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Is domain-general object recognition ability a novel construct?

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Author Note

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Abstract

Domain-general object recognition ability (*o*) is the ability to recognize individual members of categories (e.g., one bicycle compared to another). It describes the general ability that applies across diverse categories, rather than an ability specific to any individual category. Interest in this ability emerged from vision research and cognitive neuroscience, and existing research has been relatively independent of the wider psychometric literature on cognitive abilities. We detail the history of *o* research and connect it to this broader literature. To assess whether *o* represents a novel construct, we compare it with preexisting constructs with which it shares similarities. We argue that abilities such as visual memory, visualization, and perceptual speed share some conceptual overlap with *o*, but that none of these existing abilities have the kind of subordinate-level discrimination at their core that *o* does, rendering them distinct. However, despite theoretical differences, some existing tests of these constructs may in fact serve as adequate indicators of *o*. We discuss implications of hierarchical models of cognitive abilities for *o*-related research and consider where *o* might fit into such models of cognitive abilities.

Introduction

Domain-general object recognition ability (*o*) is the ability to discriminate between objects at the subordinate level. This requires differentiating between individual members of a category (e.g., one key versus another), as opposed to basic-level categorization, which is discrimination between different categories (e.g., a chair versus a table). The ability is domain-general in that it describes the ability to recognize objects from every kind of category. This stands in contrast to the focus of most prior research in individual differences of high-level vision, which has usually been concerned with domain-specific abilities (e.g., ability to recognize faces, cars, food). Additionally, *o* is general across different task designs, for instance, those that tap perceptual matching and those that tap long-term memory. While acknowledging that performance on high-level visual tasks is influenced to some extent by domain-specific abilities and non-perceptual cognitive abilities, research into *o* asks a different question. Should we expect a person who is really good at identifying birds or matching images of fingerprints to also be very good at learning to categorize types of blood cancer? One motivation to study a domain-general object recognition ability is that many domain-specific kinds of perceptual expertise have societal value (e.g., in medical or security fields), so a general ability that contributes to all of these specific abilities may be especially useful. Another reason is that the ability to discriminate between objects may place constraints on other activities, such as learning in domains that include perceptual information, the interpretation of data visualizations or the ability to be an accurate eyewitness. Lay people tend to assume that individuals vary less in perceptual skills than in cognitive skills, and that the acquisition of perceptual expertise mainly requires cognitive abilities, motivation and the right training (Gauthier, 2018), but the research on *o* suggests otherwise.

Ostensibly, *o* is a recently identified construct (see Gauthier et al., 2022). Following up on initial work showing that recognition abilities for different object categories were correlated (Richler et al., 2017), Richler et al. (2019) found that a single higher-order factor could explain abilities with many different object categories, when those abilities are measured using several different object recognition tests. Further work has sought to position *o* in relation to other abilities (Chang et al., in press; Smithson, Chow, Chang et al., 2024; Smithson, Chow, & Gauthier, 2024) and to use *o* as a predictor of performance on tasks requiring perceptual abilities (Chang & Gauthier, 2021; Sunday et al., 2018). This line of work has been touted as novel, primarily because individual differences have not classically been the focus of those studying high-level vision. Most of the foundational work on object recognition (e.g., Biederman, 1987; Marr & Nishihara, 1978; Rosch et al., 1976) was concerned with the common mechanisms used to recognize objects. Cognitive neuroscience has focused on domain-specific influences (e.g., Epstein & Kanwisher, 1998; Kanwisher et al., 1997; Sergent et al., 1992) or emphasized the role of visual appearance, including dimensions like size, animacy, or curvature (e.g., Konkle & Caramazza, 2013; Yue et al., 2014). But despite the relative novelty of individual differences methodology for scientists and cognitive neuroscientists studying high-level vision, the study of individual differences in cognitive abilities has a long history. A close reading of this literature could help inform understanding and future research involving *o*.

Most of the prior research into individual differences in object recognition has concerned abilities with specific categories, such as faces (Levin et al., 1975). Where the research has concerned ability across a broader range of objects, it has usually been limited to a particular task-design. For example, some ability test batteries include measures of recognition for multiple object categories, but only use a matching task with subsequent presentation (target followed by target/distractor), which restricts the ability measured by them to one dependent on short-term memory (e.g., recognition of pictures from the Differential Abilities Scale; Elliot, 2007b). Other researchers are explicitly interested in measuring the matching ability for simultaneously presented stimuli (e.g., Growns et al., 2024). In contrast to these kinds of effort, *o* might represent a novel construct, because it seeks to generalize across object categories and task formats. However, many psychological traits or abilities are merely renamed copies of existing concepts (T. L. Kelley, 1927), and so it is important to compare *o* with already-described abilities. If *o* will prove to be an important domain-general ability with wide explanatory power, it is likely that researchers would have brushed up against it in the past, even if to a limited extent. This is especially so when we consider that the study of object recognition itself is not novel (e.g., J. M. Cattell, 1886). Several research areas touch upon abilities that may be related to *o*. Such areas include individual differences in cognitive abilities, neuropsychological tests for impaired facial and object recognition, vision research, and perception and memory neuroscience. Constructs such as perceptual speed, visual processing, and visual memory, share conceptual similarities with *o*. This review assesses the similarity between these constructs and their indicators with *o* and its indicators, and links *o* to the broader research on cognitive abilities.

Development of the *o* construct

One cause of the common focus in vision research on recognition ability within particular domains is the evidence that some brain areas respond maximally to specific object categories such as faces (e.g., Kanwisher et al., 1997; Kanwisher & Yovel, 2006), houses and places (e.g., Epstein & Kanwisher, 1998), tools, and animals (e.g., Chao et al., 2002). Given the importance of the face in social interaction, it may not be surprising that face recognition has received the most attention of any object category. Research in this area has been spurred on by interest in prosopagnosia, which is considered by some to be a selective impairment in face recognition (Corrow et al., 2016; McNeil & Warrington, 1993). Numerous facial recognition or matching tests have been developed, including the *Glasgow Face Matching Task* (A. M. Burton et al., 2010; White et al., 2022), the *Benton Facial Recognition Test* (Benton & Van Allen, 1968), the *Warrington Recognition Memory for Faces Test* (Warrington, 1984), and the *Cambridge Face Memory Test* (CFMT; Duchaine & Nakayama, 2006). All of these tests assess individuation of faces by requiring examinees to decide whether different face images show the same person. Several of these tests also require memorization of faces. Non-face object recognition tests have usually been category-specific too, such as the *Cambridge Car Memory Test* (CCMT; Dennett et al., 2012).

However, the common focus on category-specific abilities ignores the portion of variance in performance that can be attributed to a domain-general ability. Initially, the extent to which object recognition might be domain general was unclear; research primarily focused on whether there was a relationship between object and face recognition, without much of a context within which to interpret the magnitude of these effects. There is a small estimated relationship between the CFMT and similar tasks using abstract art (*r* = .26; Wilmer et al., 2010, 2012), and a slightly larger estimated relationship between the CFMT and the CCMT (r = .37; Dennett et al., 2012). Such results were sometimes interpreted to suggest that face recognition was distinct from recognition of other object categories, and authors sometimes explicitly assumed that the CCMT was an appropriate test of general object recognition (e.g. Shakeshaft & Plomin, 2015). However, the correlations between recognition tests that use different object categories range widely in size. The *Vanderbilt Expertise Test* (VET; McGugin et al., 2012) is a battery of tests similar in format to the CFMT and CCMT, but applied to a broader set of categories. Estimated cross-category relationships for the VET vary from *r* = .02 for cars and leaves, to *r* = .56 for butterflies and leaves. The correlation between performance with faces and cars observed by Dennett et al. (2012; *r* = .37) does not appear to be a clear outlier in the context of these correlations, although McGugin et al. (2012) reported that face recognition was generally less strongly correlated with other categories than most categories are. Of the non-face object categories that have been tested, car recognition seems to be the most distinct (Ćepulić et al., 2018; Sunday et al., 2019), and is therefore an ironically poor stand-in for other categories despite its frequent use as such. This pattern of findings challenges the notion that face recognition is particularly distinctive and that recognition of non-face objects is undifferentiated. However, these observed differences between categories do not exclude the possibility that there may be a general component that applies across categories; Van Gulick et al. (2016; based on a reanalysis by Richler et al., 2017) found an average correlation of *r* =.33 between recognition accuracies for different object categories, and an average correlation of *r* =

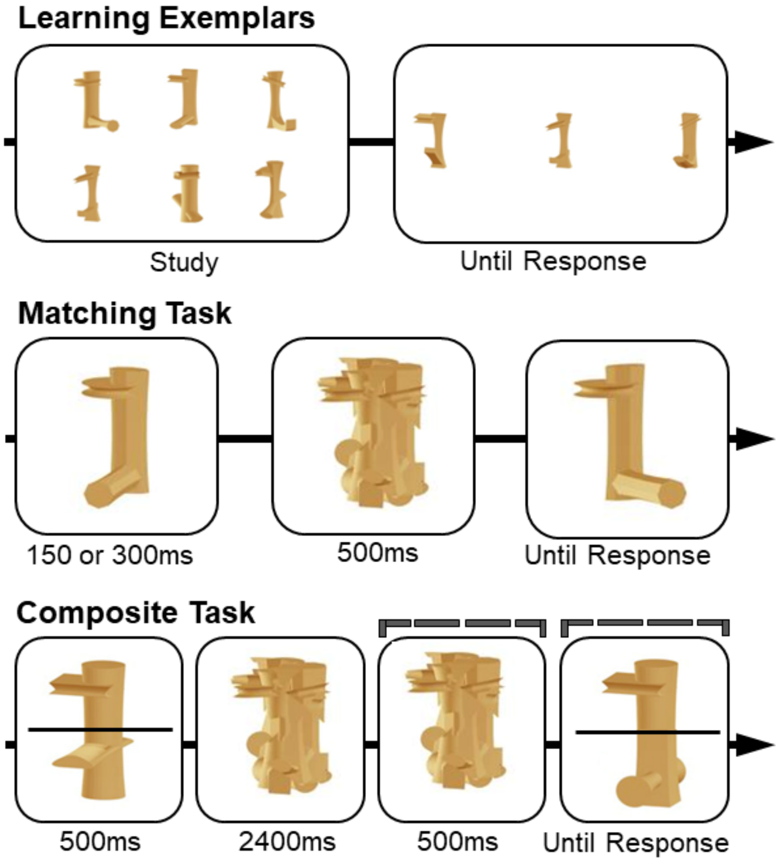
.47 when accuracy for single categories was compared with accuracy aggregated across all other included categories.

Following up on this work with familiar categories, Richler et al. (2017) constructed object recognition tests (*Novel Object Memory Test*; NOMT), similar in format to the CFMT, the CCMT, and the VET, but with novel object categories. The advantage of using novel objects is that individual differences in experience are controlled for; this approach also yielded sizable correlations in recognition accuracy between categories. The average correlation between performance on single categories and the aggregate performance across all other categories was $r = .49$. Richler et al. (2017) also demonstrated that little of the shared variance between pairs of NOMTs was explained by general intelligence, suggesting some degree of independence between general object recognition ability and intelligence. This is a necessary first step in establishing the existence of an ability, as all ability tests tend to correlate, and the covariance between all such tests is usually attributed to general intelligence. However, there are issues with relying solely on correlations between object recognition tests that use the same task format, but differ only in their stimuli, to determine the generality of recognition ability, because the correlations between these tests can be due to method-specific variance. The other abilities affecting task performance may or may not be domain-general and hence may influence the size of the correlations between different abilities. Additionally, because of measurement error, the correlations between directly observed variables typically underestimate the correlations between the constructs the variables are intended to measure, as the presence of error variance limits the observable correlations (Spearman, 1907).

To address these problems, Richler et al. (2019) used confirmatory factor analysis to model domain-general object recognition as a latent variable. By modelling latent variables as causes of performance on multiple tests, it is possible to more cleanly estimate relationships between the ability of interest and other variables and to do so freely from measurement error (Bollen, 2002). Object recognition ability was tested for five novel object categories. Object stimuli from each category were used in conjunction with three different task designs (Figure 1) to construct 15 object recognition tests (three for each object category). Although the tasks differed in design, they all required subordinate-level discrimination. Therefore, a large share of covariance between the three types of tasks should be due to this subordinate-level discrimination ability, while test-specific variances may be attributable to methods. When the recognition abilities for each object category were modelled as latent variables with three indicators each, a higher order latent variable was able to explain 89% of the variance in the abilities for specific object categories (Figure 2). In other words, the abilities for each category of objects were very closely related. Due to the possibility that some amount of experience might be necessary for stable individual differences to emerge, participants had been pretrained to recognize four of the five categories. However, they were completely naive when tested on the fifth category. This difference in experience across categories did not cause differences in the way individual differences were expressed, suggesting that the same ability is present whether or not participants had prior exposure to the category. Richler et al.'s (2019) analyses also suggest that this ability is distinct from other general abilities that could be hypothesized to explain performance on these tests, including general intelligence, visual short-term memory, and global/ local perceptual style. In another test of the generality of *o*, Sunday et al. (2022)

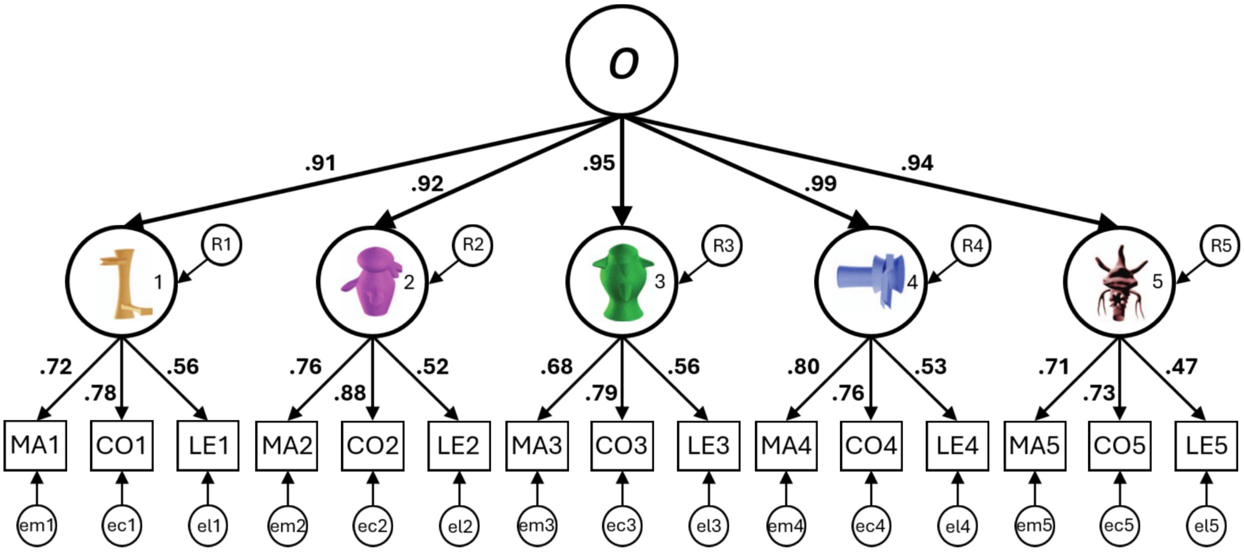
conducted a confirmatory factor analysis and found that *o* was the same ability for novel object categories as for familiar object categories such as birds and planes (r = .98), which is consistent with Richler et al.'s (2019) finding that pretraining did not affect individual differences in performance.

