key measure of VS task success, specifically: accuracy and RTs; other measures, such as sensitivity to the signal and slope will also be taken into account.

*Experts*: Experts were regarded as those who have had training and have acquired knowledge through previous experience in the same VS domain in which they are being tested; for instance, x-ray screeners being tested with an x-ray search task. Those having undertaken short training sessions carried out only for the purposes of the experiment will not be considered experts.

### 3.5. *Screening and data extraction*

Abstracts were screened by two researchers, based on eligibility criteria and a list made of all studies to be full text screened, and any disagreements were reconciled by the most senior author. The number of abstracts and full-texts screened as well as the outcomes of the screening and data extraction process are reported in the PRISMA diagrams (Fig. 1a and b). A detailed list of all included studies is available in Supplementary Table 1 reporting data extracted using the data extraction form (see Study Materials available at the following link: https://osf.io/qdj52/).

### 3.6. *Timeline*

A first search of the literature was performed in August 2022, the overall search was completed in January 2023, paper selection and data extraction were conducted from February to October 2023 and the writing up was finalised in January 2024.

## 4. Results and discussion

In the current section we will offer a general picture emerging from the included studies in each subcategory of traits and cognitive abilities, with a brief narrative to highlight the rationale and gist of each of the studies. The breadth of detail may vary, as our reporting is strictly functional to the review, and what is relevant to this context may not always coincide with the original focus of the source reports. Additional details for all of the included studies can be found in Supplementary Table 1 (part (a) for traits and part (b) for cognitive abilities). At the end, a brief summary is provided with the main take-home messages and recommendations based on the general issues and themes emerging from the current systematic review.

### 4.1. *Data screening and eligibility*

The diagrams in Fig. 1a and b summarize the outcome of our initial search, screening and selection workflow, conducted in accordance with the preregistered methods.

### 4.2. *Participants*

Most of the participants were young adults (18–35 years) although a few studies included older participants, especially when professional groups were involved or when the study focus was on changes in VS skills with age. Reported sample sizes vary between 11 and 636 per experiment, with about 70% of them positioned between 11 and 99; larger sample sizes are typical of studies testing a larger battery of tests and having a primary aim of better understanding individual differences. As is typical in psychology research, the gender ratio favoured female participants (approximate average ratio: 1.3:1; number of studies with equal sample sizes or larger male than female sample: 17). In most of the studies, participants were individuals (and, mostly, students) without a specific expertise or whose level of expertise was not assessed. Three studies included either in the general sample or as a separate sample some individuals whose professional expertise was relevant to one or more of their VS tasks.

### 4.3. *VS tasks*

About 12% of the studies investigated a VS task with complex or real-world images (e.g., simulating a search for prohibited items in x-ray baggage images, for target items in aerial photographs, for a person in a drawing of a crowded natural scene). These images are characterised by a certain degree of clutter, roughly corresponding to set size in traditional VS displays (Rosenholtz, Li, & Nakano, 2007). However, it does not appear to be standard practice in this kind of literature to provide any image-based indices of clutter, such as feature congestion, edge density, sub-band entropy. The remaining 78% focused on traditional VS, and most frequently on some version of the T among Ls search task, with rotation applied to the letters and a slight offset in the intersection of the strokes in the distractor Ls, to make the task more difficult, or on variable types of conjunction search. Set sizes vary from 2 to 383. The radial frequency search task (e.g., Almeida, Dickinson, Maybery, Badcock, & Badcock, 2010b), deserves a separate mention as it can be used to reproduce and study in a controlled and simplified way the same basic challenges of complex and real-world images (such as embedding and superposition of items, normally absent in traditional search tasks). Its image-based difficulty is typically measured via set size rather than clutter though.

### 4.4. *Individual differences*

Fig. 2 shows the relative frequency of the individual differences addressed by the included studies. When providing descriptions, we have flagged whether a single article contributes to multiple sections.

### 4.5. *Traits*

#### 4.5.1. *Personality*

Six of the collected papers investigated the relation between personality traits and VS performance (see Table 1 and Supplementary Table 1a). A theme emerging from this group of studies concerns the relation between personality and task complexity. Where more complex VS tasks were used (as indicated for example by the variability and range of set sizes and/or average RT and accuracy), a significant positive correlation between conscientiousness and accuracy is reported. For the rest, VS has been rather inconsistently reported to benefit from higher introversion, understood as low extraversion, from either lower or higher openness and from lower agreeableness.

On the one hand, Biggs et al. (2017) presented to a sample of TSA officers a randomly rotated T target among randomly rotated pseudo-Ls, making the task more difficult than a basic T among Ls search task. Of the Big Five traits, only conscientiousness was significantly related to accuracy in such a task. More precisely, officers with lower trait conscientiousness tended to miss more targets ($r = -.25$, $p < .01$, $BF_{10} = 4.53$). A similar result was obtained by Grady, Cox, Nag, and Mitroff (2022), whose search task required the identification of prohibited items in simulated bags at a virtual airport security checkpoint. The aim here was to explore if trait conscientiousness moderates the relationship between state fatigue and VS performance. As predicted, the authors found that fatigue negatively affects VS and, more interestingly, that conscientiousness is linked positively to search accuracy and acts as a moderator of the effect of fatigue on task performance. Indeed, the self-reported energy state (used as a proxy

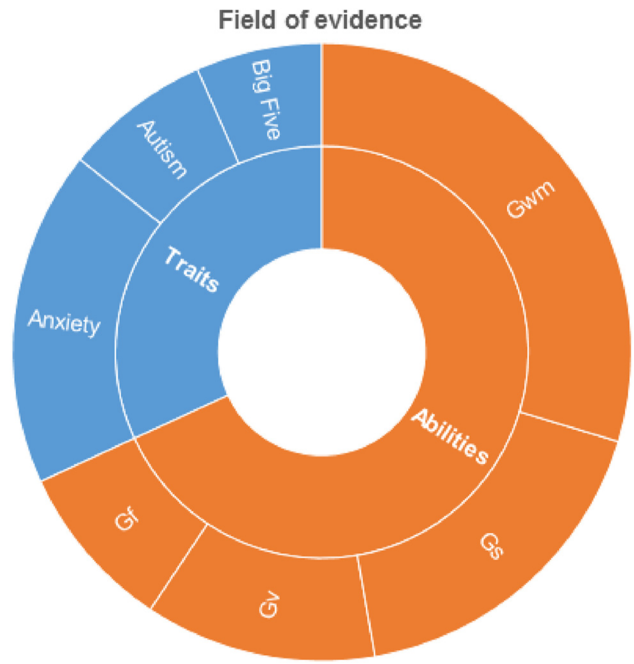


**Fig. 2 – The field of evidence on which this systematic review is based, with areas proportional to the number of contributing studies, is shown. 62 studies either were directly aimed to probe or assessed in exploratory analyses the relation between one or more measures of cognitive ability and VS performance. Gwm was the most frequently considered ability (27) followed by Gs (16), Gv (11) and Gf (8). 29 studies were concerned with the relation between self-reported traits and VS performance. Anxiety was the most frequently considered trait (16), followed by autistic traits (7) and the Big Five (6). A number of studies addressed both traits and abilities, more than one trait or more than one ability, hence the sum of the relevant sources contributing to the field of evidence is larger than the total number of articles included in this review.**

for fatigue) was weakly but significantly related with task performance in low conscientiousness individuals only ($r = .176$, $p = .017$).

On the other hand, Peltier and Becker (2017a) also used a rotated T as target among offset Ls aiming to find predictors of search accuracy by using low (10%) and high (50%) target prevalence search, but without varying set size. Correlational analysis revealed that accuracy on low-prevalence search was weakly but significantly associated only to imagination/intellect (i.e., openness; $r = -.19$, $p < .05$), whereas a multiple regression model, including extraversion and cognitive variables, showed that extraversion alone was a significant predictor of target detection accuracy (hits − false alarms: $b = -.15$, $p = .009$) and target-absent RTs ($b = -.14$, $p = .04$), with more introverted subjects performing better at low prevalence search. In accordance with Eysenck (1967), introverts may maintain a higher level of baseline arousal, which allows them to perform monotonous tasks, such as low-prevalence search tasks, for longer periods. Bendall, Eachus, and Thompson (2022) focused on extraversion in

**Table 1 – Summary of the main associations reported between personality traits and visual search performance (see Section 4.5.1).**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | O | C | E | A | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Biggs | 2017 | 122–130 | S: 8, 16, 24, 32 | 50% | Misses | | – | | | |
| Grady | 2022 | 374 | C: 3 (S: 6–16) | 50% | Accuracy | | + | | | |
| Peltier | 2017a | 141 | S: 24 | 10% | Accuracy | – | | – | | |
| | | | | | T-absent RT | | | – | | |
| | | | | 50% | | | | | | |
| Bendall | 2022 | 47 | C: 3 | 100% | | | | ° | | |
| Avisar | 2011 | 84 | S: 4, 8, 16, 32 | 50% | Combined slope | | | | + | |
| Lange-Küttner | 2021 | 65 | S: 6, 10, 14 | 50% | Accuracy | ++ | | | | |
| **N of studies reporting associations between personality traits and VS performance** | | | | | | 2 | 2 | 1 | 1 | 0 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); VS = visual search; O = Openness, C = Conscientiousness, E = Extraversion, A = Agreeableness, N = Neuroticism; T = target; ++ reported moderate significant positive association; + reported weak significant positive association; – reported weak significant negative association; ° no significant association found.

relation to a search and discrimination task with a coloured letter (an upright or rotated T or L) embedded in a valenced (positive, negative or neutral) real-world coloured scene. Their main aim was to investigate whether the influence of valence on the allocation of attention changes with the level of extraversion. They found that the relation between extraversion and VS performance (accuracy or RT) was not significant. In addition, no interaction was found between valence in a VS task and extraversion.

Avisar (2011) aimed to investigate the personality profile associated with difficulties in selective attention. A simple conjunction VS task where a blue square had to be identified among red squares and blue circles was used to engage selective attention, and analysed in relation to the Big Five dimensions of personality, among other measures. The author observed a significant positive correlation between agreeableness and a combined search slope (RT/accuracy) in the VS task for the healthy control sample ($r = .271$, $p < .05$), indicating that greater agreeableness was associated with less efficiency.

Finally, Lange-Küttner and Puiu (2021) used a VS task that required finding an element that differs from the others in three conditions, each containing a pop-out and a conjunction version: simple, visually complex, and mixed. When testing correlations between personality traits and performance, the authors found an effect of personality traits on accuracy in their simplest condition. They report that women scoring higher in openness were more accurate in identifying the target (although it should be noted that the correlation coefficient reported in the article is negative: $r = -.34$, $p = .037$, but it is unclear whether error rates rather than accuracy rates were entered in the analyses, as accuracy rates are typically reported in other sections). The authors recall the link between openness and a heightened esthetic sensitivity for composition (Palmer, Schloss, & Sammartino, 2013) to explain that VS display with singletons might have particularly benefitted from a creative sensitivity to the composition of the whole array.

In conclusion, conscientiousness seems to be the personality trait with a higher influence on VS performance when the task involves some difficulty in target detection (Biggs et al., 2017; Grady et al., 2022). For Biggs et al. (2017), such a relation is not surprising, especially in the context of demanding tasks that require attention to be sustained for a long period, as this trait is defined by the ability to control impulses, be organised and goal directed (Roberts et al., 2009), moderating the effect of fatigue produced by task difficulty (Grady et al., 2022). In less challenging VS tasks, Peltier and Becker (2017a) and Lange-Küttner and Puiu (2021) obtained a significant correlation between openness and accuracy on VS. Interestingly, the former found a weak, negative correlation, while the latter claimed a moderate and positive correlation between constructs. Peltier and Becker (2017a) found also a significant negative relation between extraversion and performance in low-prevalence VS, and concluded that introverted participants perform better in monotonous tasks. In contradiction, Bendall et al. (2022) did not find a relation between trait extraversion and performance in their VS task. Finally, only one study found a moderate correlation between agreeableness and combined search slope (Avisar, 2011).

#### 4.5.2. *Autistic traits*

Seven papers investigated the relation between autistic traits and VS performance (see Table 2 and Supplementary Table 1a). Three of the studies predicted higher autistic traits to be associated with an advantage in VS performance (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2013; Lange-Küttner & Puiu, 2021; Rusconi et al., 2015); the other four predicted higher autistic traits to be associated with a deficit in performance or in some derived measures of performance (Amodeo, Wiersema, Brass, Nijhof, & Wiersema, 2021; Anderson & Kim, 2018; Dowd, Kiyonaga, Egner, & Mitroff, 2015; Pomè, Binda, Cicchini, & Burr, 2020). None of the studies was preregistered. The three former studies reported an advantage, in association with higher autistic traits, of small to moderate size; in the remaining four, the null hypothesis could not be rejected and/or evidence for lack of an association between autistic traits and behavioural performance was reported and/or a more nuanced picture than expected emerged. In follow up analyses, one of the latter studies reported a weak association with autistic traits in the opposite direction than initially predicted (i.e., an advantage with higher autistic traits was found). Thus, only evidence for an advantage of higher autistic traits in VS has been reported with some consistency, as detailed below.