Figure 1. Object recognition tests used in Richler et al. (2019)



Note. These tasks were repeated for each of five distinct novel object categories. On the composite task, either half, or both halves of the object can change from study to test, the cue indicates which half the same/different decision should be based on. Accuracy was indexed by *d'*, the congruency effect that is typically measured with this task was not analyzed.

Figure 2. Confirmatory factor model from Richler et al. (2019)



Note. Circles represent latent variables, squares represent tasks. Three task types (MA – Matching; CO – Composite; LE – Learning Exemplars) were repeated across five object categories (1 – Vertical Ziggerins; 2 – Asymmetrical Greebles; 3 – Symmetrical Greebles; 4 – Horizontal Ziggerins; 5 – Sheinbugs). The latent recognition ability for each object category was allowed to predict tasks that use that category as stimuli. The higher-order *o* factor is allowed to predict the abilities for the five object categories. The R terms represent the category-specific abilities that are not explained by *o*. The e test-specific variances were allowed to correlate within-task-type across object categories, but these correlations are not shown.

Factor models of data collected in other work have suggested that *o* may not be limited to the visual modality. One study identified a very high correlation at the construct level between visual object recognition and auditory object recognition (*r* = .96; Chow et al., 2023). Three visual novel object recognition tasks were used from Smithson, Chow, Chang, et al. (2024; see Figure 3) while the auditory tests had similar designs adapted to the auditory modality. These tests required matching the identities of people based only on the sound of their laughter, remembering birdsongs, and comparing sounds associated with different types of mechanical keyboards. Chow et al. (2023) also found that the correlation between these abilities was little reduced when general intelligence was partialed out (*r* =.92). A replication using the same tasks with a larger sample also suggested a large relationship (*r* = .80; Smithson, Chow, & Gauthier, 2024) that remains substantial once *g* is partialed out (*r* = .60). The magnitude of the relationship between visual object recognition with haptic recognition ability has been assessed in two studies, one at the level of observed variables (e.g., *r* = .33; Chow et al., 2022), and one at the construct level using latent variables (*r* = .53; Chow et al., 2024). These findings suggest that there may be a high-level multimodal object recognition ability that contributes to performance on modality-specific tasks in conjunction with modality-specific recognition or lower-level perceptual abilities. The relative contributions of these hypothesized sources of variance are yet to be investigated.

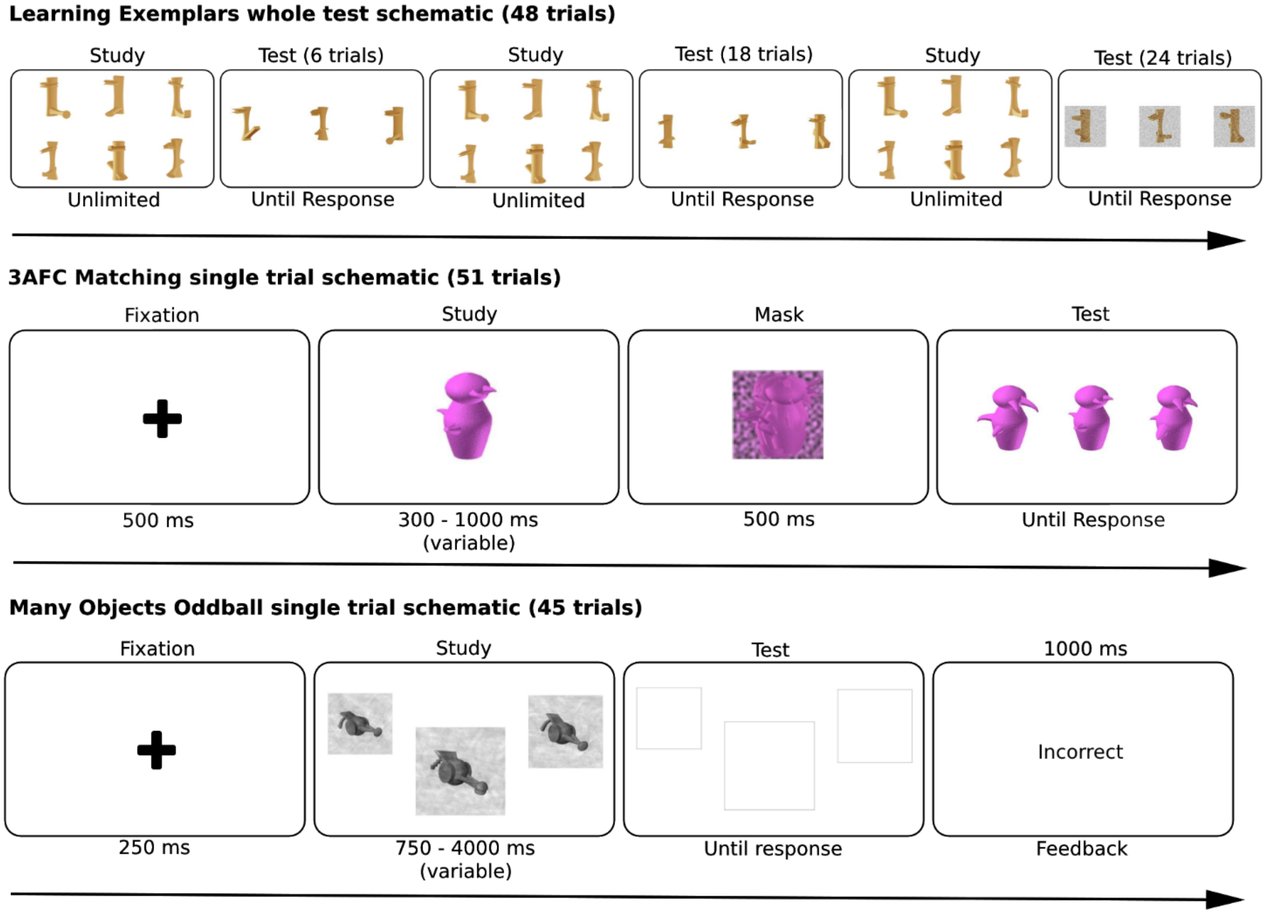
When exploring a novel construct expected to be 'general', we learn about its boundaries by extending the set of indicators that are used to define it. In a study focused on improving the measurement of *o*, Smithson, Chow, Chang et al. (2024) shortened and reformatted the existing *o* measures for easier use and introduced an additional third object recognition task. The tests (Figure 3) vary substantially in format, and two are adaptations of those in the foundational article on *o* (Richler et al., 2019). The *Learning Exemplars* (LE) format is similar to the CFMT/CCMT/VET/NOMT and is a memory test in which participants study 6 objects and then have to recognize them among distractors. The *Three-Alternative Forced-Choice Matching* (3AFC MA) test was also used, consisting of a one-back matching design in which participants choose the target object from among three options. An entirely new task format was used in the *Many Objects Oddball* (MOO) test. The MOO requires participants to determine the odd one out of three objects on each trial. Smithson, Chow, Chang, et al. (2024) demonstrated that the aggregate of these three tests is reliable longitudinally, and that it cannot be fully explained by intelligence, low-level perceptual ability, and perceptual speed, suggesting some separability from these related abilities. A structural equation model suggested that the *o* construct is highly stable over the course of a month (*r* = .93). Such stability of a construct is useful to establish if it is to be used in predicting criterion variables across longer time periods.

The MOO test was designed to explore the boundaries of visual *o* in one important way. In the LE test, long-term memory can be used because representations of the to-be-remembered exemplars have to be stored for more than a few seconds (Unsworth, 2010, 2019) and because six items typically exceed working memory capacity limits (Cowan, 2001). The 3AFC MA format has less of contribution from long-term memory because the task only requires memory for the most recently encountered target. But both of these tasks allow for category-specific learning to occur across trials as participants gain familiarity with the object category, and thus knowledge of the relevant dimensions for individuation. The MOO test is distinct from both of these tests in that the object category changes across trials, preventing this kind of learning. MOO is also distinct from LE and 3AFC MA because the objects are presented simultaneously and, therefore, the role of memory is even more limited.

The definition of *o* may be refined as a broader set of putative indicators is used – and as they get more varied, it becomes increasingly important to ensure that the common variance is distinguished from other general factors such as general intelligence. For instance, there is still uncertainty about whether memory is an essential aspect of the *o* construct. It could be conceived as a purely perceptual discrimination ability, or alternatively, it could be a recognition ability for which that discrimination must occur in memory. The introduction of the MOO test allows for measurement of an ability that may not be based on memory at all. Future work will need to determine how separable a purely perceptual ability is from an ability measured by tests that require memory (note that such a distinction has been proposed for face recognition; Wilhelm et al., 2007). Under conditions of theoretical uncertainty, the use of heterogeneous indicators is preferable to the use of homogenous indicators for the purposes of triangulating a construct (Little et al., 1999). When greater theoretical clarity is reached, it can guide task design to support better measurement.

Another important step in the development of the *o* construct is its use as a predictor of criterion variables. Most relevant studies have used an aggregate approach in which *z*-scores for different tests that tap into *o* are averaged for each participant, rather than modeling *o* as a latent variable. Such aggregates predict the successful identification of lung nodules in mammographs, with incremental validity over intelligence and experience alone (Sunday et al., 2018; see also Trueblood et al., 2018). They can also predict successful category learning, with those scoring higher on *o* tests also more rapidly learning to categorize white blood cells as cancerous or non-cancerous when feedback is given during the learning process (Smithson et al., 2023). A relationship has also been found between *o* and successful music reading (Chang & Gauthier, 2021), recognition of food (Gauthier & Fiestan, 2023), and estimation of summary statistics for groups of objects (Chang et al., in press; Chang & Gauthier, 2022). More work is needed to establish in which areas of performance *o* could be most predictive.

Figure 3. Three *o* tests from Smithson, Chow, Chang, et al. (2024)



Note. *The Many Objects Oddball Task uses different object categories on different trials. Figure first published in Behavior Research Methods, 2024, by Springer Nature*.

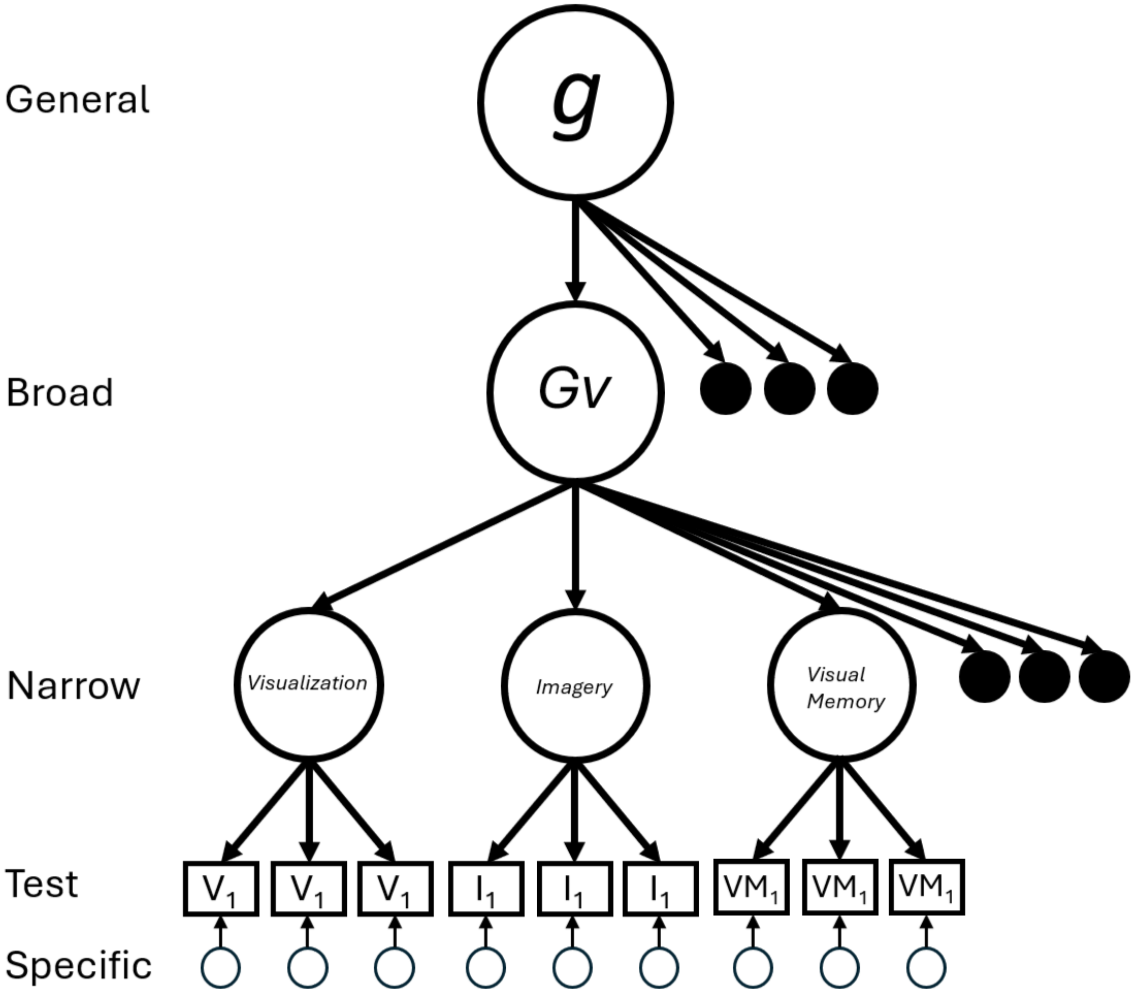
The structure of cognitive abilities

The work we have outlined so far on the domain-specific and domain-general individual differences relevant to object recognition has not attempted to relate these abilities to the wider literature on cognitive abilities. Researchers in the correlational tradition (Cronbach, 1957) have been acutely aware of the need to investigate abilities in the context of their relationships to other abilities. The relationships between constructs, between tests, and between constructs and tests have been termed the *nomological network* (Cronbach & Meehl, 1955). The mapping out of this network allows researchers to define constructs by their relations with other variables, and so to investigate whether two abilities are the same or different by virtue of whether or not they share the same profile of correlations with external variables. For example, if two measures are very closely related, they have convergent validity (Campbell & Fiske, 1959), and if they have equivalent correlations with external variables, they have extrinsic convergent validity (Fiske, 1971; Gonzalez et al., 2021), which suggests they are equivalent. Relating constructs to each other also allows for the development and testing of theories that explain such relationships. Additionally, the measurement of multiple abilities allows for better isolation of the construct of interest if the variance caused by other abilities can be partialed out (Nye et al., 2020; L. L. Thurstone, 1935). Through the factor-analytic approach, in which covariance between tests is ascribed to a smaller number of latent factors, researchers have attempted to discover the underlying structure of human cognitive abilities (Carroll, 2003; L. L. Thurstone, 1938, 1950).

Spearman (1904) invented the earliest form of factor analysis, which he used to support his two-factor theory – the idea that scores on each ability test are due in part to a specific factor, and in part to a general factor (*g*) that is responsible for the correlations between all such tests. However, Spearman's critics pointed out that his data were not inconsistent with the existence of multiple group factors (Thomson, 1916). L. L. Thurstone (1935, 1938) was particularly influential in developing multiple factor analysis, and he claimed to discover seven primary mental abilities that explained correlations between the great number of diverse ability tests used in his research. Initially, it was thought that these primary abilities were independent, but by allowing these factors to correlate with one another by using oblique rather than orthogonal factor rotation, a higher-order *g* could be extracted. This hierarchical structure provided a compromise between the two-factor theory and the multiple-factor theories and was eventually accepted to some degree by both Spearman and Thurstone (Spearman & Wynn Jones, 1950; L. L. Thurstone, 1948). Other researchers such as Burt and Vernon also settled on a hierarchical model (Burt, 1949; Vernon, 1961). These early hierarchical models bear a strong resemblance to the hierarchical models of today. While some other theorists have proposed non-hierarchical models of the structure of cognitive abilities (e.g., Guilford, 1959), such models have largely fallen out of favor.

Two of the most influential hierarchical theories have been the Cattell-Horn extended *Gf*-*Gc* theory (Horn & Cattell, 1966; Horn & Noll, 1997) and Carroll's (1993) three-stratum theory (3S). Both posit the existence of broad abilities, such as *processing speed* (*Gs)* and *visual processing* (*Gv*). These broad abilities explain the covariance between multiple narrow abilities, such as *length estimation* or *perceptual speed*, which themselves explain the covariance between multiple psychometric tests. However, where the theories differ most is that the *Gf-Gc* theory does not posit the existence of a higher-order *g* factor of intelligence, while the 3S theory holds *g* to be an essential concept (Canivez & Youngstrom, 2019). The similarities between these theories allowed for a slightly uneasy unification in the form of Cattell-Horn-Carroll (CHC) theory (Figure 4; Canivez & Youngstrom, 2019; Schneider & McGrew, 2018), which is now the predominant conception of the structure of cognitive abilities. To connect *o* research with the broader literature on abilities, it is worth considering where *o* could fit into CHC, and whether *o* is comparable to abilities already included within CHC or other models of cognitive abilities. Within such taxonomies, there are multiple abilities measured by tests that share similarities with *o* tests, and these abilities are likely to be the best candidates for existing *o*-like abilities. However, it is also theoretically possible that a set of tasks that appear on the surface less like *o* tasks could also converge on an ability similar to *o*. For example, the tests for narrow abilities under *Gv* can be quite diverse, yet different combinations of them would theoretically be expected to converge on the same *Gv* ability.

Figure 4. Structure of CHC demonstrated through the broad visual processing ability.



Note: At the apex is *g*, followed one step down by broad abilities such as *Gv*, followed another step down by narrow abilities such as *visualization* or *Imagery*, and finally followed by psychometric tests and their specific variances. The circles represent latent variables, and the squares represent observed variables. Arrows represent the direction of causal relations. The filled circles represent the many more abilities that exist at each layer.

Perceptual Speed

Although no broad ability within CHC appears to be exactly synonymous with *o*, some narrow abilities have clear relevance. One such ability is *perceptual speed*, which falls under the broad ability *Gs* (although it has sometimes been placed under *Gv*; see Carroll, 1993). Perceptual speed is the ability to rapidly search for or compare visual stimuli. It was one of the first factors to be included in models of cognitive abilities, appearing as one of L. L. Thurstone's (1938) primary mental abilities. Perceptual speed shares with *o* this requirement for perceptual discrimination of visual stimuli. Some authors argue that perceptual speed can be further decomposed into narrower abilities, making a distinction between *searching* and *comparing* perceptual speed abilities (Ackerman et al., 2002; Carroll, 1993; Schneider & McGrew, 2018). The comparing subfactor may be most similar to *o* due to its explicit emphasis on perceptual discrimination, although the perceptual discrimination required is not usually fine-grained in the manner that *o* tests require. Additionally, comparing-perceptual speed tasks usually require visual comparison between a target and other stimuli that are simultaneously presented, whereas *o* tasks usually employ sequential presentation[1], presumably invoking a greater reliance on memory. Examples of perceptual speed tasks that require comparison include the *Hidden Patterns* and *Identical Pictures* tests (Ekstrom et al., 1976a; Figure 5). Even with featural overlap between targets and distractors, few errors would be expected on perceptual speed trials if responses were not speeded. Speeded responses are not required in *o* tests, and therefore it is expected that mistakes should stem from difficulties in individuating perceptually

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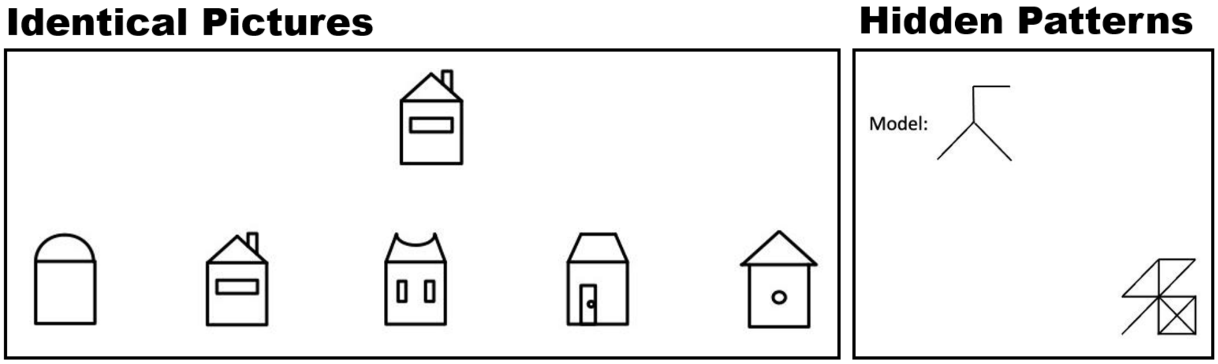
[1] The MOO test is an exception to this rule, but unlike many perceptual speed tests, the presentation time of the stimuli is limited.

similar stimuli in addition to the challenge of encoding the level of detail required for discrimination.

Perceptual speed is measured using *speed* tests, whereas *o* is generally measured using *level* tests. Speed tests are those that pertain to the ability to do something quickly, whereas level tests are those that pertain to accuracy (Carroll, 1993; Lohman, 1979b). Response times are also not ordinarily analyzed in *o* tests, which emphasize accuracy, avoiding some of the difficulties the use of response times can pose in achieving reliable measurement (Draheim et al., 2019). These differences at the level of the two constructs and between the tasks that are generally used to measure them provide an *a priori* reason to expect *o* and perceptual speed to have an imperfect relationship. However, subordinate-level discrimination, the core of the *o* construct and a prerequisite of the kind of individuation that is critical for many perceptual experts, is well-suited to be tested in tasks that limit encoding time. Some existing *o* tests are likely to tap into the speed of discrimination because they require rapid encoding of perceptual stimuli; for example, target presentation times in the 3AFC MA task are limited (varying from 300 to 1000 ms across different trials). Varying presentation times as a means of adjusting the difficulty of trials will necessarily cause the test to capture some variance attributable to perceptual speed. However, other *o* tests place little emphasis on rapid encoding and, therefore, speed is not considered a critical feature of the measurement of *o*, but instead is used similarly to other manipulations (such as image or viewpoint change, noise, short delay) to ensure that errors are made.

Figure 5. Example trials of two perceptual speed tests used in Smithson, Chow, Chang et al. (2024) and (Chang et al., in press).



Note. Test stimuli are from Ekstrom et al. (1976a).

Despite some clear theoretical differences between *o* and perceptual speed, and differences between their corresponding indicators, empirical evidence suggests a strong relationship between *o* and comparing-perceptual speed tasks. Smithson, Chow, Chang et al. (2024) found a zero-order correlation of $r = .56$ ($r = .63$ corrected for measurement error; Spearman, 1907) between an aggregate of the MA, LE, and the MOO *o* tests and an aggregate of the Hidden Patterns and Identical Pictures tests. A study that modeled *o* and perceptual speed as latent variables in a structural equation model, using two *o* tests as indicators, and the same two comparing-perceptual speed tests as Smithson, Chow, Chang et al. (2024), found a relationship between the two constructs as high as $r = .81$ (Chang et al., in press). Beyond the requirement for rapid encoding in some *o* tests, another explanation for this close relationship may be that greater facility with perceptual discrimination could allow for both faster responding on speeded tests and greater recognition ability on *o* tests. In part, the degree of relationship may depend on how important the memory aspect of *o* tests is to the construct, given the limited role of memory in perceptual speed tests. Another explanation for the close relationship is the use of perceptual speed tests requiring figural matching that, while not difficult, still involves "objects" or a certain complexity. Although there are clear similarities between *o* and perceptual speed, there are also clear theoretical differences. Future work should continue to compare refined versions of the *o* construct with a broader range of perceptual speed tests.

Visual processing – visual memory and visualization

Given that *o* was originally defined as an ability for *visual* object recognition, a close relationship with visual abilities might be expected. *Gv* is the broad ability to process and reason with visual stimuli or mentally simulated visual imagery. It is often referred to in the literature as spatial ability. The narrow abilities under *Gv* are quite diverse, but none of them directly concern subordinate-level discrimination. However, some of these abilities may still be closely related to *o*. One narrow ability that is often placed under *Gv* (e.g., Schneider & McGrew, 2018), but sometimes under *learning and memory* (e.g., Carroll, 1993), or *Learning Efficiency* (e.g,. Woodcock et al., 2018) is *visual memory*. This has been defined as the ability to create and store mental representations of visual stimuli and to be able to recall them or recognize them later (Flanagan & Dixon, 2014).