Almeida et al. (2013) first reported a significant negative correlation, of moderate size, between the AQ and slope (i.e.,

**Table 2 – Summary of the main associations reported between autistic traits and visual search performance (see Section 4.5.2).**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | AQ | ad | as | AQ-10 | SRS-A |
|---|---|---|---|---|---|---|---|---|---|---|
| Almeida | 2013 | 44 | S: 2, 4, 8, 16, 32; 4, 8, 16, 32 | 50% | Slope | −− | | | | |
| Lange-Küttner | 2021 | 65 | S: 6, 10, 14 | 50% | RT | −− | | | | |
| Rusconi | 2015 | 215 | C: 3 | 50% | Accuracy (T-present) | | ++ | | | |
| Dowd | 2015 | 74 | S: 4 | 100% | Attentional capture | | + | − | | |
| Pomè | 2020 | 27 | S: 3 | 100% | | ° | | | | |
| Anderson | 2018 | 181 | S: 6 | 100% | Attentional capture | + | | | | |
| Amodeo | 2021 | 99 | S: 6 | 50% | | | | | ° | ° |
| **N of studies reporting associations between autistic traits and VS performance** | | | | | | 3 | 2 | 1 | 0 | 0 |

VS = visual search. S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); AQ = Autism Quotient; ad = attention to detail subscale of the AQ; as = attention switching subscale of the AQ; SRS-A = Social Responsiveness Scale – Adult version; T = target; ++ reported moderate significant positive association; + reported weak significant positive association; −− reported moderate significant negative association; − reported weak significant negative association; ° no significant association found.

individuals with higher AQ performed VS more efficiently). They adopted a series of radial frequency (RF) search tasks variably tapping on local processing of curvature and global detection of shape primitives. Given that the correlation was significant with all the different versions of the RF task (*r*s between −.620 and −.441, all *p*s < .01), the authors suggested that the advantage associated to higher autistic traits reflects superiority in the search process both at the local and at the global level. Subsequently, Lange-Küttner and Puiu (2021) found individual AQ scores were negatively correlated with RTs in a VS task with simple stimuli (singletons differing from distractors for orientation, in the pop-out condition, or for orientation and size, in the conjunction condition), but only for males ($r = -.48$, $p = .012$). In other words, "men with higher autistic traits were quicker to decide about target presence" (p. 155). However, no relation between the AQ and search accuracy was reported with simple stimuli, or between the AQ and search RTs or accuracy with more complex or unpredictable stimuli.

Focussing on a specific subscale of the AQ, the Attention to Detail scale, Rusconi et al. (2015) probed the connection between self-reported detail focus and behavioural differences in a security x-ray screening task. Security x-ray images are peculiar, as they may require identifying a target in a clutter of overlapping items. Rusconi et al. (2015) probed whether an advantage for individuals reporting higher detail focus could be found with real hand-luggage x-ray images; they reported a significant positive association between Attention to Detail scores and target detection accuracy ($b = .74$, $p = .003$). Further analyses identified in a group of items in the Attention to Detail subscale, that is those concerning heightened attention to regular systems of elements rather than simply noticing details or remembering detailed information, the likely source of this relation.

Taken together, these three studies point to a potential advantage, in terms of accuracy (for spotting security threats in images with clutter and object superposition), speed (for spotting simple singletons in the midst of well-distanced distractors) or efficiency (in searching for singletons, based either on local or global processing), of self-reported autistic traits in traditional and real-world VS tasks.

Dowd et al. (2015) focused on attentional guidance by working memory in VS. In a regression model including also self-reported ADHD traits, they found that self-reported attention to detail and attention switching traits are significant linear predictors of attentional capture by cues retained in memory (Attention Switching: $b = -.22$, Attention to Detail: $b = .20$, $p = .008$ for the regression model). Interestingly, the Attention Switching score was related to weaker attentional capture, similarly to ADHD self-reported symptoms ($b = -.29$), and the Attention to Detail score was related to stronger attentional capture instead. On the other hand, Pomè et al. (2020), posited that individuals with higher autistic traits may be dominated more by sensory information than by past experience (Pellicano & Burr, 2012) and predicted autistic traits would negatively correlate with the strength of prior expectations and of top-down perceptual effects in a traditional VS task (Maljkovic & Nakayama, 1994). Their VS task required participants to locate a target via its colour and then to judge its shape. Although the study predictions and main finding concern changes in pupil dilation, data are also provided for behavioural performance. Substantive evidence was found for there being no correlation between the AQ and the cumulative perceptual priming effects on pop-out search from previous trials ($r = -.15$, $p = .458$, $logBF = .7$; disattenuated correlation: $r = .22$, $logBF = -.56$). A reduced pupillary response to switch, compared to repetition, was found to associate with higher autistic traits. However, the effect did not correlate with behavioural performance measures nor accumulate over trials, suggesting these indices may capture different aspects of the priming phenomenon in VS.

Anderson and Kim (2018) set out to test whether any impairments to social attention, related to autistic traits, may be captured by the costs, in terms of VS performance, of the presence of (non-social) distractors predicting socially relevant information, as set in an initial training phase. However, no such relation was found, and in follow-up analyses a positive rather than negative correlation emerged between autistic traits and the valence-driven attentional capture effect but only in the group of participants trained with positively valenced social cues ($r = .258$, $p = .018$). Finally, Amodeo et al. (2021) probed whether autistic traits may be negatively correlated with self-bias in a VS task. The self-bias effect was defined as the difference in mean RTs between searching for the name of a close other and searching for one's own name. A series of correlational analyses failed to find a significant correlation between measures of autistic traits and the self-bias effect, with Bayesian analyses offering evidence in favour of the null hypothesis ($r = .018$, $p = .805$, $BF_{10} = .201$).

Taken together, these four studies suggest how deficits in social attention, learning and memory that have been previously associated to autism, and that may be expected to influence performance in certain VS tasks, do not actually emerge in neurotypical individuals in association with their self-reported autistic traits. When different attention-related autistic traits are considered, their effects may be opposing, they may depend on the memory context, and emerge only in demanding conditions.

In conclusion, and with due caveats (none of the studies was preregistered and some of the reported results were found in exploratory analyses), the available evidence points to the existence of a relation between autistic traits in the neurotypical population and VS performance. In line with the literature indicating superior performance in individuals with clinical or sub-clinical autism in certain tasks requiring visual processing (e.g., Shah & Frith, 1993; Simmons et al., 2009; Jolliffe & Baron-Cohen, 1997), an advantage in terms of accuracy, efficiency or speed at VS tasks was found for individuals with higher AQ scores overall or Attention to Detail scores (Almeida et al., 2013; Lange-Küttner & Puiu, 2021; Rusconi et al., 2015). Since the advantage spans from very simple traditional VS to simulations of real-world tasks with more complex and cluttered displays, it could either derive from multiple sources or be related to a very fundamental property of the visual processing system, such as low-level discrimination abilities, with a cascade of consequences on the following stages (e.g., Almeida et al., 2013) and on the attention system. Indeed, the attentional style typical of the autistic constellation of traits, albeit present at a subclinical level and not necessarily in conjunction with other autistic traits (e.g., Rusconi et al., 2015), appears to afford, on the one hand, a higher detail-focus and, on the other, lesser flexibility which may also impact on VS by modulating attentional capture during VS in either direction (Dowd et al., 2015). Conversely, traits that imply a deficit of some kind (e.g., social attention, associative learning, top-down control of attention) do not appear to affect individual performance in simple VS, involving neutral, social or emotional stimuli (see Table 2).

#### 4.5.3. *Trait anxiety*

Sixteen of the selected papers investigated trait anxiety (see Table 3 and Supplementary Table 1a). Most of the included studies measured anxiety using the State and Trait Inventories (STAI). The studies can generally be divided into two groups: both test the notion that trait anxiety is linked to altered processing of visual information, with the former testing the notion that individuals with a higher tendency to appraise situations as threatening have a lowered ability to deal with new and distracting information. The second group test the more selective notion of trait anxiety being linked with altered processing in search involving emotive or threatening targets or distractors. The evidence supporting a link with VS and anxiety is more consistently seen in this second group of studies.

4.5.3.1. Non-emotional stimuli. Eight studies utilised non-emotional stimuli, of which seven studies aimed to investigate how trait anxiety may link with suppression of distractors or interference measures. The remaining study, probed the link between anxiety and cognitive functioning including VS.

**Table 3 – Summary of the main associations reported between trait anxiety and visual search performance involving non-emotional or emotional stimuli (see Section 4.5.3). Information between brackets next to n/a, refers to an inference based on the available information, although the datum itself is not explicitly provided in the source.**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | Non-emotional | Emotional |
|---|---|---|---|---|---|---|---|
| Zaninotto | 2022 | 96 | S: 5, 10, 14, 20 | 50% | | ° | |
| Salahub | 2021 | 48 | S: 10 | 100% | | ° | |
| Berggren | 2012 | 38 | S: 4 | 100% | Cueing benefits | −− | |
| Alfimova | 2014 | 266 | n/a | n/a (100%) | Bottom-up capture | − | |
| Moran | 2014 | 122 | S: 10 | 100% | Attentional capture | ++ | |
| Sadeh | 2011 | 65 | S:1, 2, 4, 6 | 100% | Attentional capture | ++/− | |
| Bishop | 2009 | 17 | S: 6 + 1 | 100% | | ° | |
| Birk | 2017 | 38 | S: 10 | 100% | | ° | |
| Raeder | 2019 | 32 | C: 3 | 50% | Attentional capture | | ++ |
| Dodd | 2016 | 40 | S: 8 | 100% | Attentional capture | | ++ |
| Byrne | 1995 | 25 | S: 12 | 50% | Threat T bias | | ++ |
| Berggren | 2022 | 58 | S: 4 | 100% | Attentional capture | | ++ |
| Pitica | 2012 | 20 | S: 9 | n/a (57%) | RT (emotional T) | | −− |
| Olatunji | 2011 | 31 | S: 12 | 100% | RT (emotional cue) | | ++ |
| Notebaert | 2010 | 21 | S: 4, 8 | 100% | Attentional capture | | ++ |
| Ouimet | 2012 | 131 | S: 16 | 70% | | | ° |
| **N of studies reporting associations between trait anxiety and VS performance** | | | | | | 4 | 7 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); T = target; ++ reported moderate significant positive association; + reported weak significant positive association; −− reported moderate significant negative association; − reported weak significant negative association; ° no significant association found.

Zaninotto, Bossi, Terry, Riccaboni, and Galli (2022) probed the nature and evolution of the association between anxiety and cognitive functioning during the lockdown period. VS was considered a measure of non-emotional cognitive functioning and involved searching for target letters of specific colours among inverted letters and different coloured letters. The study calculated a derived index of performance, specifically the ratio between individual RTs and the mean proportion of correct answers, in trials with the highest (20) and the lowest set sizes (5). The higher this index, the greater was the cost of serial VS in terms of performance decrease. The relationship between this bias measure and anxiety scores at the beginning of the study was weak and non-significant ($r = -.13$, $p = .29$), and it remained so following the four-month study period ($r = -.14$, $p = .33$). Thus, the findings offer no support for the theory that cognitive performance is significantly related to trait anxiety. However, the use of a bias measure of Inverse Efficiency may result in the loss of key information of performance (Bruyer & Brysbaert, 2011).

The results of Salahub and Emrich's (2021) study, also failed to find evidence to suggest trait anxiety was correlated with response latencies in a task examining distractor suppression ($rs < .22$ considering trait and state anxiety separately). The fact this was an easy speeded search task introduces the possibility that the lack of cognitive demand may have impacted the outcome. Moreover, with a high probability rule-based learning paradigm adopted in a cueing VS study by Berggren and Derakshan (2013a), it was shown that anxiety was related to a reduced cueing effect. This was shown by a significant negative correlation between anxiety scores and cueing benefits, calculated as cue-invalid RTs minus cue-valid RTs ($r = -.324$, $p < .05$). This finding is in line with the idea that anxiety may affect updating in attentional control (Berggren & Derakshan, 2013b).

A further study, looking at top-down attention and investigating the link between selective attention and genes, adopted a simple but very different search – words among rows of letters (Alfimova, Korovaitseva, Lezheiko, & Golimbet, 2014). Participants were also asked whether they noticed the colour of letters in the task, which allowed for a measure of bottom-up attention capture. The findings revealed that highly anxious participants had a significant relation with both bottom-up and top-down attention; therefore, suggesting that although higher anxiety may result in using more resources to process irrelevant stimuli, it may confer an advantage (Alfimova et al., 2014).

Moran and Moser (2014) predicted that ipsilateral distractors would compete more with targets than contralateral distractors and that performance in ipsilateral distractor trials would be associated with anxiety in their adapted additional singleton search task. Looking at behavioural variations based on anxiety scores, they found that ipsilateral cost scores were significantly correlated with trait anxiety scores ($r = .49$, $p < .001$) and appeared to be driven by the lateral target/ipsilateral distractor trials ($r = .46$, $p < .001$). However, the lateral target/contralateral distractor trial results were also found to be significantly associated with anxiety ($r = .25$, $p < .01$). The authors suggest these findings are in line with the notion that trait anxiety is associated with attentional bias favouring enhanced attentional capture by salient stimuli in general (Moran & Moser, 2014).

Offering further depth to the understanding of attentional control and anxiety Birk, Opitz, and Urry (2017) examined the direction of the association. In this study an anxiety induction was utilised, and attentional control investigated pre-induction and post-induction (Trier Social Stress Test) in a between-subjects design. The study task involved ignoring emotionally neutral distractors. The results showed that distractors increased RTs, but higher trait anxiety was not associated with higher distraction cost ($r = .191$, $p = .098$) and distraction cost did not predict any self-reported anxiety measures. Overall, the results of this study do not align with the idea that trait anxiety is linked with impaired performance in VS. However, this study only recruited individuals with moderate to high trait anxiety, which may have led to a narrow distribution of scores, which can hinder individual differences analyses.

In terms of perceptual load, Sadeh and Bredemeier (2011) probed the association of trait anxiety with selective attention using a perceptual load task (adapted from Maylor & Lavie, 1998). The results suggested at medium perceptual loads (load 4) anxiety was positively correlated with RT interference, but this was not the case for load 1 or 2. Furthermore, RT interference in the highest load (6) was found to be negatively correlated with trait anxiety. These findings suggest perceptual load is important when considering the relationship between anxiety and VS RTs. The authors suggest that the varied results in the two highest perceptual loads, based on trait anxiety, may be due to the compatible distractor creating more interference than the incompatible distractor when load demands are high (Sadeh & Bredemeier, 2011). On the other hand, Bishop (2009) also studied whether perceptual load modulates the association between trait anxiety and attentional control using a similar task to Sadeh and Bredemeier (2011); however, the perceptual load task used in Bishop (2009) displayed a target string of letters above or below a congruent/incongruent distractor but with no trials where the target letter appeared in the extreme positions of the letter string. The results revealed a trend for both state and trait anxiety, with slower target identification across conditions (state: $r = .45$, $p = .07$; trait: $r = .47$, $p = .06$) but anxiety did not influence performance as a function of perceptual load. It should be noted that the sample size was very small ($n = 17$), which is way below that expected in an individual differences study and may in part explain the variation in results from that of Sadeh and Bredemeier (2011), together with the variations in tasks adopted across the studies.

To summarize, the studies on trait anxiety with non-emotional stimuli vary widely in sample size and methodological approach and give a very mixed message. On the one hand, four studies showed significant associations between trait anxiety and some form of VS performance measure; on the other hand, four failed to show any associations. The variation in sample sizes is notable and the issue of adopting a small sample size is clear in studies where behavioural measures were a secondary aim.

4.5.3.2. Emotional stimuli. Emotional stimuli were considered in eight studies. The paradigms included: faces as emotional primes, cues, targets, or distractors (relevant or irrelevant), search for threat-relevant (spider) stimuli and search with valence conditioned stimuli.

In a study by Raeder et al. (2019) a speeded target detection task involving a learning stage, allowing for the formation of spatial contextual memories was adopted. The results showed anxiety was significantly negatively correlated with emotional distraction (calculated as accuracy on fearful distractor trials − accuracy on neutral trials). There was no significant association found between trait anxiety and neutral distractor trials accuracy or performance during the memory stage. These findings suggest emotional distraction was independent from memory-based orienting of attention, and trait anxiety may impair disengagement from threat (Raeder et al., 2019).

In a further study investigating relevance of emotions in search of faces, the overall findings did not reveal any significant associations between state or trait anxiety and accuracy or RT in the search tasks (Dodd, Vogt, Turkileri, & Notebaert, 2016). However, when calculating an attention bias index (happy face RTs − angry face RTs) higher levels of trait anxiety were associated with a greater attention bias to angry over happy faces when the facial emotion was irrelevant to the task. Further analyses showed this was driven by slowed RTs to happy faces ($r = .35$, $p = .027$) and not faster responses to angry faces ($r = .052$). This was not the case in the emotion-relevant condition, which may be the result of goal-orientation mediating the effects of anxiety.

A further study looking at relevance of emotional stimuli adopted a task where irrelevant colour-filtered emotional faces were displayed prior to a VS task (Berggren, 2022). Non-emotional distractors with the same colour as a category of emotional face (happy, neutral, angry) were displayed in the search arrays, with the correlational results showing individuals with higher trait anxiety experienced colour presence costs following angry face cues only ($r = .382$, $p = .003$). A further experiment investigated the associations when the face was relevant to the task. These findings showed no significant relationship between trait anxiety and colour presence costs. This suggests that individuals high in trait anxiety are more prone to disruption in their ability to control attention during VS when a task irrelevant stimulus is present.

Byrne and Eysenck (1995) also investigated the relationship between trait anxiety and performance in VS for emotional faces. The study was split over two sessions where different music was used to elicit mood states. Mood induction had no significant impact on results. The results based on a bias score, which was calculated by subtracting mean RTs to angry targets from mean RTs to happy targets, found a significant positive correlation with trait anxiety across the group ($r = .48$, $p = .025$). These findings suggest that high trait anxiety is associated with facilitated detection of threatening targets.

Associations between trait anxiety and the anger superiority effect in search for emotional faces among other emotional faces have also been investigated by Pitica, Susa, Benga, and Miclea (2012). This study tested search for real emotional faces VS with the results showing participants were faster detecting angry over happy faces. However, there were no significant interactions with trait anxiety. Results did show a significant negative relationship between trait anxiety and RTs overall indicative of higher scores on trait anxiety being associated with faster search for emotional faces ($r = -.44$, $p < .05$) (Pitica et al., 2012). This is not in line with the findings of Olatunji, Ciesielski, Armstrong, and Zald (2011) where measures of general anxiety *positively* correlated with RTs during VS after presentation of facial expressions (anger, fear, disgust, happy, neutral). In this study, trials following a fearful facial expression were completed faster when compared to trials following other facial expressions. This supports the idea that fear expressions heighten vigilance to a target. The STAI-T was shown to have a general but non emotion-specific association with VS following the presentation of facial expressions, suggesting a potential detriment to attentional control that comes with high levels of trait anxiety. Notebaert, Crombez, Van Damme, De Houwer, and Theeuwes (2010) also considered threat in their investigations, adopting a between-subjects paradigm in which the control and experimental group searched for a fear conditioned stimulus (electro-cutaneous at tolerance level) in a paradigm investigating spatial predictability in attentional bias to threat. In this study, the experimental group had a spatially predictable conditioned stimulus, and the control group had a random threat location. Analyses considered the association between trait anxiety and performance measures in the groups, finding a significant correlation between the amount of interference caused by the conditioned stimulus and trait scores in the control group but not the experimental group ($r = .44$, $p < .05$) (Notebaert et al., 2010). However, it should be noted, that there were only 21 participants in this analysis. The results suggest that when the conditioned stimulus was not predictable there may be a difficulty in disengaging from the threatening stimulus for individuals with higher anxiety levels or it may be that the threatening information is prioritised in such circumstances (Notebaert et al., 2010).

The final study of this section is that of Ouimet, Radomsky, and Barber (2012). Here, engagement and disengagement to threat-relevant stimuli were investigated, in this case stimuli related to spiders whereby an odd one-out paradigm was adopted. Engagement trials were those with spiders as targets in a display of distractors, which were a different category of bugs, whereas disengagement trials were trials with other bug categories as targets and spiders the distractors. The study investigated dispositional anxiety but found no significant association between anxiety scores and bias measures of disengagement or engagement. As a sample of the general population was tested, it may be that the specific threat-relevant stimuli were not relevant for the sample being tested.

In summary, the results from the studies utilising emotional stimuli appear to be more convincing than the ones with non-emotional stimuli, with seven of the eight studies finding some link between anxiety and VS performance (mostly based on bias measures). Four studies found evidence to support the idea that trait anxiety is linked with enhanced processing of threatening stimuli. One study showed fearful faces facilitate search across the sample but found slowed responses related to anxiety scores following the presentation of emotional stimuli (not fear specific), and another specifically highlighted the role of predictability on the effects of a fear-conditioned stimulus. A further showed general variation in RT related to trait anxiety in search for emotional faces but not as a function of emotion. The results also pointed to the notion that task irrelevant emotional stimuli may have a greater impact on VS performance for individuals with higher trait anxiety.

Overall, the evidence indicates that trait anxiety is associated with VS, but specifically when emotional stimuli are used (see Table 3). It supports the notion that anxious individuals show enhanced processing of threatening stimuli, which may be due to difficulty in disengaging from threat stimuli or enhanced engagement to stimuli. There is also some evidence, although inconsistent, that in general, individuals higher in anxiety fail to efficiently suppress irrelevant stimuli, which can lead to slower search in such conditions. This points to variations in bottom-up processes. It should also be noted that the variation in the six different questionnaires being used can impact the anxiety-related behaviours measured across the studies. For instance, the measurements captured from use of the STAI-trait version are often highly associated with severity of depression as well as anxiety symptoms. A systematic review of studies supports the notion that this questionnaire should be considered a tool for measuring negative affect rather than trait anxiety (Knowles & Olatunji, 2020). Therefore, measures which also probe negative affect, such as the HA scale, WAS, and Depression scale of the MMPI may indeed capture the important measures related to an individual's propensity to anxiety but may do so in a way that results in global scores hiding the drivers of an individual's scores (Balsamo et al., 2013).

### 4.6. *Cognitive abilities*

#### 4.6.1. *Fluid reasoning (Gf)*

From the papers exploring the relation between VS and cognitive abilities, eight comprised tests of Gf (see Table 4 and Supplementary Table 1b). A distinctive element of these works is the type of task used to measure such ability, which variably focused on inductive reasoning, quantitative reasoning and sequential reasoning, according to the CHC model. This variability, however, did not systematically affect the outcomes.

Chaiken (1994) included two Gf measures as a proxy for the g-manifold to control for any shared effects these may have with VS performance. ABC30 and Cattell's intelligence test were chosen in order to examine two different paradigms (arithmetic and induction respectively) for measuring general intelligence. Significant negative correlations were found for both measures in relation to RT in VS (ABC30: $r = -.32$, $p < .01$; Cattell: $r = -.26$, $p < .01$), meaning that participants with higher Gf scores performed faster in VS. A negative correlation of similar size was found between VS RTs and Gf in a study by Schweizer (1998) ($r = -.34$, $p < .05$). Furthermore, Matthews et al. (2015) found reasoning ability to be predictive of response speed, in both emotional and non-emotional VS tasks. Taken together, these studies offer support for the notion that subjects higher in Gf were significantly faster in both emotional and non-emotional VS tasks than those with lower reasoning ability.

However, this association has not been found in all studies. For instance, Bueichekú, Miró-Padilla, and Ávila (2020) explored performance in the matrix reasoning test (WAIS III) and VS and failed to find any significant correlations between reasoning ability and VS accuracy or RT. When considering RT, an association was only found for RTs in threat absent trials in a simulated x-ray screening task ($r = .201$, $p < .05$), while no such associations were found in a traditional VS task (Peltier & Becker, 2020). This suggests that participants with higher Gf levels committed fewer selection errors in the x-ray search task and were slower to exhaust search in threat absent trials. Positive associations between Gf and accuracy were found for both VS tasks (x-ray screening, $r = .319$, $p < .01$; and traditional search, $r = .319$, $p < .01$). Thus, it is not only in RT measures that associations have been found.

In fact, a similar simulated x-ray screening task was also adopted by Hättenschwiler et al. (2019) when exploring whether the same visual cognitive abilities are needed in students and professionals for success in traditional and security x-ray VS. Gf, as measured with Raven's progressive matrices (SPM; Horn, 2009), was one of the abilities hypothesized to predict performance in traditional VS and x-ray image inspection in both students and professionals. However, the significant correlations were found between Gf and sensitivity measures in both VS tasks for students and professionals

**Table 4 – Summary of the main associations reported between Gf and visual search performance by narrow ability (see Section 4.6.1). Information between brackets next to n/a, refers to an inference based on the available information, although the datum itself is not explicitly provided in the source.**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | I | RQ | RG |
|---|---|---|---|---|---|---|---|---|
| Chaiken | 1994 | 178; 190 | S: 7 or 8 | n/a (50%) | RT | – | – – | |
| Schweizer | 1998 | 45 | n/a (S: 2, 4, 6) | 78% | RT | | | – – |
| Matthews | 2015 | 129 | S: 1, 4 | 50% | RT | | | – |
| Bueichekú | 2020 | 42 | S: 6 | n/a (50%) | | ° | | |
| Peltier & Becker | 2020 | 134 | S: 24; C: 3 (S: 16) | 10% | Accuracy and RT | + | | |
| | | | | 50% | Accuracy and RT | + | | |
| Hättenschwiler | 2019 | 128; 112 | S: 25; | 50% | Sensitivity and RT | + | | |
| | | | C: 3 (S: 16) | | Sensitivity | + | | |
| Treviño | 2011 | 636 | S: 4, 12 | 100% | | | ° | |
| Rogers | 1994 | 70; 70 | S: 4 | 100% | RT | + | | |
| **N of studies reporting associations between Gf and VS performance** | | | | | | 4 | 1 | 2 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); I = Induction, RQ = Quantitative reasoning; RG = General sequential reasoning. + reported weak significant positive association; – – reported moderate significant negative association; – reported weak significant negative association; ° no significant association found.

($rs > .24$, $ps < .05$) and not RTs. A further study, adopting several experimental and neuropsychological tests (Treviño et al., 2021), found no correlation between VS performance (slope) and Gf, as measured by an arithmetic task.

Finally, Rogers, Fisk, and Hertzog (1994) explored age-related differences in ability-performance links in relation to skill-acquisition to better understand which are the key abilities for different VS tasks during skill acquisition. Three Gf tasks, defined by the authors as induction ability, were included among the tested cognitive abilities: mathematical reasoning, Raven's progressive matrices, and letter sets. Induction had a high loading on the higher general ability factor, which was found to be related to initial performance in the VS task for both groups of ages. The role of general ability decreased in relevance with performance improvements over the course of the training (Rogers et al., 1994).

The association between Gf and VS performance should perhaps be expected given that Gf is understood as the capacity to solve problems in novel situations using deliberate and controlled strategies (Schneider & McGrew, 2017). Indeed, when the studies are taken together there is general evidence to suggest individuals higher in reasoning ability achieve better performance in the VS tasks (see Table 4). Nonetheless, two of the examined works did not find any significant relation between the variables of interest (Bueichekú et al., 2020; Treviño et al., 2021). Interestingly, no noteworthy differences were found in the type of VS task, as both traditional and real-world VS tasks were found to significantly correlate with the range of Gf tasks implemented. Also noteworthy is the finding suggesting that when Gf is controlled for (e.g., Chaiken, 1994), the correlation between performance in other tasks and VS persists, indicating the concomitant contribution of Gf-independent broad abilities.