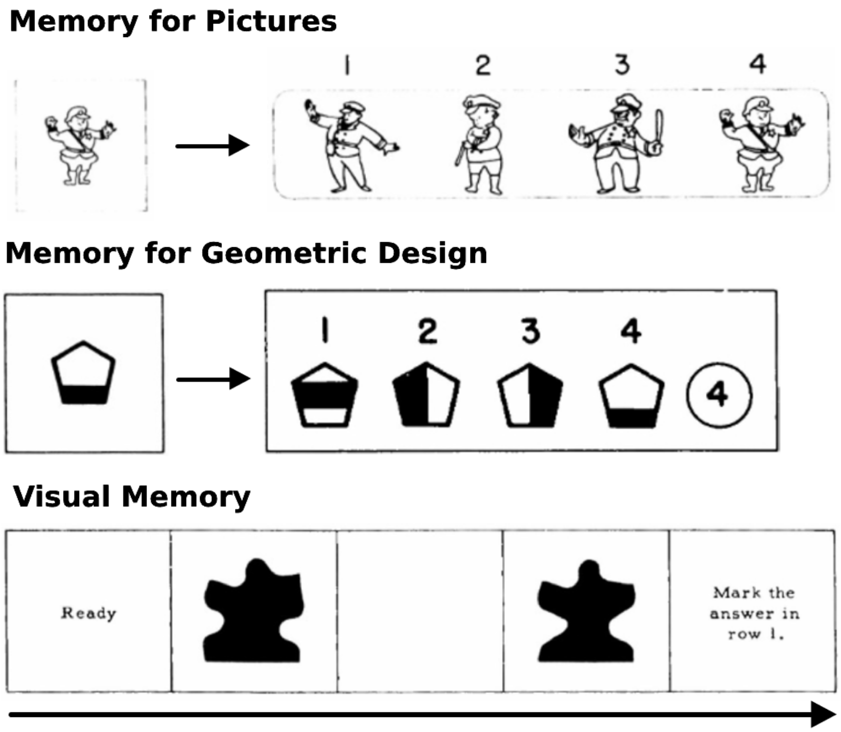
Early visual memory tests. The existence of a visual memory factor is based on a long history of research. Carlson (1937) and L. L. Thurstone (1950) both proposed the existence of a visual memory factor. Further studies suggested that visual memory was a distinct factor from other visual or memory abilities (Guilford et al., 1952; Guilford & Lacey, 1947). However, tests that load onto the visual memory factors in these studies measure quite a variety of abilities. For example, Guilford et al. (1952) analyzed tests from the Army Air Forces Sheppard Field Battery of Experimental Aptitude. One such test is *Map Memory*, in which a schematic map is studied for 4 minutes before participants answer questions about the map. Another test is *Visual Memory*, in which the participant is given one minute to study a large aerial photograph, before having to choose from several smaller photographs, the ones which contain cropped and rotated portions of the original large photograph. Other tests involve spatial visualization, visualization of plane maneuvers, and memory of plane positions. The visual memory factor had positive correlations ranging from r =.28 to r = .33 with visualization, spatial orientation, spatial relations, spatial scanning, and perceptual speed. Several of the tests included in Guilford et al.'s (1952) analysis may appear at first glance to be measures of object recognition ability. However, on closer inspection, these tests measure other abilities. For example, *Object Recognition* and *Object Identification* assess the ability to visualize changes in orientation. Many studies investigating visual memory have used tests that require memory for position and spatial orientation rather than mere memory of identity, suggesting that researchers have not always made a clear distinction between these kinds of abilities. However, two paired-associates tests included in this battery did require subordinate-level discrimination. *Plane Name Memory* and *Memory for Plane Silhouettes* require examinees to study plane silhouettes and drawings alongside their associated names, and during test, to correctly pick which name belongs with which plane. In Guilford et al. (1952) these tests loaded onto what is arguably a memory factor alongside a *Plane Position Memory* test. In a larger battery of tests created for the Army Air

Forces, these two tests loaded onto a factor with two other visual paired-associates tests (Guilford & Lacey, 1947). One was *Memory for Ships*, in which examinees have to study photographs of 10 ships that are all taken from the same angle with the ships travelling in the same direction. The nationalities of the ships are given next to the photographs. During the test, examinees are presented with 12 ships and have to associate the ships with their respective nationalities and detect which ships are new. The other test was *Memory for Landmarks*, in which examinees are shown drawings of the basic outlines of geographical features and their associated names. For example, on one study page, 15 drawn outlines of lakes are presented alongside made-up names. During the test, 10 of these diagrams are presented alongside the original 15 names. Examinees have to match the names with their respective lakes. As these tests require subordinate-level discrimination, it is likely that they would relate strongly to *o*. In the case of Memory for Ships and Memory for Plane Silhouettes particularly, the perceptual discriminations are quite challenging. Conceptually, they differ from *o* in their requirement for memory for association. However, the difficulty of the discrimination required to correctly memorize these associations connects these two abilities; there is evidence that subordinate-level visual recognition memory correlates with hard, but not easy, paired-associate learning (Samuels & Anderson, 1973). The stimuli in the Army Air Forces paired-associates tests are largely limited to planes and ships due to a desire to give the tests face validity.

Other illustrative examples of Visual memory tests are those included in a factor-analytic study by L. L. Thurstone (1949). Participants completed 32 visual tests, including three designed for the assessment of visual memory (Figure 6). The *Memory for Pictures* test presented participants with 84 drawings (e.g., police officer, elephant), before participants received an answer booklet containing rows of possible answers. On each row, one drawing was one of the 84 targets, and another three drawings were different versions of the type of object in the target drawing. This ensured a requirement for perceptual rather than semantic memory. The *Memory for Geometric Design* test followed a similar format with 24 geometric designs. The *Visual Memory* test involved a same/different sequential matching task with shapes. These tests appear to require subordinate-level discrimination (targets and distractors within the same category), but only the visual memory test requires fine perceptual discrimination. In L. L. Thurstone's analysis, these tests were split across two factors. The first factor had loadings of .47 from memory for geometric designs, .53 from Memory for Pictures, and 0 from Visual Memory. The second factor had loadings of .29 from memory for pictures, .39 from Visual Memory, and .22 from Memory for Geometric Design, in addition to .42 from a block assembly task. These factors were distinct from an intentional memory factor, suggesting a separation from other memory abilities. L. L. Thurstone speculated that the first factor involved sustained memory for visual stimuli, while the second related to short-term retention of precise perceptual details, which is conceptually similar to *o*. Both factors moderately correlated with various spatial factors (from r = .20 to r = .41), and the second correlated strongly with induction (r = .56). Interestingly, neither factor had significant loadings from *Identical Forms*, a comparing-perceptual speed test. Lohman (1979b) reexamined L. L. Thurstone's (1949) data using updated factor-analytic methods and multidimensional scaling, finding that the three visual memory tests formed a unique cluster, which suggested the existence of a singular visual memory factor. This result was further confirmed by a reanalysis in Carroll's (1993) momentous survey of factor-analytic studies.

Christal (1958) attempted to explore the factorial structure of visual memory abilities. One of the included tests is very similar to *o* tests; the *Pattern Detail Memory Test* was developed as a measure of form memory. Examinees were shown 15 complex patterns formed from straight lines and were later asked to select each one from five very similar patterns. This task loaded onto a factor of an unclear nature. It did not form a clear factor with other purported tests of form memory, but it was the only test requiring the kind of memory for perceptual detail that is needed for subordinate-level discrimination. Although the patterns consist only of straight lines organized in various arrangements, the difficulty of the discrimination from memory would likely make this test load highly onto *o*.

Figure 6. Visual memory tests used in L. L. Thurstone, (1949)



Note. Adapted reproduction from Thurstone & Thurstone, (1949) Many studies have also made use of a set of visual memory tests put forth by Ekstrom et al. (1976a), which includes a *Shape Memory*, a *Building Memory*, and a *Map Memory* test (e.g., Czarnolewski & Eliot, 2012; Jones et al., 2011). Of these three, the Shape Memory test appears closest to an *o* test. Participants study a set of irregular shapes that are sometimes blackened and outlined. Then, they are presented with smaller sets of new and previously presented shapes and asked whether these shapes were in the original study set and in the same relative positions and orientations. The new shapes have slight differences in detail from the study shapes. The Building Memory test measures the ability to remember the positions of buildings on a map. The Map Memory test requires participants to select small maps that are accurate reproductions of previously studied maps. Ekstrom et al. (1976b) defined the visual memory factor as 'the ability to remember the configuration, location, and orientation of figural material' (p. 109), which, while possibly related, is less akin to subordinate-level object discrimination than definitions adopted by other authors. This visual memory factor has moderate correlations with closure speed, spatial relations, visualization, and visual imagery (L. J. Burton, 2003; L. J. Burton & Fogarty, 2003).

Visual Memory in Ability Batteries. Many general ability batteries have also included visual memory tests that sometimes explicitly require object recognition. The British Ability Scales 3 (BAS3; Elliot & Smith, 2012) and its American counterpart The Differential Ability Scales II (DAS-II; Elliot, 2007b) were designed for use with children, and both include a *Recognition of Pictures* measure. This requires the child to memorize one to four pictures and subsequently identify those pictures from among a group of four to seven similar pictures. Some trials require individuation between similar objects. The batteries also include tests requiring delayed recall of objects, but these have no recognition aspect to them. The Recognition of Pictures test has a sizable factor loading (.58) onto a *Gv* factor, which also has large loadings from a pattern construction and a recall of designs task (Elliot, 2007b; Elliot et al., 2018), indicating a relationship between these abilities. When modeling the structure of the DAS-II, allowing cross-loadings from the recognition for pictures task onto short-term memory or long-term retrieval does not significantly improve model fit (Keith et al., 2010), suggesting that these abilities need not be invoked to explain performance on the task. In factor-analytic models *g*-loadings for *Recognition of Pictures* range from .42 to .59 across age ranges (Elliot, 2007c; Keith et al., 2010), and are usually lower than for most other tests (e.g., Keith & Reynolds, 2018). Reliability estimates for this test are the lowest of any included in the DAS-II (.77-.79; Elliot et al., 2018; Willis et al., 2008).

The Woodcock-Johnson IV (WJ-IV; Schrank et al., 2014) also includes a *Picture Recognition* test of a similar design to that in the DAS-II, which is supposed to measure recognition of stimuli held in passive storage in the visual cache, a theorized part of the working memory system (Logie & Pearson, 1997). It is a test only of short-term recognition and does not require long-term memorization. As is the case for the Recognition of Pictures test in the DAS-II, the picture recognition test in the WJ-IV has the lowest reliability of any in the battery (.74; Schrank & Wendling, 2018). Estimated *g*-loadings have often been lower than for other tests in the GJ-IV of (.35 - .45; Dombrowski et al., 2017, 2018; Schrank et al., 2016), and exploratory factor analyses suggest that the task loads onto a factor that also had loadings from *Visualization*, and *Analysis-synthesis*, which is the ability to use concrete rules in deductive reasoning (Dombrowski et al., 2017). Picture Recognition also tends to have a low communality in factor models; little of the test variance is explained by common factors (Dombrowski et al., 2017, 2018).

The Weschler Adult Intelligence Scale—fourth edition (WAIS-IV; Weschler, 2008) includes a *Picture Completion* test that requires the examinee to view pictures and indicate the missing part. This relies on the comparison of the image with stored exemplars in memory but does not require subordinate-level discrimination. The Weschler Nonverbal Scale of Ability (WNV; Weschler & Naglieri, 2006) is designed for use with children, and includes a *Recognition* test, in which the child first looks at a page containing geometric patterns, and then has to choose a match from several different options. The Weschler Memory Scale—fourth edition (WMS-IV; Weschler, 2009) includes a subscale specifically for visual memory. For each item in the *Designs I & II* subtests, examinees are shown a page containing a 4x4 grid containing abstract designs in some of the rectangles for 10 seconds. The examinee is then given a blank grid and a set of cards with designs on them and has to choose the correct designs and place them in the correct locations on the grid. The examinees are given the same task again after a 20-30 minute delay, so that both immediate and long-term memory can be tested. The other two visual memory tests are reproduction tests that require recall. This combination of short-term and long-term memory testing allows for assessment of a more general visual memory ability. Performance on the test requires memory for both identity and location, making it distinct from *o* tests. The previous version of this scale, the WMS-III (Weschler, 1997) included *Faces I & II* subtests in which examines are shown a series of 24 target faces and are then shown a series of 48 test faces, half of which are the targets and half of which are distractors. Examinees must decide whether each test face is a target or a distractor. The same test procedure is repeated again after a delay. This is a test of face individuation, in both short-term and long-term memory, and is therefore domain-general in method, but not in object category. The Faces subtests were removed in the WMS-IV because they did not load highly onto the visual memory factor (Millis et al., 1999; Tulsky & Price, 2003). It is unclear whether this low loading onto visual memory is because such individuation tasks have a low relationship with visual memory, or because faces are a unique object category due to high levels of experience.

The RIAS-II (Reynolds Intellectual Assessment Scales – second edition; Reynolds & Kamphaus, 2015) includes a *Nonverbal Memory* test in which a target picture is presented for 5 seconds, followed by an array of six pictures, from which the examinee must identify the target. The stimuli can be concrete, abstract, and without meaning, such as cats, dot patterns, or shapes. Unlike in other intellectual assessment scales, this test is not considered part of a visual processing factor, but the scores are instead part of a composite memory index, created by combining this score with that from a verbal memory test. Targets and distractors are from the same general category as each other but are perceptually discriminable with relative ease.

In general, the recognition tests included in the BAS3, DAS-II, WJ-IV, WNV, and RIAS-II require short-term memorization only, rather than testing a combination of long and short-term memory. They tend to have a lower *g*-loading than many other tests, and lower reliabilities. As these batteries are designed to include tasks from across the range of broad and narrow abilities, only one test is typically included as a measure of visual memory. Consequently, a visual memory ability that is captured by these measures will be contaminated by method variance. All these tests require memory of different kinds of objects or visual stimuli, making the visual memory ability general to different object categories, rather than specific. However, these tests generally include stimuli that are easily distinguishable and do not require precise perceptual discrimination that is central to the *o* construct. This is especially true for those tests that aim to measure visual memory in children. Picture recognition tests also tend to have low or no loadings onto *Gv*, the broad ability they are intended to measure. Caemmerer et al. (2020) conducted a cross-battery CFA using six intelligence batteries. The Woodcock-Johnson III (Woodcock et al., 2001) Picture Recognition test loaded onto learning efficiency (*Gl*) and did not significantly load onto *Gv*, while the Recognition of Pictures test loaded .44 onto *Gv*.