#### 4.6.2. *Working memory capacity (Gwm)*

Gwm and its relationship with VS was the subject of 27 studies included in this systematic review (see Table 5 and Supplementary Table 1b). Traditional VS stimuli involving a search for a letter/shape/character among distractor letters/shapes/characters were adopted in most of the studies. Given the abundance of studies this section has been divided into thematic subsections.

4.6.2.1. Changes across the lifespan. Four studies offered insight into changes across the lifespan that may affect the association between VS and working memory (WM). Aziz et al. (2021) adopted a task where participants were instructed to find a figure with specific facial/clothing features in feature and conjunction search conditions. To manipulate WM load the target figure was either shown before or along with a search array. The take home message suggests WM abilities are important in VS. For instance, higher SYMSPAN scores predicted faster VS RTs for both age groups in the conjunction search condition. However, findings also suggest there may be changes to the relationship between WM and VS across the lifespan. Indeed, for younger adults, location memory predicted RTs but this was only seen in the highest distractor condition for older adults; item memory predicted search RTs for older adults but this was only seen in the lowest (3) and highest (15) distractor conditions. Aziz et al. (2021) suggest this may be indicative of older adults relying more on verbal storage than visuospatial storage. Moreover, as the relationship between SYMSPAN and search RTs was altered for the younger adults when the target template was displayed during the search, the authors suggest this may be the result of their enhanced use of peripheral vision resulting in more use of the target template (Aziz et al., 2021).

In a further study, interest was in exploring the importance of information load on WM in younger and older adults (Vaughan & Hartman, 2009). WM was measured by using a delayed match-to-sample (DMTS) task using the same meaningful and abstract stimuli as the VS task. Findings revealed a significant correlation between performance in the DMTS task and VS slope for the younger ($r = -.53$, $p < .001$) and older adult groups ($r = -.62$, $p < .001$), supporting the link between WM capacity and VS slopes with tasks involving the same objects.

In the context of a study on older female drivers (61–84 years), Guerrier, Manivannan, and Nair (1999) assessed their participants on WM (also Gs and Gv, as reported in the respective sections), as measured by an addition task. The VS task involved locating a ], >, #, (in a display with on average 345 background characters. There was no association found between performance in the WM task and VS performance (RTs and accuracy) for this small group of older females.

An interest in age was also the theme in a study adopting a cued VS paradigm involving a search for a T among rotated Ls (Hahn & Buttaccio, 2018). Guiding of attention in VS could be carried out by cue-target associated learning, with different cues predicting different target colours. Analyses on error rates, slope and RTs revealed a greater set size effect for older adults than younger adults. Older adults had also significantly lower recall accuracy in the visual WM task. Regression analyses revealed visual WM capacity positively predicted log-transformed RT in the search task and that there was a significant visual WM capacity and age group interaction. Visual WM capacity was shown to predict cue-target association recall and findings also suggested visual WM capacity altered the predictive ability of age. Thus, suggesting that visual WM capacity has a key role in learning in cued VS and that visual WM could help explain age effects on VS performance.

The findings of these studies offer support for WM being positively associated with VS, with only one low-powered study showing no significant associations. It is possible that while WM remains important in VS performance at the individual level, changes may take place across the lifespan. Thus, ageing may bring about a need to adopt different strategies to overcome declined performance in certain attentional processes.

4.6.2.2. Training. Two of the included studies investigated WM and VS in the context of practice or training. Differences in ability-performance relationships that reflect skill acquisition were explored by Rogers et al. (1994). This 10-session training study aimed for a greater understanding of the key abilities important for different VS tasks during skill acquisition. WM tasks were included in the test battery of cognitive abilities. However, no direct association was reported between WM and initial performance measures in the VS tasks, independent of a general ability, and no significant results were reported specifically for the contribution of WM to VS.

**Table 5 – Summary of the main associations reported between Gwm and visual search performance (see Section 4.6.2).**

| First author | Year | N | Size/Clutter | Prevalence | WM test | RT | Acc | d′ | Slope | other |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Changes across the lifespan* | | | | | | | | | | |
| Aziz | 2021 | 47; 48 | S: 4, 8, 12, 16 | 100% | OSPAN | | | | | |
| | | | | | SYMSPAN | – | | | | |
| | | | | | Visual | – | | | | |
| | | | | | Verbal | – | | | | |
| Vaughan | 2009 | 36; 35 | S: 4, 8, 12 | 50% | DMTS | | | | –– | |
| Guerrier | 1999 | 26 | S: 346 | n/a (100%) | Addition task | ° | ° | | | |
| Hahn | 2018 | 38 | S: 6, 12 | 100% | Change detection | –– | | | | |
| *Training* | | | | | | | | | | |
| Rogers | 1994 | 70; 70 | S: 4 | 100% | Computation span | ° | | | | |
| | | | | | Listening span | | | | | |
| | | | | | Alphabet span | | | | | |
| Kundu | 2013 | 30 | S: 8, 16* | 50% | VSTM | –– | | | | |
| *Larger cognitive test batteries* | | | | | | | | | | |
| Martin-Rios | 2022 | 171 | S: 18-383 | 100% | Letter-number sequencing | | + | | | |
| Trevino | 2021 | 636 | S: 4, 12 | 100% | Visual WM | | | | –** | |
| Sisk | 2022 | 234 | S: 8, 16 | 100% | Change detection | | | | ° | |
| *Target prevalence* | | | | | | | | | | |
| Schwark | 2013 | 32 | S: 100; C: 3 | 4% | AOSPAN | ++ | ++ | | | |
| | | | | 50% | | | | | | |
| Peltier | 2017a | 141 | S: 24 | 10% | Change detection | | + | | | |
| | | | | 50% | | | | | | |
| Peltier | 2017b | 37 | S: 24 | 10% | Change detection | | + | | | |
| | | | | 50% | | | | | | |
| | | | | 90% | | | | | | |
| Peltier | 2020 | 134 | S: 24; C: 3 (S: 16) | 50% (L&T) | Change detection | | ++ | | | |
| | | | | 10% | | | | | | |
| | | | | 50% | | | | | | |
| *Type and difficulty of VS task* | | | | | | | | | | |
| Dowd | 2015 | 74 | S: 4 | 100% | OSPAN Change detection | | | | | + |
| Hättenschwiler | 2019 | 128; 112 | S: 25; C: 3 | 50% | WSI | | | + | | |
| Luria | 2011 | 18 | S: 6 | 100% | Change detection | | ++ | | | |
| Williams | 2018 | 33–54 | S: 6, 12 | 100% | Change detection | | ++ | | | |
| | | | | 50% | | | | | | |
| Kane | 2006 | 120; 197 | S: 1, 4, 16; 3, 9, 18 | 50% | OSPAN, RSPAN | | + | | | |
| Adamo | 2017 | 72 | 25 | 100% | Attentional blink | | + | | | |
| *Attention to distractors* | | | | | | | | | | |
| Emrich | 2009 | 11 | S: 10 | 50% | Change detection | ––– | | | | |
| Gaspar | 2016 | 48 | S: 10 | 100% | Change detection | –– | | | | –– |

(continued on next page)

**Table 5 – (continued)**

| First author | Year | N | Size/Clutter | Prevalence | WM test | RT | Acc | d′ | Slope | other |
|---|---|---|---|---|---|---|---|---|---|---|
| Tay | 2022 | 41; 44 | S: 16 | 50% | Change detection | ° | | | | |
| Robison | 2017 | 137; 156 | S: 6 | 100% | OSPAN, SYMSPAN, RSPAN | | | | | – |
| Xie | 2022 | 88 | S: 4 | 100% | Change detection | | | | | + |
| Couperus | 2021 | 205 | S: 24 | 100% | DMTS | – | ++ | | | |
| Takahashi | 2011 | 96 | S: 16, 32 | 50% | Spatial WM<br>non-spatial WM | | | | | ° |
| Anderson | 2013 | 17 | S: 6 | 50% | Change detection | | | | | ° |
| **N of studies reporting associations between Gwm and VS performance by index** | | | | | | 7 | 10 | 1 | 2 | 4 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); VS = visual search; ++ reported moderate significant positive association; + reported weak significant positive association; – – – reported strong significant negative association; – – reported moderate significant negative association; – reported weak significant negative association; ° no significant association found. *Data for set size 16 were not included in the analyses; **Performance in visual search (RT) was reverse scored in the original article, hence the correlation was reported as positive. “Other” includes bias measures (e.g., attentional capture/guidance, Dowd et al., 2015; Robison & Unsworth, 2017; response latency standard deviation, Gaspar et al., 2016; distractor suppression, Xie et al., 2022; Anderson et al., 2013).

A WM capacity training study adopting an adaptive visual dual n-back training task was carried out to investigate transfer effects in other cognitive tasks including VS (Kundu, Sutterer, Emrich, & Postle, 2013). Behavioural correlations for the full sample were offered for pre-training results and showed visual WM capacity was related to VS efficiency ($r = -.44$, $p = .03$, RTs of target present correct trials) in a search for a letter among distractor letters. Further analysis suggested training improved search performance.

These studies vary in their methodologies and offer uncertain support for WM being important in VS performance. However, the use of different WM tasks may emphasise different facets of the WM construct (Salthouse & Babcock, 1991).

#### 4.6.2.3. Gwm and VS in the context of larger cognitive test batteries

The components of executive function were investigated in a study aiming to establish a neuropsychological battery for measuring executive function in smokers (Martin-Rios, Lopez-Torrecillas, Martin-Tamayo, & Lozano-Fernandez, 2022). The authors predicted that the results would support Miyake's (2000) model which includes an update, a flexibility/change, and an inhibition component to executive function. Tasks included the letter-number sequencing task (WM) and a VS and attention task, which the authors state focused on sustained attention. A weak correlation was found between performance in this VS task (total stimuli detected) and total number of correct responses of the letter-number sequencing task ($r = .177$, $p < .05$).

However, Treviño et al. (2021) probed the relationship between an online battery of cognitive tasks and an online battery of neuropsychological tests. The neuropsychological tests included measures of WM and Gs (Hoelzle, Simons, Meyer, & McGrew, 2023). WM performance was found to weakly correlate with VS slope ($r = .14$, note correlation co-efficient flipped for RT measures). Further findings suggested WM tasks tap into an attentional capacity factor, while traditional VS loads on to a general search factor (albeit with a lower factor loading than tests often considered measures of Gs; Hoelzle et al., 2023).

In an investigation into the impact of COVID-19 concerns on attention, Sisk, Toh, Jun, Remington, and Lee (2022) carried out preregistered online testing of participants in a battery of tasks including a change detection task measuring WM as well as VS tasks. The study reported no significant correlations between the WM capacity and conjunction search slope ($r = -.06$). However, conjunction search slope was reported to have poor split-half reliability ($r = .05$, $p = .46$).

Taken together, the results of these studies support a weak association between individual differences in WM and VS performance.

#### 4.6.2.4. Target prevalence

Four of the studies set out to investigate the link between WM and VS, based on target prevalence, which is known to influence VS performance variability (Wolfe et al., 2007). The ability of individuals with high WM capacity to ignore irrelevant stimuli was considered by Schwark et al. (2013), by using the Automated Operation Span Task (AOSPAN) and adopting both medium (50%) and low (4%) target prevalence VS conditions. Results of correlations between hit rates and AOSPAN scores in the low prevalence block revealed a significant correlation ($r = .35$, $p < .05$), while correlations between RTs in the target absent block and AOSPAN scores were also significant ($r = .37$, $p < .05$). However, no significant results were found for the 50% prevalence block. The positive correlation between RTs in target absent condition in the low prevalence block with AOSPAN score suggests individuals with higher WM capacity had longer search time, suggesting they have a higher threshold for exhausting search. It appears that no corrections were made for multiple comparisons and the low sample size should also be kept in mind.

Peltier and Becker (2017a) further explored the effect of target prevalence on the association between VS performance and individual differences by testing participants in high (50%) and low (10%) search prevalence paradigms. Results showed accuracy in the low prevalence search condition was predicted by WM capacity. The regression model for RTs on the low prevalence search revealed WM capacity did not meet significance thresholds as a predictor ($p = .06$). Further findings suggested fewer false alarms made by individuals with higher WM capacity and a weak to moderate correlation between WM capacity and RT in target absent trials (albeit it is unclear whether results have been adjusted for multiple comparisons). Thus, supporting the notion that the link between WM and search performance is driven by variations in quitting thresholds.

In a further study by Peltier and Becker (2017b), VS tasks with 10%, 50%, and 90% target prevalence were adopted. However, it appears no corrections were carried out for multiple comparisons, which would leave significant negative correlations for only the 10% condition miss rate and the overall miss rate with WM. Similarly for RTs, the only significant correlation would be between target-absent RT performance in the 90% prevalence condition. Finally, eye-tracking data from this study suggested both selection errors and identification errors were negatively correlated with WM capacity.

To improve the understanding of what mechanisms may drive variation, Peltier and Becker (2020) used eye-tracking measures in a further study. The VS included a T among Ls task (target prevalence: 50%) and a simulated baggage search paradigm (target prevalence: 10% and 50%). Accuracy performance in the 50% prevalence simulated baggage and T among Ls tasks significantly predicted accuracy performance in the low prevalence simulated baggage task, as did WM capacity. However, WM capacity did not predict high prevalence simulated baggage performance. Eye-tracking analyses revealed increased WM capacity was associated with fewer percentage of misses due to not fixating on the target. Percentage of misses caused by failure to identify a fixated target was also associated with WM capacity, therefore, both mechanisms appear to be driving the link between WM capacity and VS performance.

Together, these studies offer evidence for higher WM capacity being linked to higher quitting thresholds, improving performance in low prevalence VS. The eye-tracking data offers further insight into the mechanisms that may be driving this relationship, suggesting individuals with higher WM capacity make fewer errors in identifying a fixated target and fewer instances of not fixating on the target.