Visual Memory vs o If a visual memory test uses complex stimuli that require fine-grained discrimination, these tests may measure an ability that is close to *o*. When multiple such tests are combined, the ability measured may also be domain general. However, in general, visual memory tests do not require fine discrimination at the subordinate level. Another difference between *o* and visual memory is that the latter is not concerned only with objects, but complex visual stimuli of any kind, including scenes and memory for spatial location. Recent work has related *o* to the ability to recognize images of prepared food, which are more like scenes than objects (Gauthier & Fiestan, 2023; Sun & Gauthier, 2023), but it is not clear whether these are truly dissociable abilities or if they reflect a single more general ability. Complicating the comparison with *o* is the wide range of existing definitions of visual memory. Some authors have suggested that visual memory is limited to the recognition of objects that have been stored in memory for under around 30 seconds (Schneider & McGrew, 2018), whereas others have defined a visual memory factor using tests that require memory over longer periods (e.g., H. P. Kelley, 1964; Stumpf et al., 2013; T. G. Thurstone & Thurstone, 1949). Although memory is central to the visual memory construct, the essential element of the *o* construct is that it requires fidelity of object representations for dimensions that separate the object from other similar objects. If the representations of similar objects are precise and rich in detail, especially for those details that best distinguish objects from one another, this should allow for good performance on *o* tests. If these representations are strong initially (during encoding), they should be less likely to be confused when tested later on. For visual memory, the fidelity of the representation is likely less important, but the strength of the memory signal over time is likely to be key. Tests of *o* have been designed to vary in their requirements for memory**.** The majority of visual memory tests included in major batteries require short-term memory for either objects or other visual stimuli, and without difficult perceptual discrimination. A goal of future research may be to examine the degree of relationship between *o* and visual memory tasks.

Visual working memory. Although there is no empirical evidence exists regarding the relationship between *o* and visual memory tests, some research has investigated the relationship between *o* and visual working memory. Some consider the visual memory factor to be different from visual working memory (Schneider & McGrew, 2018). For example, the WMS-IV contains separate visual memory and visual working memory subscales. The relevance of these findings to the relationship between *o* and visual memory is unclear. However, some tests that are supposed to be tests of visual memory are also claimed to measure aspects of visual working memory (e.g., Picture Recognition in the WJ-IV; Schrank et al., 2016; Schrank & Wendling, 2018), so the distinction between visual working memory and visual memory has not always been adhered to in theory or in test design. Richler et al. (2019) found that visual short-term memory capacity, measured by a change detection task, accounted for little of the relationship between recognition abilities for different object categories. Other evidence suggests a moderate relationship between *o* and visual working memory capacity; Chang and Gauthier (2021) found correlations between an aggregate measure of *o* and working memory capacity for musical notes (*r* = .46; *r* = .54 corrected for error) and for colors (*r* = .4; *r* = .45 corrected for error). Although visual working memory *capacity* is clearly dissociable from *o*, no research has investigated the relationship between visual working memory *precision* and *o*. The precision and the capacity of working memory are separable (Awh et al., 2007; Fukuda et al., 2010). Given the requirement for fine perceptual discrimination in *o* tests, the precision of working memory might have a closer relationship with *o* than working memory capacity has.

Visualization. Another narrow ability that falls under *Gv* and may be related to *o* is *visualization*. Visualization concerns perception of complex patterns and mental simulation of transformations, such as rotation and changes in size (Flanagan & Dixon, 2014)**.** Of all the abilities under *Gv*, visualization loads onto it to the greatest extent (Carroll, 1993; Lohman et al., 1987). L. J. Burton & Fogarty (2003) conducted a confirmatory factor analysis of a large test battery of spatial ability and visual imagery tests. Visualization had a loading of .91 onto the *Gv* factor. In comparison, the visual memory factor, which was measured using the three tests included in Ekstrom et al.'s (1976a) kit, had the lowest loading onto *Gv* (.56) of the included spatial abilities. Despite the clear distinction between visualization and visual memory, many tests have historically conflated the two abilities. Some early tests of recognition required the identification of objects across large spatial rotations**,** such as *Visual Memory* in the Army Air Forces Sheppard Field Battery (Guilford et al., 1952).

One reason to expect some relationship between visual *o* and visualization is that the 3AFC MA and the LE tests of *o* include trials on which the target object has been rotated, both as a method of increasing difficulty and as a way of ensuring that participants make judgments about objects rather than pictures. However, the rotations employed in these tests are small (e.g., 30 degrees), so such trials are unlikely to heavily require visualization. Smithson, Chow & Gauthier (2024) examined the relationship between *o* and *Gv*, using spatial tests that primarily required visualization (*Paper Folding*, *2D Rotation*, *3D Rotation*). A large relationship between visual *o* and *Gv* was found at the latent level (*r* = .74; Smithson, Chow & Gauthier, 2024). However, the estimated relationship was no larger than the relationship between visual *o* and an auditory *o* ability (*r* = .8), or between auditory *o* and *Gv* (*r* = .69). The relationship was also similar in size to the relationship between visual *o* and *g* (*r* = .71), as measured by a Raven's matrices task, a grammatical reasoning task, and a number series task. When *g* was partialed out, the relationship between visual *o* and *Gv* was no longer significant. However, the extent of the residual relationship between visual *o* and *Gv* was difficult to precisely estimate due to the extremely close relationship between *g and Gv* (*r* = .94). Although there is clearly a strong relationship between *o* and *Gv*, and therefore visualization also, it is unclear whether this relationship exists independently of a shared relationship with *g.* The fact that the relationship between *Gv* and auditory *o* was so high suggests that it may not.

Relations between *o*, face recognition, and other domain-specific recognition abilities.

Although some abilities share similarities with *o*, especially those falling under *Gv*, no abilities within CHC are theoretically synonymous with *o*, as they do not require fine subordinate-level discrimination. In line with our reasoning that *o* appears most similar to the narrow abilities under *Gv,* it has previously been suggested that face processing might fit into the CHC model under *Gv* (Walker et al., 2023). The possible existence of a face processing factor (e.g., detection, memory, perception) has been proposed on the basis of correlations between face processing tasks (Verhallen et al., 2017; Wilhelm et al., 2010). Due to the finding that different tasks using different familiar object categories lead to the same *o* as is measured with novel objects (Sunday et al., 2022), we might expect face recognition to be very closely related to *o.* However, face recognition appears to be a relatively special category with respect to individual differences. Of course, there are an infinite number of different familiar categories, most of which we have no data for, and the pairwise correlations between them certainly vary (McGugin et al., 2012). But for a number of reasons[2], we have more data on individual differences with face tasks than any other domain. It is therefore interesting to consider how face recognition, which like *o* requires subordinate-level discrimination, has been positioned within hierarchical models of abilities. Wilhelm et al. (2010) showed that three differentiable face cognition abilities, detection, perception, and memory, are distinct from immediate and delayed memory, general cognitive ability, and mental speed. Face cognition abilities were suggested to be facets of social and emotional intelligence abilities. This point of view has also been advanced by Meyer et al. (2021). Some authors have also suggested that there is little influence of general cognitive ability on face recognition ability (Wilmer, 2017; Wilmer et al., 2014). However, based on a meta-analysis, Walker et al. (2023) found that face processing

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[2] Some of which theoretical, because face recognition is assumed to be especially important, or supported by a special mechanism, but others more practical, because faces are well-behaved complex visual stimuli for experimental purposes.

abilities are positively correlated with intelligence. The correlation between face recognition and intelligence was estimated to be *r* =.41, when only studies using excellent measures of intelligence were included. Walker et al. identified *Gv* as the broad ability with the closest theoretical relationship with face processing. It is interesting to note that a test of face recognition was removed in the fourth edition of the Wechsler Memory Scale (Weschler, 2009) because it failed to correlate substantially with other tests of visual memory (Tulsky & Price, 2003). As such, empirical evidence for a close relationship with the most theoretically similar narrow abilities under *Gv* is lacking.

If we did not have more data available for faces than for any other specific domain, in the context of a discussion of *o*, faces may not appear so special. We would expect that different tasks would correlate more highly if they all use the same category. Likewise, different tasks with food are used to measure food-recognition ability (e.g., Gauthier & Fiestan, 2023) or different tasks with musical notation are used to measure a music reading ability (Chang & Gauthier, 2021). In both such examples, *o* was also measured (with novel objects) and it was concluded that it explained some, but not all, of the variance on these tasks. In other words, performance with factors denoting abilities for specific object domains (including faces, see Richler et al., 2019) is in part accounted for by a domain-general ability, *o*, and in some part by domain-specific influences (these are typically related to experience when they are explained).

A single task measuring face recognition would be conceptually expected to be related to general intelligence, to *o,* and to a face-specific ability – this simply follows from conceiving of these abilities as organized in a hierarchical framework. Measure development involves minimizing the overlap between a construct and ‘sibling constructs’ (Lawson & Robins, 2021).

Ideally, our understanding of what *o* is will progressively build on better measures that target its core features rather than intelligence or experience in specific domains. In practice, removing the contribution of domain-specific influences is much easier. At the single task level, it can be achieved through the use of novel objects and at the factor level, via the use of a set of indicators from a varied number of familiar domains (e.g., Sunday et al., 2022). Domain-general influences are more difficult to remove at the task level – they generally must be partialed out.

Do face recognition tasks have more important contributions from domain-specific influences than tasks from other domains? And, as a corollary, are they poorer indicators of o than measures using other kinds of objects? The empirical relationship between *o* and individual face recognition tests is moderate; Richler et al. (2019) identified a correlation of *r* = .28 between latent *o* and the CFMT after correcting for measurement error. One explanation for this weak relationship may be that humans have extremely high levels of experience with faces, making faces more unique than most other object categories (Sunday et al., 2019). In further support of this view, car recognition also shows a smaller relationship with *o* than other object categories do (*r* = .27; Richler et al., 2019, also see Ćepulić et al., 2018). These findings are expected given earlier work suggesting that face and car recognition correlate with other object categories to a lesser extent (McGugin et al., 2012; Richler et al., 2017)**.** However, analyses using latent variables based on multiple tests of recognition for faces and cars would likely find a higher relationship with *o* than analyses using a single measure.

One view of face and car recognition is that they could be conceived of as crystallized measures of object recognition ability, wherein the fluid ability, *o*, has contributed to expertise with a specific category, much akin to how fluid intelligence has been theorized to give rise to crystallized intelligence through repeated investment (R. B. Cattell, 1963; Hebb, 1942; Horn & Cattell, 1966). To be clear, a small or moderate amount of experience with an object category does not appear to strongly influence individual differences (Richler et al., 2019; Sunday et al., 2022). However, the influences on individual differences for objects for which people may have a lifetime of experience individuating could differ substantially from those that affect performance with other objects. Such a theoretical distinction between fluid and crystallized object recognition ability might only exist at very high levels of experience, but this proposition has not been tested experimentally (nor is it clear whether such a high level of experience can feasibly be obtained in the laboratory).

***O* in relation to CHC Theory.** Firm conclusions on where *o* would fit best into CHC require factor-analytic research with a large battery of ability tests so that alternative models can be compared. Future research could explicitly test the relationship between *o* and narrow *Gv* abilities, such as visual memory and visualization, as well as abilities from other broad factors. However, the challenge of answering this question is greater than a lack of data and also lies with limitations of the CHC framework. Despite the widespread reliance on CHC theories for the construction of psychometric test batteries, these theories have received substantial criticism (Canivez & Youngstrom, 2019; McGill & Dombrowski, 2019; Wasserman, 2019). Failures to replicate the factor structure of cognitive abilities in data from psychometric batteries whose designs were based on CHC are challenging to this theory, with exploratory factor analyses suggesting alternative structures and confirmatory factor analyses yielding poor fit statistics (Dombrowski, 2013, 2014a, 2014b; Dombrowski et al., 2017, 2018; but see Caemmerer et al., 2020 for conflicting results).

Whether or not the existing CHC theory represents the best organization of cognitive abilities, some theoretical ideas that have informed the development of the taxonomy are useful in conceptualizing *o.* Acknowledgement of the hierarchical nature of abilities can inform research investigating *o*'s utility in predicting criterion variables. This theoretical understanding encourages the partialing out of *g* or other abilities from *o*'s relationship with a criterion and thus facilitates interpretation. Some studies of *o* have used an aggregate measurement approach, wherein scores for multiple tests are combined to decrease the proportion of variance due to method variance and non-construct factors (Smithson, Chow, Chang, et al., 2024). Because test performance is composed of common and specific variance, all tests of the same construct should contain construct variance and test-specific variance. When increasingly diverse tests are selected, shared method variance between the tests is limited such that aggregation will increase the ratio of construct-related variance to specific and error variance. However, because *g* also permeates all cognitive ability tests, this process will increase the proportion of variance attributable to *g* (Lubinski, 2004). The domain-generality of *o* makes the issue particularly acute. For these reasons, it is useful to measure *g* alongside *o* when predicting a criterion so that the influence of *o* can be isolated. Ideally, latent-variable models can be used to properly control for the confounding construct and for measurement error (Cole & Preacher, 2014; Westfall & Yarkoni, 2016).

As the general factor explains a substantial amount of variance in all kinds of aptitude tests, it predicts a range of real-world outcomes. Cognitive ability strongly predicts occupational success (Hunter, 1986; Hunter & Hunter, 1984) and strongly relates to educational attainment (Deary et al., 2007). Specific abilities usually contribute little to occupational outcomes beyond the influence of *g* (Ree & Carretta, 2022; Ree & Earles, 1991; Schmidt & Hunter, 2004). Relatedly, concerns about CHC from applied practitioners include the limited incremental validity over *g* that is provided by using broad and narrow factors in predicting criterion variables (Benson et al., 2016; McGill & Busse, 2015), and the often limited reliability of cognitive ability profiles (Watkins, 2017; Watkins & Canivez, 2004; Watkins & Smith, 2013). To the extent that such concerns are warranted, these issues are likely to also apply to *o*. However, specific abilities might still contribute beyond *g* when the criterion is of greater specificity (Nye et al., 2020). Evidence from education research also suggests that while *g* explains most variance, specific factors can predict additional variance in specialized subject areas (Canivez, 2013; Nelson et al., 2013; Pokropek et al., 2022). Some authors have called for researchers to search for constructs that have greater independence from *g* such that there is greater opportunity for independent predictive power (Nye et al., 2020).

For this reason, it is useful to establish how closely related *o* is to *g*. Early evidence suggested a small relationship between individual tests of object recognition and measures of intelligence. Richler et al. (2017) found a correlation of $r = .3$ between the average of NOMT performance using multiple object categories and a matrix reasoning test. Almost none of the covariance between NOMTs using different object categories could be explained by scores on tests of matrix reasoning and vocabulary, or the SAT. Chang & Gauthier (2021) found a correlation of $r = .31$ ($r = .41$ corrected for error) between an aggregate measure of *o* and Raven's Matrices, while Chow et al. (2022) found a correlation of $r = .16$ ($r = .22$ corrected for error) in a similar analysis. Latent variable analyses have found higher correlations. In study 2 of Richler et al. (2019), participants were tested on multiple object recognition tasks using two object categories in addition to three fluid intelligence tests, Raven's Advanced Progressive Matrices, Number Series, and Letter Sets. A structural equation model suggested that the correlations between fluid intelligence and recognition ability with single categories were moderate (*r* = .57 & *r* =.46), while 71% of the covariance between performance with different categories was independent of intelligence. Unpublished modeling results from Chow, Palmeri, Pluck, et al. (2023) suggest a correlation of *r* = .54 between *o* and a matrix-based test of fluid reasoning and semantic knowledge. The highest relationship between *o* and *g* was found by Smithson, Chow, & Gauthier (2024), who used three fluid intelligence tests: a short adaptation of Raven's Matrices, Number Series, and a Grammatical Reasoning task. The relationship between *o* and *g* was *r* = .71. When visual and auditory *o* abilities were modelled as being caused by a higher-level multimodal *o*, this multimodal ability correlated very strongly with *g* (*r* = .80). Adequate measurement of *g* is necessary to obtain accurate correlational estimates, and quality generally increases as a greater number of tests that tap into different broad abilities are used (Gignac & Bates, 2017). The higher estimate from Smithson, Chow, & Gauthier (2024) is likely to be the most accurate due to superior measurement and larger sample size, and *o* should probably be considered as having a strong relationship with *g*. The size of the relationship is closer to what is typically found for broad abilities than for narrow ones. Similarly high relationships with *g* can be found for other constructs (e.g., spatial ability, working memory, attentional control) that occupy important places in cognitive theories (Burgoyne et al., 2022, 2023; Colom et al., 2004; Kyllonen & Christal, 1990).

The existing body of research into individual differences in cognitive abilities can also inform us about some of the likely causes of individual differences in *o*. Strong evidence from behavioral genetics suggests that genetics can explain a substantial portion of the variance in both general and specific abilities, including when the general ability has been partialed out of the specific abilities (over 50%; Plomin et al., 2016; Procopio et al., 2022). To understand how heritable *o* might be, analyses of the heritability of similar traits can be informative. The authors of one twin study explicitly claimed to assess the heritability of object and face recognition using the CCMT and the CFMT (Shakeshaft & Plomin, 2015). The heritability of both car and face recognition was high ($h^2 = .58$ for cars, $h^2 = .60$ for faces), and higher than for *g* in this sample, while the influence of shared environment was minimal. Because *g* contributes to all cognitive abilities, some of the heritability in cognitive abilities can be attributed to the heritability of *g*. Multivariate genetic analyses can be used to estimate the proportion of heritability in a trait that can be explained by genetic effects that are shared with another trait. Only 10% of the heritability of performance in the CCMT was explained by genetic influences shared with *g*. However, object recognition measured by a single test is likely to have a smaller *g* component than object recognition ability measured by several tasks, so the shared genetic influence between *o* and *g* could be substantially higher. Other studies have also supported the conclusion that face recognition has substantial heritability (Wilmer et al., 2010; Zhu et al., 2010). Although there are no extant data on the heritability of *o*, its place in a hierarchical model of abilities lies in between *g* and domain-specific abilities such as face recognition and car recognition, which suggests that *o* is also likely to be highly heritable.

Structure-of-Intellect Model – Memory and Evaluation for Figural Units

The structure-of-intellect (SOI) model was developed by Guilford (1959) as a taxonomy of cognitive abilities. In its original and non-hierarchical version, 120 proposed factors were supposed to lie at the intersections of five kinds of operations (cognition, memory, divergent production, convergent production, and evaluation), four kinds of content (figural, symbolic, semantic, and behavioral), and six kinds of products (units, classes, relations, systems, and implications). Although the model was once influential (Sternberg & Grigorenko, 2001), it was criticized for its rigidity, its expansive number of proposed factors (Cronbach & Snow, 1977), and the inadequacies of the factor-analytic evidence supporting it (Horn & Knapp, 1973, 1974; Undheim & Horn, 1977).

Among the plethora of abilities proposed by SOI, two appear relevant to *o*. One is memory for figural units (MFU), which concerns memory operations with unit-level figural content (i.e., content that is sensorily perceivable). Being a unit ability, it concerns memory for individual objects. Consequently, some proposed tests of this ability require subordinate-level, rather than basic-level, discrimination; if the objects to be remembered were from different categories, measurement would be confounded by memory for figural classes. Bradley et al. (1969) investigated SOI figural-memory abilities and included five proposed tests of MFU in a factor-analytic study of 52 tests. *Figural Letter Recognition* requires participants to examine a page of scattered letters, each a different letter and printed in a different style. During test, each study letter appears among four variants printed in subtly different styles. *Figure Recognition* requires participants to study detailed geometric figures. During test, these figures appear among an equal quantity of new figures; examinees select the figures they recognize. There is also a recall variant of this task. *Object Recognition* requires participants to study 15 drawings of familiar objects (e.g., sunglasses, bowties). In the four-alternative forced-choice test trials, each target object is presented alongside variants of the same kind of object. *Remembering Faces* is a recognition test for face drawings.

Five tests were identified as having loadings > .30 onto an MFU factor. These were Figure Recognition (.57), Remembering Faces (.52), Figural Letter Recognition (.46), Object Recognition (.36), and two tests that had initially been proposed as measures of other factors. *Recognition of Figural Classes* (.44) was designed as a test of memory for figural classes, while *Remembering Hand-Object Pairs* (.40) was designed as a test of memory for figural implications and is a paired-associations memory test. Bradley et al. (1969) suggested that the Remembering Hand-Object Pairs test may have loaded onto MFU because the items were difficult to discriminate in memory. Hand-Object Pairs not only requires association memory, but also discrimination between drawings of different hands and objects at a subordinate-level. It was also suggested that Recognition of Figural Classes could rely on memory for individual figures, albeit visually dissimilar ones. The only one of the five intended MFU tests that did not load onto this factor was the *Figure Recall* test. Bradley et al. (1969) speculated that this may have resulted from the simplicity of the stimuli, which may have allowed them to be memorized as separate classes. Sample stimuli included in the published report suggest that Figural Letter Recognition, Object Recognition, and possibly Remembering Faces require sufficiently subordinate-level discrimination to measure *o*, while stimuli in the other MFU tests appear more readily discriminable.

Bradley et al. (1969) recommended that the Figure Recognition, Remembering Faces, and the Figural Letter Recognition tests should serve as measures of MFU in future research. Two of the selected tests include stimuli with which people have exceptional levels of experience, letters and faces, which may make these tests less effective at measuring a domain-general ability. These recommendations are in contrast to recommendations by Guilford & Hoepfner (1966) that *Reproduction of Designs*, in which examinees reproduce geometric designs, and the Map Memory test from Guilford & Lacey (1947), be used as measures of MFU. These two sets of tasks differ substantially, and only the ones recommended by Bradley et al. (1969) might be said to involve subordinate-level discrimination approaching the kind that *o* theoretically involves. Most tests that have been used to measure MFU do not require subordinate-level discrimination, and it is not central to the definition of the construct. Guilford & Hoepfner (1966) associated MFU with visual memory when they mapped SOI abilities to their common names.

The utility of Bradley et al.'s (1969) analysis is limited by the use of orthogonal factor rotation methods, as was common practice in early SI research, preventing analysis of correlations between factors and the extraction of higher-order group or *g* factors. Guilford’s model never did accommodate Spearman’s *g* (Carroll, 1997), although he later came to accept that the SI factors should be oblique and that higher-order factors could be extracted (Guilford, 1981). An additional concern is that the factor rotation in Bradley et al. (1969) was performed to achieve maximal congruence with a target matrix (Cliff, 1966). SOI research was frequently criticized for this practice, as, although it aided in interpretation, the practice limited opportunities for the model to be falsified. Horn & Knapp (1973) demonstrated that target matrices determined in a random manner produced factors with substantial test loadings as often as target matrices based on the SOI model, while Undheim (1979) suggested that Bradley et al. (1969) had capitalized on chance and failed to find the same factors when reanalyzing their data. Carroll (1993, p. 283) also reanalyzed this dataset and did not find evidence of the six figural memory abilities claimed to be identified by Bradley et al. (1969). Instead, he reported that many of the recall and recognition tests loaded onto a more general memory factor, and to a smaller degree onto a visual memory factor, while most tests in the dataset loaded onto a *Gv* factor.

The other SOI ability with similarities to *o* is Evaluation of Figural Units (EFU), which has been defined as 'the ability to judge quickly and accurately units of figural information as being similar or different based upon minor aspects of the information' (Guilford & Hoepfner, 1966, p. 12). Recommended tests for this ability are L. L. Thurstone's (1938) Identical Forms and the *Guilford-Zimmerman Perceptual Speed* test (Hoepfner et al., 1964). Both tests are comparing-perceptual speed tests, which tend to correlate highly with *o* tests. Unlike *o* tests, the forms are readily discriminable, as L. L. Thurstone (1950, pp. 517-518) noted, 'Everyone can do this easily'. When defined by these tests, EFU can be considered synonymous with comparing-perceptual speed (Guilford & Hoepfner, 1966). However, Guilford (1972) argued that level and speed tests of EFU loaded onto the same factor, based on the results of Hoffman et al. (1968). In this study, three tests loaded onto the EFU factor. Once again Identical Forms (.48) was used, while the other two were not primarily speed tests. In *Judgment of Size* (.60) a geometric figure was compared with four surrounding figures that had the same shape but differed only in size. The examinee had to judge which figure was the same size as the target. *Judging Figural*

Combinations (.43) required the examinee to decide which of five squares contained all of the same small geometric figures as were in a target set. The figures could differ in position but had to be of the same size and shape as the target ones. The factor rotation in this study was also performed to maximize congruence with a target matrix. These results were taken as evidence that EFU could more appropriately be described as 'perceptual accuracy' than 'perceptual speed' (Ingebretsen, 1969). However, even the non-speeded tests do not closely resemble *o* tests, as they do not require subordinate-level discrimination based on small variations in object features that are arranged in a consistent configuration across objects. Consequently, these level ability tests do little to bridge the gap between EFU and *o*. However, Guilford (1972) suggested that the Visual Memory task from L. L. Thurstone (1949; figure 6), which is highly comparable to *o* tests, is probably a measure of EFU.

The figural content factors were later split into separate visual and auditory content domains (Guilford, 1971, 1988), in recognition that such abilities have a degree of modality-specificity. This produced separate visual and auditory MFU and EFU factors (MFU-V; MFU-A; EFU-V; EFU-A). Additional tests were designed to measure these auditory factors, and they differ substantially from tests used for auditory *o*. For example, Feldman (1970) created an auditory discrimination test requiring matching of phonemes to measure EFU-A, whereas MFU-A was measured with an auditory letter memory task and a digit span task that would now be considered a measure of working memory. In summary, MFU-V tests such as Figure Recognition are similar to *o* tests, whereas most are closer to visual memory. EFU-V tests are generally tests of comparing-perceptual speed, and the MFU-A and EFU-A tests bear little resemblance to auditory *o* tests.

Neuropsychological tests of Object Perception and Recognition

Neuropsychologists develop tests of cognitive abilities to identify impairments in functioning. The short history of individual differences testing in high-level vision was strongly influenced by neuropsychological tests and specifically motivated by their inadequacy for use in normal populations (e.g., Duchaine & Nakayama, 2006). Neuropsychological tests tend to have ceiling effects when used in the normal population, both patients and control participants can often use alternative test strategies to achieve scores in the normal range, and a perfect score on any one of these tests does not necessarily mean that a function is 'normal' (Duchaine & Weidenfeld, 2003). Many of the abilities measured by neuropsychological tests correspond to those measured by cognitive ability tests. This similarity has even led some researchers to attempt to integrate tests of cognitive abilities and neuropsychological tests within a single framework (Miller, 2013; Miller & Maricle, 2018).

Tests for visual impairments. Visual agnosia describes a general impairment in object recognition (Biran & Coslett, 2003; Devinsky et al., 2008; Farah, 2004). However, there are also domain-specific visual impairments, the most famous being prosopagnosia, which has an acquired and a developmental form (Corrow et al., 2016) and is often considered a specific impairment with face recognition (but see: Bukach et al., 2012; Geskin & Behrmann, 2018). Research into agnosia has generated multiple tests and even test batteries for both object and face recognition. These tests were precursors of tests designed for research into domain-general recognition (McGugin et al., 2012; Richler et al., 2017). A non-exhaustive list includes the CFMT, the CCMT (Dennett et al., 2012), the *Cambridge Bicycle Memory Test* (Dalrymple et al., 2014), the *Warrington Recognition memory for Faces Test* (Warrington, 1984) and the *Easy Recognition*

Memory tests for buildings and faces (Clegg & Warrington, 1994). Many tests of face matching also exist (e.g., Benton & Van Allen, 1968; A. M. Burton et al., 2010; Fysh & Bindemann, 2018; Stantic et al., 2021; White et al., 2022). Many of these individuation-based tests should probably be considered valid tests of *o* if used in conjunction with other tests that use different object categories and different task formats. Other neuropsychological tests do not require subordinate-level discrimination but may measure abilities that have similarities with *o*. Some of these measures are worth examining.