4.6.2.5. Type and difficulty of VS task. The link between VS performance and WM is likely to vary depending on the specific VS task used. Dowd et al. (2015) adopted two dual-task serial search paradigms, one with binary stimuli one with unitary stimuli to probe attentional guidance by WM. Visual WM capacity predicted attentional capture in the binary stimuli condition, the binary condition likely being the more challenging paradigm from a WM aspect. It was also found that performance in the unitary and binary conditions was not significantly related at an individual level, suggesting that these tasks are assessing performance driven by different underlying mechanisms.

To probe variations in the underlying mechanisms required for success in different search tasks for individuals with different levels of search experience, Hättenschwiler et al. (2019), examined whether the same cognitive abilities predict VS performance using a traditional and x-ray screening task in novices and professional screeners. WM was measured using an online test battery (WSI; Hell, Päßler, & Schuler, 2009). The study found WM was important for success in the search tasks. Although the regression models showed similar standardised coefficients for both tasks, WM was only a significant predictor for the x-ray screening task. The authors suggest this may be due to WM becoming more important in task success for the harder x-ray screening task where targets and distractors are more complex.

Luria and Vogel (2011) investigated the reliance on WM storage during VS by measuring an event-related potential (ERP) component that reflects the amount of information that is currently active in WM. However, the authors also offered correlational analysis between visual WM capacity and VS accuracy. Significant findings were shown between performance in these tasks in the medium difficulty condition ($r = .61$, $p < .05$), whereas the $p$-value of the association in the more difficult condition exceeded the standard alpha $= .05$ ($r = .45$, $p = .059$). These findings suggest that although difficulty of search may influence the reliance on WM, the idea that task difficulty plays a part in modulating the relationship between WM capacity and VS performance is not straightforward.

In a further investigation into WM reliance and different VS paradigms, Williams and Drew (2018) tested the idea that WM capacity would be more predictive of search involving novel targets than search involving repeated targets. The idea being that template maintenance would require greater WM resources in the novel target condition. Results revealed small to moderate correlations between WM capacity and search accuracy but offered no support for the relationship between WM capacity and response time or search efficiency. As the correlations between WM capacity and performance in novel and repeated target measures were, in general, not found to be different when looked at for separate experiments, the findings support the notion that there is no significant additional reliance of WM for novel targets over repeated targets. However, for correlational analyses these sample sizes are small.

A further study tested participants with more and less organised VS, spatial configuration, conjunction, anarchic, and command (searching in a clockwise manner) VS tasks. The correlation between target-absent trial error rates for medium arrays in the conjunction search task and WM capacity was the only correlation of note ($r = -.142$, $p < .05$), offering little support for a relationship between individual differences in VS and WM. However, Adamo, Cain, and Mitroff (2017) used the Attentional Blink task to measure attention including aspects of WM and correlated performance with second-target detection in a VS task. They found significant correlations between modulation, as measured by blink recovery, and second target misses in a multiple-target VS task. Thus, in a task where attentional resources are depleted, WM was found to be important in search success.

Taken together these results give some weight to an association, albeit often weak, between VS performance and WM capacity. However, the findings do not offer great clarity on difficulty of search and its impact on the relationship between WM and VS performance.

4.6.2.6. Attention to distractors. WM ability may affect the attention biasing mechanisms during VS making some individuals more susceptible to allocating and re-allocating attention to distractors. This was the subject of eight studies. Emrich, Al-Aidroos, Pratt, and Ferber (2009) tested whether high-capacity individuals benefit from an ability to find a target quicker than low-capacity individuals due to spending less time revisiting distractors. They found a strong inverse relationship between visual WM capacity and search RTs ($r = -.84$, $p = .001$). The results suggest visual WM capacity may limit VS task success.

A further study focussing on neural signatures to better understand the link between WM capacity and attentional control, adopted a competitive and VS task (Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016). Correlational analyses revealed individuals with higher visual WM capacity were faster at VS and had a less variable response latency. The authors propose this is this is driven by higher capacity leading to better attentional capabilities and greater consistency in task performance (Gaspar et al., 2016).

A further look into distractor suppression versus target enhancement and their links with WM capacity was afforded by Tay and McDonald (2022). Carrying out two experiments and using a Go/No-Go version of search where participants were required to withhold responses to a pop-out target depending on the stimulus array colour, the study aimed to test the association between neural markers of target enhancement and WM capacity with findings being presented on the relation between ERP markers of target enhancement and WM capacity. The findings failed to show associations between individual mean RTs and WM capacity in either experiment ($rs \leq -.13$, $ps \geq .394$). The significant correlation found between ERP components related to target enhancement and individual differences in WM capacity in the search condition requiring more control suggests WM is linked to target enhancement processes, not only processes related to distractor suppression (Tay & McDonald, 2022), however, such associations are not shown at a behavioural level in this study.

Robison and Unsworth (2017) afforded an insight into whether WM capacity was related to learned control, that is, they investigated whether individuals with higher WM capacity adopt the more efficient strategy for prevention of attentional capture by salient distractors. The results of their second study, which allowed for the learned control to be explored, revealed WM capacity was a significant predictor of attentional capture ($\beta = -.22$, $p = .004$), These results suggest individuals with greater WM capacity have an enhanced ability to use learned information to control attention.

Adopting brain imaging measures to probe distractor suppression performance, Xie, Jin, Jin, Zhang, and Li (2022) found a significant correlation between WM capacity and ability to suppress distractors ($r = .255$, $p = .017$). Thus, offering more support for the notion that individuals with higher WM capacity appear to less affected by salient distractors.

Couperus et al. (2021) also explored neural activity and behavioural measures to better understand the relationship between VS and WM. VS accuracy was shown to have a significant positive correlation with spatial WM ($r = .312$, $p < .01$) and was shown to be linked with more negative N2pc amplitudes. Regression analysis revealed higher spatial WM ability resulted in higher VS accuracy with visual WM controlled for, however, this was not the case for search RTs as faster responses in VS were associated with higher visual WM ($r = -.174$, $p < .05$). This study supports the key role of ability to maintain spatial information in VS processes and suggests spatial WM and visual WM play different roles during VS.

Disentangling the role of spatial WM and non-spatial WM in conjunction and disjunction VS performance (RT slope) was the focus of a further study (Takahashi & Hatakeyama, 2011). Regression analysis conducted on pop-out distractor interference suggested a trend that individuals with lower spatial WM scores were more affected by the pop-out distractor ($\beta = .21$, $p = .06$). No significant effects of spatial WM ability on disjunction search performance or non-spatial WM on pop-out interference or disjunction performance were found.

The final study explored differences in attention to non-drug reward-related distractors for individuals with a history of drug addiction and a control group (Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013). The findings revealed a significant correlation between visual WM capacity and impairments to VS RTs by distractors across participants; when looked at as groups there was no significant correlation found for healthy controls (but a medium effect – $r = -.46$). However, it is of note that only seventeen participants were tested in each group thus, results may reflect the lack of power.

Taken together, these studies offer support for the notion that individuals with better WM abilities are conferred an advantage in VS involving distractors.

Overall, the findings of the 27 studies involving Gwm, evince a relationship between Gwm and VS performance, with only seven studies offering null results or not providing analyses that clearly revealed the direct relationship between VS and WM (see Table 5). However, there do appear to be caveats. For instance, in the studies looking at target prevalence, the relationship between WM and VS is more robust at low target prevalence levels and with indices of overall accuracy, or RTs for threat absent trials specifically. The overarching message of this literature being that higher quitting thresholds are linked to WM. Furthermore, the combined evidence suggests that the importance of WM may change as VS parameters are modified, such as when target or distractors are more complex, as is the case in real world x-ray screening tasks.

Taken together, the studies offer evidence for an advantage for individuals with higher WM abilities with salient distractor conditions. There is also some support for the idea that spatial WM may be more important than non-spatial WM for certain VS tasks; however, more studies are required to offer insight into this distinction and the indices of VS performance most affected. In conclusion, the body of research reviewed here adopted numerous different WM tasks and often the associations found between VS performance and Gwm were weak but significant.

#### 4.6.3. *Visual processing (Gv)*

Eleven papers presented relevant evidence for the possible relation between Gv and VS performance (see Table 6 and Supplementary Table 1b). Only one of these reports was preregistered (with peer-review; Wagner et al., 2020), however the preregistered hypothesis did not specifically concern the relation between Gv and VS, which was assessed in exploratory analyses instead. On the whole, a moderate positive association emerges between various measures of Gv and one or more indices of VS performance with both traditional and real-world stimuli.

4.6.3.1. Studies on traditional VS. In Schweizer's (1998) study, VS RTs were correlated with two measures of ability from a German testing battery constructed with reference to Thurstone's (1942) intelligence factors. Negative and significant correlations of similar size were found between RTs and both reasoning ($r = -.34$, $p < .05$) and mental rotation ($r = -.34$, $p < .05$), that is, subjects with higher ability were faster than subjects with lower abilities (thus replicating the well-known speed-ability relationship; e.g., Barrett, Eysenck, & Lucking, 1986).

Bellaera, von Mühlenen, and Watson (2014) used a T among Ls search task modified for higher difficulty. Within the VS task, their focus was on contextual cueing, measured by subtracting mean RTs to old displays from RTs in new displays in the second half of their experiment. Two different theoretical accounts were pinned against each other: the configural learning account (e.g., Chun & Phelps, 1999), which maintains that it is the global spatial layout that provides useful information about the possible target location; and the subset account (e.g., Kourkoulou, Leekam, & Findlay, 2012), which maintains that learning is driven by the local subset of distractors surrounding a target. Individual attentional bias was measured with a version of the Navon task based on regular geometrical shapes (Tan, Jones, & Watson, 2009), and calculated by subtracting correct RTs in trials where the shape was present at the global level from correct RTs in trials where the shape was present at the local level. The correlation between the Contextual Cueing Effect and the Attention Bias Index was found to be negative and significant ($r = -.56$, $p < .001$); in other words, contextual cueing decreased as a function of participants' attentional bias towards the global level thus providing evidence in favour of the subset account.

Agnew, Phillips, and Pilz (2020) used a classical conjunction VS task and focused, for correlations, on RT and accuracy scores for the larger set size only (i.e., 16), as these provided the highest level of variability across participants. Their proxies for Gv were tasks requiring biological motion perception (Johannson, 1973), the more complex of which had a search component and required the detection of a point-light stimulus walking in the target direction amidst one to three distractors walking in the opposite direction. Unlike in the conjunction search task, attention was distributed across fixed positions on the display and performance data were limited to the set size 4. Since the main focus of the study was on age differences in visuospatial attention and biological motion perception, correlations were tested separately for the group of younger adults and for the group of older adults. None of the correlations would pass the significance threshold after correction for multiple comparisons. Rather surprisingly,

**Table 6 – Summary of the main associations reported between Gv and performance in traditional or applicative real-world visual search tasks (see Section 4.6.3). Information between brackets next to n/a, refers to an inference based on the available information, although the datum itself is not explicitly provided in the source.**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | Traditional | Applicative |
|---|---|---|---|---|---|---|---|
| Schweizer | 1998 | 45 | n/a (min S: 3, 5, 7) | 78% | RT | −− | |
| Bellaera | 2014 | 40 | S: 12 | 100% | Contextual cueing (RT) | +++* | |
| Agnew | 2020 | 42 y | S: 4, 8, 16 | 50% | RT | −− | |
| | | 39 o | | | Accuracy | ++ | |
| Guerrier | 1999 | 26 | S: 346 | n/a (100%) | | ° | |
| Almeida | 2010b | 50 | S: 2, 4, 8, 16; 4, 8, 16, 64 | 50% | Slope | ++ | |
| Almeida | 2010a | 45 | S: 2, 4, 8, 16 | 50% | Slope | ++ | |
| Almeida | 2013 | 44 | S: 2, 4, 8, 16, 32; 4, 8, 16, 32 | 50% | Slope | ++ | |
| Almeida | 2014 | 31 | S: 2, 4, 8, 16, 32 | 50% | Slope | +++ | |
| McDonald | 1987 | 95 | C: 3 | n/a (100%) | Accuracy | | +++ |
| Hättenschwiler | 2019 | 128; 112 | S: 26; C: 3 | 50% | Sensitivity | | ++ |
| Wagner | 2020 | 29 | C: 3 | 50% | Accuracy | | −− |
| | | | | | RT | | ++ |
| | | | | | Sensitivity | | −− |
| **N of studies reporting associations between Gv and VS performance** | | | | | | 7 | 3 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); VS = visual search; *contextual cueing (learning from previous trials) increases as a function of focus on local level; y = younger; o = older; +++ reported strong significant positive association; ++ reported moderate significant positive association; + reported weak significant positive association; −− reported moderate significant negative association; − reported weak significant negative association; ° no significant association found.

the reported correlation coefficient between RTs in the target biological motion detection task and RTs in the conjunction search task for the younger group was negative ($r = -.315$, $p = .042$), whereas for accuracy the correlation coefficient was positive ($r = .384$, $p = .012$). A similar pattern was reported in the older group although the correlations were farther from significance. It should be noted, however, that multiple comparisons were conducted on the same dataset and that the study was underpowered (groups two-three times as large would be desirable, for a single correlational analysis with an expected effect size of .30).

Guerrier et al. (1999) investigated the potential connection between a selection of cognitive abilities and indices of performance in a lab-based simulation of decisions to make a left turn at an intersection in a sample of elderly female drivers. Their tests of cognitive abilities included the EFT and a VS task requiring to look for characters among a series of distractor characters. The authors report a multiple correlation analysis across all tasks, showing no association between the EFT and VS ($r = .096$). Also, the sample size of this study is relatively small, and no information is provided on what specific indices of EFT and VS performance were entered in the analysis.

In more recent years, a coherent and theoretically-driven series of studies investigated the relation between performance in the EFT and performance (as measured with slope) in the RF search task (Almeida, Dickinson, Maybery, Badcock, & Badcock, 2008). RF patterns are closed-contour shapes created by introducing sinusoidal variation in the radius of a circle as a function of polar angle. The number of modulation cycles required to complete one revolution determines the RF number. At certain amplitudes of modulation, a pattern with RF3 will resemble a triangle, a pattern with RF4 will resemble a square, a pattern with RF5 a pentagon, and so forth. In the RF task employed by Almeida et al. (2010b), a target RF3 stimulus with 50% prevalence was to be detected among a variable number of RF4 distractors. Set size and degree of overlap were manipulated so that in a condition (singles) there was no overlap between the elements presented on the display (targets and distractors), in another condition (pairs) there was overlap between pairs of elements and in a third condition (quads) there was overlap between four elements. The authors reasoned that VS in these three conditions might tap different skills. Whereas differentiation or discrimination of shapes would be sufficient to perform a successful search in the singles condition, the pairs and quads conditions could tap the capacity to extract a simple shape from overlapping features (i.e., disembedding). However, Pearson's correlations between search slopes and performance speed in the EFT were very similar throughout conditions (singles: $r = .40$, $p < .01$; pairs: $r = .35$, $p < .05$; quads: $r = .35$, $p < .05$; uncorrected). These results are consistent with an ability to discriminate between display items, rather than a specific disembedding ability, enabling performance both in the RF search task and in the EFT. These correlations are likely to be an overestimate, due to the fact that the sample actually comprised two groups, selected for their AQ scores (low AQ and high AQ), with significantly different performance in both the RF task and in the EFT.

Almeida, Dickinson, Maybery, Badcock, and Badcock (2010a) added a segmentation/clutter element to a condition similar to the singles condition of Almeida et al. (2010b; that is where targets and distractors are not touching or overlapping) by adding two lines that may intersect a target or distracter, run alongside the contour of a target or distracter or run near a target or distracter without directly touching it. All these segmentation/clutter conditions may be found in the EFT but they are not varied systematically as in the RF task. A condition with no segmentation lines was also included in the design. Also in this case, individual RTs in the EFT were significantly correlated with search efficiency (slope) for target present trials in each of the seven conditions, with correlation coefficients ranging from a minimum of $r = .321$ $p < .05$ (uncorrected) in the condition where a segmentation line intersected the target to a maximum of $r = .541$, $p < .001$ (uncorrected) in the condition where a segmentation line intersected a distractor. Again, the correlations may have been overestimated as the sample comprises two selected groups (low AQ and high AQ) performing differently in both the RF task and in the EFT. Based on the results, visual clutter (and hence abilities related to deal with increasing clutter) does not seem to influence the relation between EFT and the RF task; rather, superior detection of single features in complex scenes might be a common core ability. RF patterns can also be used to study both global and local contributions to visual shape discrimination (e.g., Bell et al., 2007) since the modulation in RF patterns appears to be detected by global processes when the modulation frequency is low and by local orientation-tuned processes for stimuli with higher RF (e.g., Loffler et al., 2003).

Almeida et al. (2013) manipulated the RF patterns in a series of experiments, so that the search task required either global or local closed-contour detection processes. In four experiments, they reported a positive correlation with the RF search task slope for target-present trials and EFT RT (first: $r = .435$, $p < .01$; second: $r = .304$, $p < .05$; third: $r = .440$, $p < .01$; fourth: $r = .400$, $p < .01$; uncorrected), showing that slower EFT performance was associated with less efficient performance in an RF task with global RF target among distractors of a different but fixed RF, that distractor heterogeneity had no impact on this relation, that globally-processed targets are not essential to the EFT-slope relation. Indeed, the local nature of the deformation detection process offers an identical picture, and so does a task where "lower" level discriminations are required, as in the case of curvature, rather than object boundaries. In conclusion, success in the EFT may associate with success in the RF task due to superior search processes rather than to any local bias in visual processing.

Finally, Almeida, Dickinson, Maybery, Badcock, and Badcock (2014) tested the correlation between performance in the RF search task (singles condition), in the EFT, and in an additional closed-contour processing (integration) task on an RF3 pattern (measured as integration slope – derived from threshold changes with increasing number of cycles). Both performance in the EFT and in the RF integration task were positively correlated with gradient in the RF search task (target-present trials – integration task: $r = .479$, $p < .01$; target-absent trials – integration task: $r = .456$, $p < .01$; target-present trials – EFT: $r = .642$, $p < .001$; target-absent trials – EFT: $r = .659$, $p < .001$; uncorrected) and so were the integration index and mean RTs in the EFT ($r = .637$, $p < .001$, uncorrected). In other words, and following the authors' interpretation of the RF integration index, improved global pooling of closed contour information is positively correlated with search ability, as is EFT performance.

Taken together, of the eight studies including a traditional task, six found consistent evidence of an association between Gv measures (mental rotation, EFT, a composite measure) and VS, whereas two (measuring Gv via biological motion detection and EFT respectively) reported a dubious or null result.

4.6.3.2. Studies including an applicative real-world search task. McDonald and Eliot (1987) were interested in the abilities underlying performance in challenging real-world tasks, such as those requiring aerial photographic interpretation, that is the “act of examining photographic images for the purpose of identifying objects and judging their significance” (Estes & Torley, 1983, as cited by McDonald & Eliot, 1987, p. 551). They had their participants perform two types of VS tasks: the Visual Search Test by Avery and Burkhart (1968), requiring participants to locate the coordinate positions of selected small cut-out pieces on an intact photograph of the same area, and the Aerial Photo Feature Identification Test developed by the authors, which required feature identification on aerial photographs varying in scale. Both tests were timed but the focus was on accuracy scores, which were very far from ceiling. These were correlated with accuracy scores from the GEFT (Witkin, Oltman, Raskin, & Karp, 1971). Both the Aerial Photo Feature Identification Test ($r = .68$, $p < .001$) and the Visual Search Test ($r = .75$, $p < .001$) showed a significant positive correlation with GEFT. However, they were also strongly correlated with the AH4 Group Test of General Intelligence (Heim, 1970; $rs \geq .71$, $ps < .001$), in turn correlated with the GEFT: $r = 81$, $p < .001$) and partial correlations were not provided. In any case, the GEFT appears to be a useful predictor of performance in aerial photographic interpretation tasks of search and identification.

The study of Hättenschwiler et al. (2019) tested whether a traditional VS task is comparable to an applied x-ray image inspection task, in terms of the visual-cognitive abilities it recruits, and whether this applies to different populations (students *vs* professionals). In addition to a T among Ls search task modified for higher difficulty, their participants performed a simulated baggage screening task, created from the Object Recognition Test (ORT; see also Schwaninger, Hardmeier, & Hofer, 2005). Both correct RTs and sensitivity ($d'$ in the T among Ls and $A'$ in the ORT) measures were considered as indices of performance in the VS tasks. Gv was measured via three tasks tapping visual memory, form constancy and figure-ground segregation respectively, whose scores were collapsed together into a single score. Correlational analyses revealed significant positive correlations of small-to-moderate size between one or more indices of performance in the two VS tasks for students and professionals, the strongest being found between sensitivity indices (T among Ls – ORT: $r = .34$, $p < .001$ and $r = .35$, $p < .001$ for students and professionals respectively), and between Gv scores and sensitivity measures in the two tasks both for students (T among Ls – Gv: $r = .35$, $p < .001$, X-ray – Gv: $r = .40$, $p < .001$) and professionals (T among Ls – Gv: $r = .38$, $p < .001$, X-ray – Gv: $r = .39$, $p < .001$). Multiple linear regression analyses revealed that the standardised score for Gv was a significant predictor of sensitivity and RTs both in the T among Ls search task ($d'$: $\beta = .299$, $p < .001$; RT: $\beta = .383$, $p < .001$) and in the X-ray inspection task ($\beta = .195$, $p < .001$; $\beta = .176$, $p = .022$), for students and professionals alike. However, in a mediation model it was also found that, although the T among Ls task did have a significant effect as a predictor of performance in the x-ray inspection task ($\beta = .130$, $p < .001$), the direct effect of the Gv scores remained significant ($\beta = .130$, $p < .001$), suggesting that their effect on x-ray inspection performance was only partially mediated by performance in the T among Ls task. VS in a prototypical traditional task (the T among Ls search task) may thus involve different underlying Gv abilities compared to VS as required by the simulation of an applied x-ray image inspection task. Given, however, that an analysis at the level of narrow abilities as measured by single Gv tasks was not included in the report, it is unclear which narrow ability/ies might subtend the partial mediation effect.

Finally, Wagner et al. (2020) used an applied x-ray image inspection task and a version of the Leuven-EFT (L-EFT; de-Wit, Huygelier, Van der Hallen, Chamberlain, & Wagemans, 2017) in the context of a registered report on parietal lobe neuromodulation. Neuromodulation did not exert any significant effects on either the x-ray task or the L-EFT, thus the study cannot confirm the two tasks share common substrates. However, in all the sessions a moderate correlation was found (range of $r$ absolute values: .38 to .50) between inverse efficiency in the L-EFT and x-ray screening accuracy, RTs and $d'$ and, in some cases, the correlation remained significant after correction. For the sham condition, these values were respectively: $r = -.47$ ($p = .011$), $r = .44$ ($p = .017$) and $r = -.44$ ($p = .018$) but would not remain significant after the Bonferroni correction applied by Wagner et al. (2020; $\alpha = .007$, for a familywise error of $\alpha = .02$).

Taken together, all three studies on an applied real-world search task reported significant correlations between classical or newer versions of the EFT, or a composite measure of Gv, and VS.

In conclusion, apart from a generalised tendency not to apply correction for multiplicity of testing and to run correlational analyses with small samples, both of which undermine the robustness and reliability of the reported results, an overall picture emerges of moderate association between measures of Gv and one or more indices of performance in VS tasks with both traditional and real-world stimuli (see Table 6).

#### 4.6.4. *Processing speed (Gs)*

Sixteen of the reviewed papers explored the relation between individual differences in Processing speed (Gs) ability and VS performance (see Table 7 and Supplementary Table 1b). Based on the CHC model definitions for the abilities comprised in Gs, the reviewed papers focused on tasks measuring perceptual speed (P), perceptual speed-search (Ps) and reading speed (Rs). Although positive results have been reported for all narrow abilities, the majority of the evidence refers to Ps.

4.6.4.1. P tasks. Kranzler and Jensen (1991) investigated whether a unitary process or several independent processes underlie psychometric g. To achieve this, they studied the relation between several elementary cognitive tasks, including the Inspection time task, but found that performance in traditional VS and the Inspection time task were not significantly correlated.

**Table 7 – Summary of the main associations reported between Gs and performance in traditional or applicative real-world visual search tasks by narrow ability (see Section 4.6.4). Information between brackets next to n/a, refers to an inference based on the available information, although the datum itself is not explicitly provided in the source.**

| First author | Year | N | Size/Clutter | Prevalence | VS Index | P | Ps | Rs |
|---|---|---|---|---|---|---|---|---|
| Kranzler | 1991 | 101 | S: 2 to 8 | n/a | | ° | | |
| Chaiken | 1994 | 178; 190 | S: 7, 8 | n/a (50%) | RT | −− | | |
| Hättenschwiler | 2019 | 128; 112 | S: 26; C: 3 | 50% | Sensitivity | + | | |
| Matthews | 1993 | 60 | S: 4 | 50% contr. | Accuracy | | ++ | |
| | | | | | RT | | ++/−−* | |
| | | | | 25% divided | RT | | ++/−−* | |
| Guerrier | 1999 | 26 | S: 346 | n/a (100%) | | | ° | |
| Potter | 2013 | 32 | S: 4, 8, 12 | 50% | Slope | | −−/+++ | |
| Chabal | 2015 | 37 | S: 8 | 100% | RT | | ++ | |
| Adamo | 2017 | 69 | S: 25 | 100% | Accuracy | | −−− | |
| Peltier | 2017a | 141 | S: 24 | 10% | Accuracy | | ++ | |
| | | | | | RT | | ++ | |
| | | | | 50% | | | | |
| Peltier | 2020 | 134 | S: 24; C: 3 (S: 16) | 50% (L&T) | Accuracy | | + | |
| | | | | 10% | Accuracy | | + | |
| | | | | 50% | Accuracy | | + | |
| Treviño | 2021 | 636 | S: 4, 12 | 100% | Slope | | + | |
| Sisk | 2022 | 234 | S: 8, 16 | 100% | | | ° | |
| Robison | 2017 | 137; 156 | S: 6 | 100% | Attentional capture | | | + |
| Agnew | 2020 | 42 y<br>39 o | S: 4, 8, 16 | 50% | | | | ° |
| Sprecher | 2019 | 20 | S: 10, 20, 30, 40 | 50% | RT | | | ++ |
| Monzel | 2023 | 104 | n/a | 100% | RT | | | + |
| **N of studies reporting associations between Gs and VS performance** | | | | | | 2 | 7 | 3 |

S = set size; C = clutter (in simulated real-world search tasks, when set size has been reported it is indicated between brackets); VS = visual search; P = perceptual speed; *These are referred to speed/accuracy of the Ps measure (hence the opposite signs). Ps = perceptual speed-search; Rs = reading speed; y = younger; o = older; +++ reported strong significant positive association; ++ reported moderate significant positive association; + reported weak significant positive association; −−− reported strong significant negative association; −− reported moderate significant negative association; − reported weak significant negative association; ° no significant association found.