One battery that has received widespread use is the BORB (*Birmingham Object Recognition Battery*; Riddoch & Humphreys, 1993), which consists of 14 tests. Several tests require perceptual similarity judgements of simple stimuli along a single dimension of low-level vision (e.g., length, size), such as *Length Match Task, Size Match Task,* and *Orientation Match Task*. These tests could have some relation to *o* due to their requirement for perceptual precision. Existing evidence suggests that *o* is correlated with tasks that require perceptual judgments along a single dimension. Smithson, Chow, Chang et al. (2024) found a sizeable correlation of r = .45 (r = .50 corrected for error) between an aggregate measure of *o* and the Hanover Early Vision Assessment (HEVA; Kieseler et al., 2022), which was designed to measure the same ability as the low-level perceptual matching tasks in the BORB. This suggests that visual *o* relies in considerable part on low-level visual perception. Some BORB tests require recognition across different viewpoints or require access to stored knowledge, such as the *Minimal Feature View Task*, the *Foreshortened View Task*, and the *Object Decision Task*. In both the Minimal Feature View Task and the Foreshortened View Task*,* examinees are shown a target object and two others that are possible matches with the target. The matching object is shown from a different viewpoint from the target. The other object is visually similar to the target object, but of a different identity. The Object Decision Task uses line drawings of animals and tools, some of which are real, and some of which are not. The non-real objects were created by switching heads and bodies of real objects. Examinees decide if the object could exist in real life, which requires them to match the visual representation of the object with stored representations of existing objects. Although both the minimal feature view task and the foreshortened view task require perceptual discrimination of complex objects, these perceptual discriminations are easy for examinees without impairments. Additionally, these tests use simultaneous presentation and do not test memory. The object decision task does require memory, but not for fine-grained perceptual detail as *o* tests would require. Instead, it relies on memory for semantic knowledge about the kinds of features an object should have. Indeed, patients with semantic dementia have shown impaired performance on this task (Hovius et al., 2003). Another test with similarities to *o* tests is the *Item Match Task*, which presents a target object, such as a chair, and asks examinees to select from two other objects the one that is from the same category as the target (i.e., another chair). However, this is a test of basic-level categorization, and so does not require discrimination at the subordinate level using fine perceptual detail, as *o* tests do.

Another widely used battery is the *Visual Object and Space Perception* battery (VOSP; Warrington & James, 1991), which consists of eight tests. The *Silhouettes* task requires that examinees identify common objects in unusual perspectives. Half the objects are animals, while the other half are inanimate objects. *Progressive Silhouettes* is similar, but in this test the object is first shown at a 90-degree lateral view and is then shown in progressively smaller rotations until it is displayed in the full-frontal view. Examinees who recognize the objects earlier have better scores. However, this test only uses two objects: a gun and a trumpet. *Object Decision* is of a similar design to the object decision task in the BORB. As with other neuropsychological tests, the VOSP suffers from ceiling effects in normally functioning samples (Rapport et al., 1998). None of the tasks in the VOSP concern subordinate-level discrimination. Instead, they require basic-level categorization, limiting their similarity to *o*.

The *NEPSY-II* (Korkman et al., 2007) is designed for children aged 3-16 years and includes two tests that asses memory for designs, one version for short-term memory and the other for long-term memory. There are also tests for short-term and long-term recognition of faces. While these tests are aimed at identifying deficits in functioning among children, the tests in the NEPSY-II capture variability across the low and high end of test-takers. Unlike in some other batteries of cognitive ability tests, the recognition tests in the NEPSY-II are considered subtests in the memory and learning domain, rather than subtests in the visuospatial processing domain. In *Memory for Designs*, examinees view a four-by-four grid containing various abstract designs. After this, examinees must select the cards that contain these same designs and place them in the correct locations. In *Memory for Faces*, examinees are first shown pictures of children's faces, and then have to select the ones they have previously seen from sets of three faces. Correlations between short and long-term versions of these tests are moderate, while the intercorrelation between memory for designs and memory for faces is only small (r = .18; Brooks et al., 2009), suggesting limited overlap between these two tasks. Although each test uses only a single object category, the combination of scores for long-term and short-term recognition tests may measure a domain-general ability. Although not a standard method of scoring, the aggregates could themselves be aggregated across both memory for faces and memory for designs, to further increase generality of the measured ability. Although the use of only two object categories can produce relatively accurate estimates of *o* (Smithson, Chow, Chang et al., 2024), this may not be the case when one of the categories is as unique from other categories as faces are (McGugin et al., 2012; Sunday et al., 2019).

Other tests used for clinical diagnosis include the *Benton Visual Retention Test* (BVRT; Benton, 1945) and the *Benton Visual Form Discrimination Test* (VFDT; Benton et al., 1994). The BVRT requires recall for a set of geometric figures. A multiple-choice version (BVRT-MC) requires examinees to examine the figures, and, after a short delay, to choose from four options the one that shows each figure in the correct orientation and without distortions (Benton et al., 1977). Education and IQ positively predict BVRT-MC scores, whereas age negatively predicts scores (Le Carret et al., 2003; Miatton et al., 2004; Wagner, 1992). Like *o* tests, the BVRT-MC requires discrimination of stimuli based on memory. However, it requires decisions according to both orientation and features. It is not clear how closely such a test would correlate with *o,* which typically relies on tasks where orientation is a feature to be ignored. The VFDT uses the same stimuli as the BVRT-MC, except that the target stimulus is displayed simultaneously with the multiple-choice alternatives, assessing perceptual discrimination rather than memory. The VFDT has ceiling effects in non-impaired populations (Campo & Morales, 2003; Lopez et al., 2005; Malina et al., 2001).

Tests of memory impairments. Tasks that appear similar to *o* tests can also be found in the literature concerning the neural bases of recognition memory in animals (Buckley et al., 2001) and human patients (Behrmann et al., 2016). Traditionally, perception and memory have been considered to rely on distinct but strongly connected neuroanatomical areas. The medial temporal lobe (MTL), a set of interconnected structures including the hippocampus, the perirhinal cortex (PRC), the entorhinal cortex, and the parahippocampal cortex, are considered to play a crucial role in long-term declarative memory (Squire et al., 2004; Squire & Zola-Morgan, 1991). The ventral visual stream (VVS), a hierarchically organized pathway from the visual cortex to the inferior temporal cortex, is considered to play a crucial role in visual perception (Goodale & Milner, 1992; Milner & Goodale, 2008). In contrast to this view, the representation-hierarchical model (Cowell et al., 2010; Murray & Bussey, 1999) argues that perception and memory depend on the same representations (Khan et al., 2011; Martin & Barense, 2023; Murray et al., 2005). Similar to other influential theories in vision (Ahissar & Hochstein, 1997; Riesenhuber & Poggio, 1999), it suggests that increasingly complex representations, from early vision to the hippocampus, support increasingly difficult tasks (regardless of whether the task is perceptual or mnemonic). Critical evidence comes from damage to an area late in this stream, the perirhinal cortex (PrC), which results in both memory and perceptual deficits, as long as the task has high feature ambiguity (FA; Barense et al., 2007; Bussey et al., 2002). FA is deemed high when items can only be discriminated through feature conjunctions rather than on the basis of simple features (Bussey et al., 2002). At least on the face of it, tasks with high FA appear to require the kind of subordinate-level judgements of complex novel objects that are required in *o* tasks.

FA is influenced by properties of a stimulus set. For example, wading birds and perching birds can be distinguished by length of legs, but two perching birds may only be distinguished by subtle differences in several features, so the latter distinction has higher FA. Although high FA tasks are generally more difficult than low FA tasks, one can create a difficult task that has low FA if the judgment relies on a single feature with values that are difficult to discriminate. For instance, in Smithson, Chow, Chang et al. (2024), two different oddball tasks can be compared: the MOO task, which is a high FA test using complex objects that vary on multiple dimensions, and the HEVA battery, which is a low FA test using simple objects that is difficult because it requires high precision on a single visual dimension at a time. These two tests were correlated ($r = .24$; $r = .31$ corrected for error) but were still very distinct despite similarity in task design. One aspect of *o* tasks highlighted here is the uncertainty of the dimension that is relevant on subordinate-level judgments – people with high *o* may not only be able to encode and access precise features, but they may be good at comparing objects (or objects and their representations) on several features, efficiently.

A recent fMRI study related *o* scores to neural sensitivity to small differences in complex objects. McGugin et al. (2023) measured neural sensitivity to visual information in an fMRI adaptation design in which participants attended to the size changes of complex novel objects. In some blocks, an object was shown repeatedly, with minor rotations across presentations, and in other blocks, the object would be alternated with another similar, but distinct, object. The difference between these objects was not task-relevant, and each block used a completely different category of objects, with no indication of the feature(s) along which the two objects would differ. The analyses assessed which of the brain areas that were sensitive to these visual changes were the most predictive of *o* scores. These neural correlates of *o* were distributed across several areas of the visual system, from the lateral occipital cortex, to the fusiform and parahippocampal gyrus. In contrast to predictions of the representation-hierarchical model, the relationship was not strongest in the PRC compared to earlier visual areas. A broad set of regions was related to *o,* and all of them can become specialized for categories which a person has expertise with, depending on the specific kind of expertise that is gained (A. C.-N. Wong et al., 2009; Y. K. Wong et al., 2012). It is possible that conclusions from the representation-hierarchical model, which in humans has been mainly tested in comparisons between normally functioning adults and those with severe impairments, are not very informative about the most relevant neural variability in the normal population. In contrast, the broad network of visual areas related to *o* in McGugin et al. (2023) was strikingly similar to the pattern of brain activation that is recruited in normal participants when comparing images that show 'minimal recognizable configurations' to very similar images that cannot be recognized easily (Holzinger et al., 2019). These minimal recognizable configurations have been proposed to be critical mid-level features that function as the atoms of object recognition (Ullman et al., 2002, 2016). It is reasonable to expect that the areas most engaged when people with high *o* look at complex objects (McGugin et al., 2023) would be the same areas that contain the best features for complex object recognition (Holzinger et al., 2019).

Currently, there are very few fMRI studies that address domain-general abilities like *o* – most of this field has been dedicated to exploring category-specific, feature-specific, and task-specific distinctions. The large literature that highlights the different patterns of activation for categories, tasks, and features (Weiner et al., 2018) is difficult to apply to a general ability like *o*. The same can be said of the extensive body of work on the neural bases of domain-specific expertise (Bukach et al., 2006; Gauthier, 2017). This represents an area ripe for exploration.

General Discussion

This review sought to answer several questions. The most central is whether there are existing constructs that are similar to *o*. Several such constructs exist. As *o* was directly inspired by research in vision science and neuropsychology into domain-specific recognition abilities, the abilities that have been studied in these fields naturally have a close conceptual relationship with *o*. Vision scientists and neuropsychologists have often tested object recognition with a single category and simply assumed that the ability being tested is general. However, using a single task with a single object category is unlikely to provide an adequate measurement of *o*, even though it taps into it. This is particularly likely to be the case when participants have varying levels of experience with the object category, as this provides an additional source of individual differences. Research from forensic psychology into object matching captures a construct that may also be very similar to *o,* as it requires subordinate-level discrimination of visually similar objects (Growns et al., 2024). However, *o* is broader than just matching ability, so there is a clear theoretical gap between these abilities, although the empirical distance is still to be determined.

Perceptual speed/EFU shares with *o* a requirement for perceptual differentiation. However, it primarily concerns the speed of discrimination rather than its difficulty, whereas *o* concerns discrimination of visually similar complex objects. Furthermore, perceptual speed has no memory component, whereas *o* may. Empirically, perceptual speed has the closest relationship with *o* of any ability that has so far been tested (Chang et al., in press; Smithson, Chow, Chang, et al., 2024), but this relationship needs to be verified with perceptual tests that more clearly exclude some of the defining features of *o* tests (like the ability to discriminate similar shapes), and sets of *o* tests that are not incidentally emphasizing speed.

Other constructs with conceptual similarities to *o* are those related to *Gv* such as visual memory, MFU, and visualization. Although visual memory and MFU concern the retention of visual stimuli in memory, their tests do not generally require subordinate-level discrimination of objects as *o* tests do. Visualization concerns mental simulation and manipulation of objects, and so may rely on processes similar to those engaged by *o*. However, it too is not primarily concerned with subordinate-level discrimination. Evidence suggests a strong relationship between *o* and *Gv* abilities but it is unclear if this exists independently of a shared relationship with *g*, and the relationship does not appear to be stronger than the relationship between visual *o* and its auditory counterpart (Smithson, Chow & Gauthier, 2024).

Aside from considering *o*-like constructs, another important question is whether existing indicators for other abilities could be used in the measurement of *o*. Multiple existing tests share similarities with the tests that have been used as indicators of *o*. Because the measurement of *o* is still in its infancy, it is possible that, as the construct is refined, the best indicators are not those that were first used to explore the construct. Some of the existing tests we have discussed would likely be adequate indicators of *o* but are not normally combined with other tests in a way that would triangulate on this construct. Existing tests of subordinate-level discrimination for specific categories can be combined with such tests for other categories, ideally using differing task designs. Although there is no theoretical requirement for visual memory tests to require such fine discrimination, some measures of visual memory do so. The visual memory test from T. G. Thurstone & Thurstone (1949) is a good example of a test which appears to fundamentally measure an *o*-like ability. Tests such as Memory for Ships (Guilford & Lacey, 1947) or the MFU test Object Recognition also require subordinate-level discrimination at the level needed to test *o*. Some tests of visual memory from widely used test batteries could also serve as indicators of *o*. Whether any individual task plausibly measures subordinate discrimination of objects is not the most important question for our purposes. Indeed, many studies have measured subordinate-level judgments with novel objects in tasks that could serve as indicators of o, but without any consideration of reliability or sensitivity to the full range of abilities. These studies usually were not interested in individual differences, or even when they noted evidence for such variability (Cooper, 1976), they never asked whether this variability was general across tasks or categories. Whereas studies using tasks for individual differences research are usually limited to a single category or combine the task with measures of quite different abilities. A list of some of the tests measuring constructs discussed in this review can be found in Table 1.

Table 1. Comparison of tests measuring constructs that may relate to *o.*

Test	Subordinate-level	STM	LTM	Stimuli
Perceptual Speed – comparing / Evaluation of Figural Units				
Designs (L. L. Thurstone, 1938) / *Hidden Patterns* (Ekstrom et al., 1976a)	No*	No	No	Line patterns
Identical Forms (L. L. Thurstone, 1938) / *Identical Pictures* (Ekstrom et al., 1976a)	No*	No	No	Diverse icons
Perceptual Speed (Guilford, 1956)	Yes	No	No	Object drawings
Speed of Identification A (Guilford & Lacey, 1947)	Yes	No	No	Plane drawings
Visualization				

Flags (L. L. Thurstone, 1938)	By orientation	No	No	Drawings of flags
Mental Rotations (Vandenberg & Kuse, 1978)	By orientation	No	No	Figures made from cubes
Cubes (L. L. Thurstone, 1938)	By orientation	No	No	Cubes with symbols
Object Identification (Guilford & Lacey, 1947)	By orientation	No	No	Drawings of planes
Visual Memory				
Map Memory (visual form; Guilford & Lacey, 1947)	No	Yes	No	Maps
Visual Memory (Guilford & Lacey, 1947)	No	Yes	No	Aerial photographs
Memory for Ships (Guilford & Lacey, 1947)	Yes	Yes	No	Ship photographs
Plane Name Memory (Guilford & Lacey, 1947)	Yes	Yes	No	Plane drawings
Memory for Plane Silhouettes (Guilford & Lacey, 1947)	Yes	Yes	No	Plane silhouettes
Memory for Landmarks	Yes	Yes	No	Line drawings of geographical features
Memory for Pictures (Thurstone & Thurstone, 1949)	No*	No	Yes	Drawings of diverse categories
Memory for Geometric Design (Thurstone & Thurstone, 1949)	No*	No	Yes	Geometric designs
Visual Memory (Thurstone & Thurstone, 1949)	Yes	Yes	No	Shapes
Pattern Detail Memory Test (Christal, 1958)	No*	No	Yes	Configurations of straight lines
Shape Memory (Ekstrom et al., 1976a)	No*	No	Yes	Shapes which are empty or blackened
Building Memory (Ekstrom et al., 1976a)	No	No	Yes	A map with drawings of buildings
Map Memory (Ekstrom et al., 1976a)	No	No	Yes	Complex patterns
Recognition of Pictures (Elliot, 2007a)	No*	Yes	No	Object drawings
Picture Recognition (Schrank et al., 2014)	No*	Yes	No	Object drawings
Picture Completion (Weschler, 2008)	No	Yes	No	Object drawings
Recognition (Weschler & Naglieri, 2006)	No	Yes	No	Shapes
Designs I (Weschler, 2009)	No	Yes	No	Abstract designs
Designs II (Weschler, 2009)	No	No	Yes	Abstract designs

Faces I (Weschler, 1997)	Yes	Yes	No	Faces
Faces II (Weschler, 1997)	Yes	No	Yes	Faces
Nonverbal Memory (Reynolds & Kamphaus, 2015)	No*	Yes	No	Common objects or abstract designs
Memory for Figural Units				
Object Recognition (Bradley et al., 1969)	Yes	Yes	No	Object drawings
Figural Letter Recognition (Bradley et al., 1969)	Yes	Yes	No	Letters in differing fonts
Neuropsychological – Faces				
Cambridge Face Memory Test (Duchaine & Nakayama, 2006)	Yes	Yes	Yes	Faces
Warrington Recognition Memory Test for Faces (Warrington, 1984)	Yes	No	Yes	Faces
Benton Facial Recognition Test (Benton & Van Allen, 1968)	Yes	No	No	Faces
Glasgow Face Matching Test 2 (White et al., 2022)	Yes	No	No	Faces
Kent Face Matching Test (Fysh & Bindemann, 2018)	Yes	No	No	Faces
Oxford Face Matching Test (Stantic et al., 2021)	Yes	No	No	Faces
Memory for Faces (Korkman et al., 2007)	Yes	Yes	No	Faces
Memory for Faces Delayed (Korkman et al., 2007)	Yes	No	Yes	Faces
Cambridge Face Perception Test (Duchaine et al., 2007)	Yes	No	No	Face morphs
Neuropsychological - Objects				
Cambridge Car Memory Test (Dennett et al., 2012)	Yes	Yes	Yes	Cars
Cambridge Bicycle Memory Test (Dalrymple et al., 2014)	Yes	Yes	Yes	Bicycles
Old/new Flowers (Dalrymple et al., 2014)	Yes	Yes	Yes	Flowers
Minimal Feature View Task, Foreshortened View Task (Riddoch & Humphreys, 1993)	No	No	No	Line drawings of objects (e.g., cup, elephant)
Object Decision (Riddoch & Humphreys, 1993)	No	No	Yes	Line drawings of real and impossible objects
Silhouettes (Warrington & James, 1991)	No	No	Yes	Object silhouettes
Memory for Designs (Korkman et al., 2007)	No	Yes	No	Abstract designs

Memory for Designs Delayed (Korkman et al., 2007)	No	No	Yes	Abstract designs
Benton Visual Form Discrimination (Benton et al., 1994)	No*	No	No	Simple shapes
Benton Visual Retention Test – Multiple Choice (Benton et al., 1977)	No*	Yes	No	Same as Benton Visual Form Discrimination
Low-level Visual Perception				
Hanover Early Vision Assessment (Kieseler et al., 2022)	No*	No	No	Simple stimuli (e.g., lines, ovals)
Length Match, Size Match, Orientation Match (Riddoch & Humphreys, 1993)	No*	No	No	Simple stimuli (e.g., lines, circles)
Estimation of Length (Guilford & Lacey, 1947)	No*	No	No	Lines
Object Recognition				
Vanderbilt Expertise Test (McGugin et al., 2012)	Yes	Yes	Yes	One object category per test
Novel Object Memory Test / Learning Exemplars (Richler et al., 2017)	Yes	Yes	Yes	Novel Objects
3AFC Matching (Smithson, Chow, Chang, et al., 2024)	Yes	Yes	No	Novel Objects
Object Discrimination				
Many Objects Oddball (Smithson, Chow, Chang, et al., 2024)	Yes	No	No	Novel objects
Novel Object Matching (Growns et al., 2024)	Yes	No	No	Prints from stamping tools

Note. This is not an exhaustive list of relevant tests. Some tests may fall under multiple categories. *These tasks require some kind of subordinate-level discrimination, but here we require that the object stimuli vary on multiple dimensions (e.g., discrimination of line lengths would not qualify), and also that the target and distractor stimuli tend to have the same basic configuration with only small continuous differences in specific features. As an illustrative example, if you averaged a large set of faces, the resulting composite would look much like a normal face. Tasks like Identical Forms require discrimination that is based on categorical presence or absence of particular features, even if the general configuration remains quite similar across objects.

Although it is difficult to identify any individual construct that is equivalent to *o*, it remains a possibility that *o* could be reducible to a combination of already existing abilities and could therefore be measured by appropriately weighting some set of existing tests that do not explicitly measure o. Although existing evidence suggests that *o* cannot be fully explained by theoretically related abilities, including general intelligence, working memory, perceptual speed, and spatial ability, we cannot say with certainty that the right combination of existing abilities would not account for *o*. One approach to addressing this issue could be to use a battery of diverse ability tests to predict *o*. The regression weights of these predictors could be used to form a composite measure of *o* using tests that were not explicitly designed to measure it. If appropriate criterion variables were identified, the incremental validity gained by including *o* tests as predictors versus using the composite alone could be quantified. Such a research design could be highly informative; *o* could be shown to be a novel and independent contribution to the taxonomy of cognitive abilities, or alternatively, a more complete understanding of the underlying abilities responsible for individual differences in object recognition could be gained. Of course, when variance is shared by tests from multiple constructs, the challenge of deciding which construct should be awarded precedence is difficult and frameworks like CHC may be invoked to aid in decision making.

Another aim of the review was to connect *o* research theoretically with the broader literature on cognitive abilities. Given that *o* did not arise directly from this research area, but rather from vision research, there may be important lessons to draw from this tradition. For example, hierarchical theories of cognitive abilities, such as CHC, suggest that abilities are downstream from *g* and from any other ability higher up the hierarchy. This has implications for whether abilities like *g* should be controlled in analyses that test hypotheses that are specific to *o*. These hierarchies also provide a useful framework for considering how abilities relate to each other across differing levels of generality. For example, a multimodal *o* could be considered more general, and thus closer to *g,* than a modality-specific *o* ability which would still be more general than a domain-specific recognition ability. One difficult question is where *o* might be best considered to fit into an ability taxonomy, and further research is required to establish this. A multimodal *o* ability could plausibly be a broad ability, with abilities specific to different modalities subsumed under it, or a modality-specific *o* might be better conceptualized as a narrow ability under an existing broad ability such as *Gv*.

All factor-analytic research on *o* up to this point has been of the confirmatory kind; the ability is assumed to exist and the tests are assumed to measure it. The covariance that occurs between such tests is attributed to *o*, and the influence of other constructs such as *g* or working memory can then be partialed out. The lack of substantial misfit in such confirmatory models lends some support to the existence of *o*, but alternative models of the relationships between tests included in these confirmatory studies could theoretically fit equally well, or better (Tomarken & Waller, 2003). From the perspective of a vision researcher accustomed to testing object recognition abilities, the confirmatory approach appears a sensible one. Some people are better at recognizing objects than others, and on the face of it, the tests measure this ability. However, many of the abilities discussed in this review emerged from exploratory factor-analytic research. In accordance with the principle of parsimony, the aim of many factor analysts has been to explain performance on the greatest number of diverse tasks with the least number of factors. This may raise the question of why *o* has not been identified in this older line of research. In one sense, it is misleading to say that existing factors have been identified in an entirely exploratory manner, because even when the factor analysis has been exploratory, test construction and selection have been assuredly not. Instead, they were guided by psychological theory or prior research. Factors can only emerge if multiple tests measuring the factors are included in the battery. Unfortunately, we cannot identify many exploratory factor-analytic studies including multiple tests that we would consider measures of *o* alongside multiple tests of other abilities. The closest such dataset is likely to be from Bradley et al. (1969). The fact that Carroll's (1993) reanalysis of this dataset did not identify an *o*-like factor is interesting but should not be considered strong evidence against the importance of such a factor. The small number of subordinate-level discrimination tests included in this dataset used relatively differentiable hand-drawn images of objects from categories (e.g., faces, hands, letters) for which recognition abilities could be expected to intercorrelate especially poorly due to extensive and unique experience with these categories. Another relevant dataset is from (Guilford & Lacey, 1947). In this case, the *o*-like tests did form a factor, but they are all in a paired-associates format, thus requiring ability for associative memory. Even the tests developed for measuring *o* may not be ideal for exploratory analyses. They are probably factorially complex – each test is likely to reflect the influence of multiple factors, which may make them ill-suited to the exploratory approach (Guilford, 1952). In some respects, this reflects a deliberate decision to create tests of *o* with diverse task designs in hope that construct-irrelevant variance is test-specific, rather than shared between multiple *o* tests (Smithson, Chow, Chang et al., 2024)

Should *o* be included in models of cognitive abilities? A common refrain among individual differences theorists is that the proliferation of factors must be avoided. Guilford's (1959) SOI model was criticized for its initial inclusion of 120 factors and its eventual expansion to 180 (Cronbach & Snow, 1977; Humphreys, 1962). CHC has been criticized for a similar tendency towards expansion (Wasserman, 2019), including far more factors than would have been acknowledged in the early models of group factors, such as L. L. Thurstone's (1938) seven primary mental abilities (and even this was too many for Spearman, 1939). Whether every identifiable ability should be included in a given structure of cognitive abilities hinges on whether it ought to resemble more closely a taxonomy, or a map. Few would criticize biologists for attempting to discover and classify novel species – there may be value in studying each one. However, from the cartographic perspective, infinite detail is undesirable, as is eloquently illustrated by Borge's allegory of the inutility of a map made to a 1:1 scale (Borges, 1946). From the perspective of research in high-level vision, however, the work on *o* has encouraged a focus on abilities that may generalize more than the domain- and task- specific abilities that were so far the basis for theoretical claims.

Research into *o* has also led to questions about the development of expertise with object categories. Although there is considerable interest in how ability level relates to expertise in the psychometric literature (Detterman, 2014; Masunaga & Horn, 2000), the question of how people become experts at recognizing particular object categories is not readily addressed. Instead, interest in this question has arisen from visual cognitive neuroscience (Tanaka et al., 2005; Tanaka & Gauthier, 1997). Research in this area could ultimately provide information on the development of expertise in a more general sense. Future research can build on a greater understanding of *o* to explore how it may mediate the influence of experience in the development of expertise. One interesting hypothesis is that *o* could perceptually facilitate the extraction of regularities from the environment, a process known as *statistical learning* (Schapiro & Turk-Browne, 2015), thus speeding up the development of expertise. This is only one of many possible mechanisms that may underlie the variability captured by *o.* Indeed, the next challenge will be to describe the mechanisms that, within each individual, cause the between-individual variation that is captured in our latent models (Borsboom et al., 2003).

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