Chaiken (1994) explored in two similar experiments manipulating ocular-motor requirement the relation between searching for a letter noun, a 2-digit number or an abstract figure (depending on instructions) and Gs. This was studied along with measures of general intelligence (IQ), to control for any shared effects from the *g*-manifold in Gs's relation to VS. A significant, negative correlation was reported between Inspection time accuracy and VS RT in both experiments ($rs > .36$). When controlling for IQ measures and VS accuracy, the correlation remained significant in both.

Hättenschweiler et al.'s (2019) aim was to explore if the same cognitive abilities can predict performance in traditional (T among Ls search) and real-world (simulated baggage screening) VS in students and professionals. They found that Gs was positively correlated with sensitivity to the signal in the letter search task for professionals ($r = .26$, $p < .01$) and in the screening task for students ($r = .22$, $p < .05$), however, multiple regression analyses revealed Gs was not a significant predictor of performance (sensitivity to the signal). Further analyses did suggest Gs significantly predicted RTs on the L/T task. These results suggest higher Gs may be linked to better visual task performance in a traditional search task.

4.6.4.2. Ps tasks. Matthews and Holley (1993) aimed to identify predictors of vigilance performance. It was predicted that the correlates of vigilance will vary depending on type of target discrimination (simultaneous or successive), and type of stimuli (sensory or symbolic). Performance in these tasks was analysed in relation to accuracy and RT on a controlled VS task, and on a divided attention task that also included a search component. The authors found that, for the symbolic version of vigilance, only the successive task was positively related with accuracy in the controlled search task ($r = .26$, $p < .05$), and RT in the divided attention search task was related with mean vigilance RT ($r = .34$, $p < .01$). For the sensory vigilance task, a significant correlation was found between accuracy in the simultaneous task and both speed ($r = -.30$, $p < .05$) and accuracy ($r = .31$, $p < .05$) of controlled search, and speed of the divided attention search ($r = -.27$, $p < .05$). When the symbolic and sensory vigilance tasks were made easier and shorter speed and accuracy on the VS predicted speed and accuracy on the vigilance tasks. A stronger relation was found between controlled search RT and successive lines task RT ($r = .47$, $p < .001$) and accuracy ($r = -.37$, $p < .01$) than for the simultaneous lines task. Only the simultaneous digit task was significantly related to VS RT ($r = .52$, $p < .001$). These results support the idea that perceptual sensitivity on high-event-rate sustained attention tasks is associated with individual differences in resource availability (Matthews and Holley, 1993). Resource-limited tasks, which required controlled search, predicted performance efficiency on both successive symbolic vigilance tasks, the simultaneous sensory task and the successive sensory task.

However, Guerrier et al. (1999) found no significant correlation between Gs (choice RT task) and VS for a group of older females. While in Potter, Madden, Costello, and Steffens (2013), Gs was explored using the Symbol-digit test (Smith, 1982) and the TMT (Reitan, 1992), and compared to RT slopes in a simple VS task with a feature and a conjunction condition, to explore slowness of information processing in a group of older adults. Pearson correlations revealed a significant negative correlation between Symbol-digit scores and VS RT slopes for target present trials in the conjunction search condition ($r = -.45$, $p < .01$), meaning that higher scores in this Gs task led to faster target detection in the search task. The TMT-B ($r = .52$, $p < .01$) and the difference between TMT-B and A ($r = .54$, $p < .01$) were found to significantly and positively correlate with VS performance. However, none of these would survive Bonferroni corrections. There were also no significant associations for the TMT-A. Sisk et al. (2022) also failed to find any significant correlations when adopting a conjunction and feature VS task and studying its relation to a task-switching task.

Contrarily, Chabal, Schroeder, and Marian (2015) aimed to explore the impact of language experience in object search and detection efficiency. For this, they used a traditional VS task and the Simon task, which allowed VS to be studied in relation to Gs, even though it was not the main aim of the study. The authors computed the Simon effect by subtracting RTs on congruent trials from RTs on incongruent trials and found a positive correlation between the Simon effect and VS RTs ($r = .33$, $p < .05$), suggesting that participants who were faster in resolving conflict in the Simon task, were also faster at locating the target object during VS.

Furthermore, Adamo et al. (2017) used a vigilance task (Temple et al., 2000), and explored if this ability had an effect on second-target detection in a VS task. They reported a significant negative correlation ($r = -.54$, $p < .001$), showing that worse vigilance ability was related to second-target misses. According to the authors, finding a first target can consume necessary cognitive resources needed to find the extra target (Adamo et al., 2017).

Similarly, Peltier and Becker (2017a) measured Gs with a vigilance task, included among other individual difference measures (see the Personality and Gwm sections), to explore their potential relation with target-prevalence effects in VS performance. The authors found that higher scores on vigilance predicted better accuracy ($r = .29$, $p < .05$) and RTs ($r = .25$, $p < .05$) in low (10%) prevalence search.

To further investigate these relations, Peltier and Becker (2020) included eye-tracking measures in a following study. Similar to their previous study, VS performance was measured with a T among Ls search task; moreover, a simulated baggage screening was included to investigate to which extent the prediction model previously found would generalize to critical real-world targets search. Here, the low prevalence effect was looked at with the baggage screening task having a 10% (low) and 50% (high) target prevalence rate. To measure Gs, the same vigilance task used in Peltier and Becker (2017a) was used here. A significant correlation ($r = .178$, $p < .05$) was found between performance in the vigilance task and low prevalence search accuracy, and between vigilance task performance and both high prevalence search accuracy ($r = .268$, $p < .01$), and L/T search accuracy ($r = .374$, $p < .01$). Nevertheless, the regression model analysis did not find vigilance task performance to be a significant predictor of accuracy or RT search performance.

Treviño et al. (2021) used three neuropsychological tests that measure Gs ability: TMT, Digit symbol coding, and Letter Cancellation, and a traditional VS task (T among Ls) in their broad investigation on the relation between attention and cognitive tests. Their correlation analyses revealed weak, but significant ($p < .001$) correlations between performance in the VS task and TMT A ($r = .15$), TMT B ($r = .16$), and Digit Symbol ($r = .19$). Also, a factor was identified comprising VS, Letter Cancellation, and TMT, possibly indicating that all of these share a search component. Importantly, the authors recognize as a significant caveat that the configural VS paradigm itself loaded less powerfully onto this factor than the neuropsychological tests.

4.6.4.3. Rs tasks. Robison and Unsworth (2017) aimed to explore whether WM capacity was related to learned control over attentional capture (see Gwm section). Among the different measures investigated, they included the Stroop test as an index of attentional control and examined its relation to a VS task, to identify individual differences in resisting attentional capture by salient distractors. The Stroop, antisaccade and psychomotor vigilance loaded onto an Attentional Control (AC) factor. The relationship between capture effect and the incongruent RTs on the Stroop was significant ($r = .19$, $p = .02$), but not the other AC tasks. AC did not predict attentional capture effect in further regression analysis. However, the study gives some evidence specific to the Stroop task and VS performance.

Sprecher et al. (2019) also explored individual differences in a conjunction VS and Gs by implementing the Stroop test. In this case, similar to Robison and Unsworth (2017), the results showed a significant positive correlation between RTs on target present trials and neutral median RTs on Stroop test ($r = .40$, $p < .05$), meaning that higher Gs was associated with faster detection of the target. Also significant negative correlations were found between missed targets in VS and correct responses on congruent ($r = -.34$. $p < .05$), neutral ($r = -.42$, $p < .05$) and incongruent ($r = -.55$, $p < .05$) trials of the Stroop task, and therefore, the more correct responses in the different conditions of the Stroop task, the less missed targets in the VS.

However, Agnew et al. (2020) also carried out a conjunctive VS, where the target object always shared one of two visual features with the distractors, making them quite similar. Among the different measures considered, they analysed if performance in task was influenced by individual differences in the Stroop task, as a measure for Gs. The authors did not find any significant correlations, either for accuracy or for RTs, on the VS task and the Stroop task.

Finally, Monzel and Reuter (2023) used the mini-q (Baddeley, 2013) to control for Gs. They used a real-world VS task with complex scene pictures where the target objects were hidden, to explore the influence of visual imagery on VS speed. They found that Gs was weakly, but significantly and positively associated with search speed ($r = .14$, $p < .001$, $N = 104$).

Thus, taken all together (see Table 7) the evidence suggests that individuals with higher Gs are conferred an advantage in

VS, which may be down to shared underling processes required for both tasks. However, with this in mind the large variety of tasks used to measure Gs is notable as they are likely to tap into different sub-processes.

### 4.7. Main findings

To recapitulate, from the literature using correlational or regression methods, an advantage emerges for a series of traits and cognitive abilities in VS performance (see Tables 1–7). More specifically, for traits:

- Higher conscientiousness is (weakly) related to better VS accuracy with challenging tasks, whereas higher introversion and higher agreeableness are (weakly) related to better VS performance, measured as accuracy and RTs for the former and as efficiency for the latter, with simpler displays and more monotonous VS tasks;
- Higher autistic traits are (weakly to moderately) related to better VS accuracy and slope;
- Higher trait anxiety is (moderately) related to higher attentional capture from emotional stimuli in VS tasks (a double-edged sword in terms of performance, as it may slow down RTs or speed them up depending on the type and role of the emotional stimuli).

For cognitive abilities:

- Higher Gf is (weakly to moderately) related to better VS accuracy, RTs and sensitivity;
- Higher Gwm is (weakly to strongly) related to better VS accuracy, RTs, sensitivity and slope;
- Higher Gv is (moderately to strongly) related to better VS accuracy, RTs, slope and sensitivity;
- Higher Gs is (weakly to strongly) related to better VS accuracy, RTs, slope and sensitivity.

Most of these relations have emerged from using traditional VS tasks and each of them has different theoretical and applicative implications depending on the operationalization of trait/ability and VS concepts. Only occasionally different traits and cognitive abilities are tested in the same study. In the few cases in which they are, ability measures appear to be more strongly related than traits to VS performance.

### 4.8. Reliability

Reliability measures, that is measures providing information on the consistency of individual responses in a questionnaire or an ability test or an experimental task, were reported for the study sample only in a small proportion of the included articles. More precisely, 16 out of 70 studies (23%) reported or stated having calculated some index of reliability (including Cronbach's $\alpha$, Spearman-Brown split-half reliability, test-retest correlation, intra-class correlation) for their data. In this count are included articles reporting or mentioning having calculated a reliability index for either the individual differences test(s) or the VS task(s), or both. Articles reporting reliability indices from a different sample (i.e., external sources) are not included. Although reliability appears to meet a standard threshold of acceptability in most of the cases in which an index is reported, there are cases in which Cronbach's $\alpha$ is found to be as low as .20 for one of the component measures of ability (Hättenschwiler et al., 2019) or a split-half correlation as low as .05 for search slope (Sisk et al., 2022). Only 9 out of 16 reported having calculated a reliability index for both an individual differences measure and a search measure (Chaiken, 1994; Dodd et al., 2016; Hättenschwiler et al., 2019; Peltier & Becker, 2020; Pomè et al., 2020; Robison & Unsworth, 2017; Sisk et al., 2022; Sprecher et al., 2019; Treviño et al., 2021), and of these only one provided disattenuated correlations (Pomè et al., 2020) (see Table 8).

**Table 8 – Articles that report having calculated one or more reliability indices for the individual differences measure(s) and/or visual search task(s) in the study sample.**

| First author | Year | Trait/Ability | Ind. Diff. measure(s) reliability | VS task(s) reliability |
|---|---|---|---|---|
| Rogers | 1994 | Gf, Gwm | Yes | No |
| Chaiken | 1994 | Gf, Gs | Yes | Yes |
| Kane | 2006 | Gwm | No | Yes |
| Olatunji | 2011 | Anxiety | Yes | No |
| Treviño | 2011 | Gf, Gs | Yes | Yes |
| Ouimet | 2012 | Anxiety | No | Yes |
| Dowd | 2015 | Gwm, Autistic t. | No | Yes |
| Rusconi | 2015 | Autistic t. | Yes | No |
| Birk | 2017 | Anxiety | Yes | No |
| Dodd | 2017 | Anxiety | Yes | Yes |
| Robison | 2017 | Gs, Gwm | Yes | Yes |
| Sprecher | 2019 | Gs | Yes | Yes |
| Hättenschwiler | 2019 | Gs, Gf, Gwm | Yes | Yes |
| Pomè | 2020 | Autistic t. | Yes | Yes |
| Peltier | 2020 | Gf | Yes | Yes |
| Sisk | 2022 | Gs, Gwm | Yes | Yes |

VS = visual search.

### 4.9. Themes and limitations

The review highlighted several common themes across the literature which will be briefly discussed in this section. These are, in order: the range of VS tasks adopted and the relevance of variations in task difficulty, the variability in the tools or tasks used to measure the same individual difference, the reasons why individual differences are expected to relate to VS, issues related to the potential use of research findings in the real world, limitations in the reviewed and in the wider literature.

The first theme relates to the variation in VS tasks adopted. This finding was expected between the traits/cognitive abilities under investigation, as the underlying theories would heavily influence the VS task selected. For instance, the theory linking anxiety with VS has its foundations in affective processing (Bishop & Förster, 2013). Thus, many of the included studies adopted threat/emotion related distractors or stimuli (see Supplementary Table 1a) but this is not the case for most of the cognitive abilities investigated (see Supplementary Table 1b). However, the variation of VS tasks adopted within the same category of individual differences was surprising. Even within the papers on anxiety, there were variations in the use of affective stimuli, the type of affective stimuli used and whether they were used as distractors, targets, cues, or primes. Overall, although 78% of VS tasks adopted across the included studies could be categorized as traditional VS, there were wide variations in task parameters, which could affect outcomes. Indeed, task difficulty was highlighted throughout the review for its potential effect on VS/individual difference relationships, with results suggesting that it is only when tasks become more demanding that the higher-level individual differences become rather consistently important, such as with conscientiousness and WM. Recently, Clark et al. (2022) reported a positive relation between task difficulty and test-retest reliability for common tasks in vision science, including a Gwm task. Their evidence suggests that if difficult task measures are utilized, the finding of a relation with a measure of individual differences may be particularly reliable, as difficulty may optimize between-participant variation (Clark et al., 2022). This has not been systematically tested in the reviewed literature, but hints could be found for both traits and cognitive abilities, with stronger or more replicable relations found between conscientiousness, autistic traits, Gwm, Gv and Gf and difficult traditional VS or challenging real world search tasks.

There was also evidence to suggest that different individual differences may be more important for specific tasks. For instance, WM was found to be more important on VS performance for an x-ray screening task over a traditional search task. Furthermore, the same tasks were shown to be related to Gs but only for novices in the x-ray screening task and for professionals in the letter search task. However, considering Gv, multiple regression with the letter search performance as a mediator, did not eradicate Gv as a predictor of x-ray screening task performance (Hättenschwiler et al., 2019), suggesting Gv was important for both tasks but for different reasons between tasks. This implies that the specificity of VS tasks must be considered when hypothesizing a relation, in an applicative or in a basic setting, with individual differences. It may be intuitive to expect performance in one VS task to be highly related to performance in another VS task. However, such intuitive relationships have often not been materialized in visual processing (e.g., Tulver, 2019). Moreover, evidence from empirical studies with VS challenges the notion, instead supporting the idea that different strategies are likely adopted in different VS tasks (Clarke, Irons, James, Leber, & Hunt, 2022), and strategies may not be related to individual differences in an obvious or intuitive way (Clarke et al., 2024). Indeed, the term VS is very broad, encompassing cognitive tasks where the purpose is to find a target among distractors. Thus, the specificities of the task are likely to have an impact on the optimum strategy for search success (Boot, Becic, & Kramer, 2009). However, the strategies adopted by individuals may not be in line with optimum strategies; for instance, research has shown that across several search tasks individuals were found to have a preferred search strategy, but this could be influenced based on performance feedback (Boot et al., 2009). Finally, based on the reviewed studies, the classical – but obsolete (Haslam, Porter, & Rothschild, 2001; Wolfe, 1998) – distinction between parallel and serial search does not appear to carry predictive value in terms of the relation between VS performance and individual differences.

A further key theme emerged related to the variability in the tool or task used to measure the individual difference. This was more apparent in cognitive abilities where tasks varied widely. To categorise studies, we referred to the CHC model (Schneider & McGrew, 2017), as well as the categorization given by the author of the study. However, with such variation in tasks it is likely the case that different sub-components of the cognitive ability under investigation were being measured. For instance, within Gf, narrow abilities including induction, general sequential reasoning, and quantitative reasoning were explored but there were instances of mixed findings even when the same narrow ability was concerned. Nevertheless, the variation in tasks adopted allows for a broader understanding of VS and individual differences, albeit at the expense of a depth of understanding, with a notable exception of the series of theory-led studies carried out by Almeida and colleagues, which explored systematic variations of the same VS task. With these caveats considered, the results did allow for a greater clarity of the categories of individual differences that have been linked to VS in the general population. It identified evidence for specific relations, of variable strength and robustness, between all the considered categories of individual differences and one or more indices of VS performance.

To understand why certain individual differences are related to VS outcomes, there is a need to consider how they manifest (see Hampson, 2012, for an interesting discussion on the processes that produce personality effects). For instance, there is an overall agreement that attentional bias to threat is robustly related to anxiety, even if the underlying mechanisms driving this relationship are often debated (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & Van Ijzendoorn, 2007). An existing meta-analysis looking at threat-bias and anxiety in studies with different experimental paradigms and different types of anxious populations (including non-clinical) found a threat-related for bias of a similar size to that of individuals with an anxiety diagnosis (Bar-Haim et al., 2007). Thus, finding a clear relationship between trait anxiety and VS performance when search included some form of affective stimuli may be expected. However, from an applicative perspective, the threats encountered in real-world tasks, such as in airport security screening are man-made and often not of an obvious category (e.g., improvised, or even improper, weapons; e.g., Frugarello, Rusconi, & Job, 2022) and thus, may not transfer to improved performance for anxious individuals in such tasks. Another example is the finding that the Big Five traits were shown to be inconsistently related to VS outcomes, with the clearest association being between conscientiousness and VS accuracy. One study found higher conscientiousness eliminated the relationship between fatigue and VS performance (Grady et al., 2022). Conscientiousness has been related, in the wider literature, to the temperament of effortful control (Ahadi & Rothbart, 2014; Hampson, 2012) as well as rule-based behaviour (DeYoung, 2015), therefore, one may expect a relationship between scores in this trait and performance in a task involving attentional control. However, there appears to be a lack of studies focused on the reasons that these traits may link with VS. In general, the area would benefit from studies allowing for a deeper understanding of advantages conferred by specific traits. Furthermore, adopting complementary methods to understand the nature of the relationship, such as eye-tracking and brain imaging studies, may help clarify the underlying mechanisms driving the advantage. In the wider literature, for example, studies have linked conscientiousness to variations in brain structure and function (Lewis et al., 2018) but the research is sparse when linked to VS. Finally, most of the studies on abilities found performance across the chosen broad abilities to be related to performance in VS, although many of the relationships found were weak to moderate, with some questionable as to their applicative value. These relationships are not trivial, given that existing research exploring a common underlying factor of perception has found performance in visual tasks to be highly task dependent (Tulver, 2019). Importantly, it appears that separable cognitive abilities, over and above a higher order general ability, are related to a range of VS tasks. And so is a series of traits. To be more precise, our synthesis found about 72% of studies exploring traits and about 77% of studies exploring cognitive abilities to return positive results. With the most promising individual difference, in terms of percentage of studies showing positive results (moderate to strong effect sizes), being Gv (91%). This could be related, on the one hand, to a genuine superiority of Gv, compared to other abilities, in terms of association with the core characteristics of VS tasks and the systematic use of Gv measures that, in their complexity, encompass more than one crucial component of VS (i.e., the EFT or one of its variants), and on the other to the relatively high proportion of complex and real-world VS tasks used in such literature. In any case, based on this review, a task measuring individual differences in Gv appears to be the safest bet if one were to try to predict individual differences in VS and had the opportunity to assess participants' ability. If this was not an option, questionnaires may be also used to measure specific traits, taking into account that their utility could heavily depend on the characteristics of the VS task.

Nevertheless, caution is required if VS performance-related cognitive abilities or traits are used as selection criteria in recruitment efforts. For instance, as any automated measures, they may introduce bias, but one may argue that this drawback has to be weighed-up against any human bias that may exist in traditional practices (Hmoud & Laszlo, 2019). Indeed, one of the criteria to define a “talented” employee is the match between an individual's abilities and characteristics and the job requirements (Chamorro-Premuzic, Winsborough, Sherman, & Hogan, 2016). Recruitment decisions have heavy consequences for applicants and selection tools should not be used without full consideration of their utility and fairness (Chamorro-Premuzic et al., 2016). At the heart of the ethical consideration is the question of whether any individual difference used as a proxy of future job-related VS performance are in fact valid. This would include understanding whether skill acquisition is related to these measures and, if individuals with a lower baseline can be trained to reach appropriate performance levels, then excluding them at the outset may be considered unfair. The wider context should also be taken into consideration and VS may not be the only task required on the job. No matter how specialized the job demands are, physiological-attentional limitations must be taken into account and it might necessary/opportune to switch regularly between different tasks, as for airport security officers. Moreover, other individual-related factors in addition to task-specific skills or predispositions are likely to contribute to job efficiency, satisfaction and retention (e.g., Diamantidis & Chatzoglou, 2019).

The reader must be alerted to two other important issues. This systematic review aimed to include all relevant material that met the selection criteria to allow for exploration of the literature on VS with key individual differences in healthy adult participants. It is likely that more studies have been carried out in the specified period but never published due to null results (Rosenthal, 1979). Moreover, several studies have been conducted and published in the specified period which did not meet our analytical approach criteria. Indeed, a popular approach consists of converting independent variables into categorical/dichotomous variables by identifying one or more cutoff points, and then using a statistical approach for categorical variables to assess group differences (e.g., via ANOVAs or *t*-tests). The choice of cutoff points is often based on a central index such as the mean or the median of the sample, on distributional subgroups (e.g., tertiles), or a predefined range of scores. In this systematic review, only studies analysing traits and abilities as continuous variables, instead of as categorical or dichotomous (i.e., the latter being the most common form of grouping across disciplines; Altman & Royston, 2006) outcomes, have been included. Although widely used, the practice of creating groups from data measured as continuous variables has been a point of concern for some time (Cohen, 1983). For instance, MacCallum, Zhang, Preacher, and Rucker (2002) demonstrate that dichotomization leads to loss of information about individual differences and to biased estimations of relationships among variables (e.g., loss of effect size and statistical significance and the appearance of spurious significant effects; see also Bakhshi, McArdle, Mohammad, Seifi, & Biglarian, 2012). Additionally, dichotomization makes the comparison and aggregation of findings across studies problematic, in contrast with the justifications typically provided for its use in published studies (e.g., to increase statistical power or to ease interpretation; MacCallum et al., 2002). Conceptually, if different individuals within a group are treated as sharing the same property on a variable that has been validated to measure finer differences, grouping causes a significant loss of information. Individuals positioned at the inner boundary of each group are treated as categorically different, whereas individuals at the inner and the outer boundaries within a group (i.e., whose scores differ much more widely than those of individuals at the inner boundary of two different categories) are treated as equivalent. Thus, the current focus on individual differences treated as continuum outcome is aimed to provide a selection of designs where power is maximised, thus lowering the risk of potential misinterpretations or spurious effects.

Overall, however, there were key limitations highlighted from the included literature. These limitations include many of the studies having low sample sizes. This was especially true of studies with individual differences (behavioural) as a secondary aim. One further drawback was the number of studies that did not make clear whether *p* values had been adjusted for multiple corrections. Such limitations, together with a lack of reporting on reliability, variability in VS task adopted, and variability in tool or task adopted to measure the individual difference introduce challenges for better understanding the reasons why certain individual differences are related to VS performance. Furthermore, they may also hinder any qualitative and quantitative analysis. This is especially true of the issue with reliability, which may render some tools unsuitable for use in individual differences (Clark et al., 2022; Hedge et al., 2018).

Nevertheless, the systematic review also allowed for insight into future research that may help move forward our current understanding of the reasons why some individuals are better than others at VS, which could help inform both theoretical models and applicative endeavours. The review included several studies that aimed to offer a depth of knowledge of specific individual differences and VS, by carrying out multiple studies using different VS tasks, with the most elegant carefully modifying task parameters, or with different groups of individuals depending on experience. Future research could benefit from more studies of this nature and studies using complementary measures to understand links, as studies that allow for an understanding of why, and not only if, the individual differences are important in VS would allow for a greater insight into VS. Pre-registering such studies could also help to move the field forward, preventing future issues found with reporting adjustments for multiple comparisons and ensuring power analysis is carried out to achieve more suitable sample sizes.

### 4.10. *Recommendations and ways forward*

To summarise, this review of the studies conducted from 1985, and treating both measures of traits or abilities and measures of VS performance as continuous variables, leads to the following recommendations, to help advance the scientific understanding the relation between individual differences and VS and its applicative potential:

- Power analysis and multiplicity of testing should be carried out/considered when planning a study;
- The reliability of tools/tasks should be checked beforehand with a sample of the relevant population;
- Reliability information should be calculated and reported for both measures of individual differences and measures of VS performance;
- Study preregistration should be performed whenever possible/suitable;
- When using tools and tasks producing continuous measures, individual differences should be analysed as continuous rather than categorical variables;
- VS task difficulty and specificities should be taken into account as they may influence reliability and justify a possible relation with the individual differences of interest;
- Measurement (and reporting) of multiple indices, with or without complementary methods (e.g., eye movement recording, psychophysiology, neuroimaging), should be considered;
- In case of targeted translational or applicative research, the inclusion of traditional VS tasks in the design would ease comparisons with the extant literature and contribute to the theoretical understanding of any reported relationship with real-world VS;
- Studies addressing systematically why, and not only if, a relation exists between individual differences and VS would be especially valuable.

## TOP Guidelines Statement

- All raw and processed data supporting this research are publicly available. See TOP Guidelines Assessment in Supplementary Information for details.
- This research did not make use of any analysis code.
- This research did not make use of any materials to generate or acquire data.
- The authors report how they determined all sample size(s).
- The authors report all manipulations.
- The manuscript does not report any measures, dependent variables, or other observations.
- The authors report whether sample inclusion criteria were established prior to data analysis.
- The authors report all data exclusions.
- The authors report all data exclusion criteria.
- The authors report whether data exclusion criteria were established prior to data analysis.
- At least part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. Study procedures were preregistered at: https://osf.io/n6hzc. There were no deviations from the preregistered study procedures.
- At least part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted. Analysis plans were preregistered at: https://osf.io/n6hzc. There were no deviations from the preregistered analyses.

## Open practices

The study in this article has earned Open Data, and Preregistered badges for transparent practices. The data, and preregistered studies are available at: https://osf.io/n6hzc.

## CRediT authorship contribution statement

**Jennifer Wagner:** Writing – original draft, Project administration, Methodology, Investigation, Conceptualization, Writing – review & editing. **Adriana Zurlo:** Writing – original draft, Investigation, Writing – review & editing. **Elena Rusconi:** Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization, Writing – review & editing.

## Supplementary Materials

Supplementary Materials to this article can be found online at https://doi.org/10.1016/j.cortex.2024.05.020.

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