Using the International Cognitive Ability Resource as an open source tool to explore individual differences in cognitive ability

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Abstract

Although the measurement of intelligence is important, researchers sometimes avoid using them in their studies due to their history, cost, or burden on the researcher. To encourage the use of cognitive ability items in research, we discuss the development and validation of the International Cognitive Ability Resource (ICAR), a growing set of items from 19 different subdomains. We consider how these items might benefit open science in contrast to more established proprietary measures. A short summary of how these items have been used in outside studies is provided in addition to ways we would love to see the use of public-domain cognitive ability items grow.

Keywords: Intelligence, Cognitive ability, Open Source, Open Science, International Cognitive Ability Resource

1. Introduction

The most unusual and for some of us most important aspect of the Society for the Study of Individual Differences and its journal *Personality and Individual*

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Differences is the continuing interest in intelligence and cognitive ability. Unlike other societies or journals with "Personality" in their name or title, intelligence has been studied as long as the society has existed. Chapters on reaction time (Jensen, 1982) and inspection time (Brand and Deary, 1982) as well as a psychophysiological model (Hendrickson, 1982a,b) appeared in Eysenck's *Model for Intelligence* (Eysenck, 1982), one year before the first meeting of ISSID. Papers delivered at that meeting and all meetings since then have continued the emphasis of integrating the study of intelligence with the general study of personality and individual differences. Unfortunately, as cogently argued by Rabbitt (2016) Eysenck's emphasis on the Galtonian tradition of reaction time and his disparagement of the experimental psychology research done elsewhere probably prevented him from considering the advances in cognitive psychology (e.g., Broadbent, 1971) that were relating reaction time to fundamental cognitive processes.

Many others have pursued the study of intelligence, both from a chronometric approach (Jensen, 1982, 2006) and from a broad unifying construct at multiple levels (Carroll, 1993, 2005, Cattell, 1943, Horn and Cattell, 1982). For life is an intelligence test and the importance of measuring intellectual ability as people respond to life's challenges can not be overstated (Gottfredson, 1997). The most recent presidential address to ISSID by Philip Ackerman continued this broad tradition (Ackerman, 2019, 2017).

As we have written previously (Condon and Revelle, 2014) an unfortunate limitation on the inclusion of intelligence in individual differences research is the proprietary nature of most measures of ability. That is, because proprietary measures are expensive, studies tend to be limited in their sample sizes, or reseachers create their own measures that are unique to their lab. But now, with the advent of easier communication between labs and the use of the web to collect data, the development of the International Cognitive Ability Resource (ICAR) (Condon and Revelle, 2014) and its web page at `https://icar-project.com` (Condon, Doebler, Holling, Gühne, Rust, Stillwell, Sun, Chan, Loe and Revelle, 2014) has made it easier for all individual differences researchers to include a common battery of items in their studies. We will review the development of the ICAR as it relates both to open science and also the impact such tools have had upon the study of individual differences.

2. A Mistrust in Intelligence Research

Although most readers of this journal recognize the importance of intelligence research, we believe that in order to move the field forward we need to recognize its darker past and why some describe the field as controversial or repugnant. Though intelligence tests were first designed to help identify students who required additional educational support (Binet and Simon, 1916), it is the unfortunate fact that they have not always been altruistically used. It has been said that in the previous century, intelligence tests were proposed to discriminate and bar immigrants from entry into the United States. However, a closer reading of the literature (Mackintosh, 2011) suggests that this is incorrect. Although Goddard (1908) adapted the Binet and Simon tests to identify the "feebleminded" as part of his work at the New Jersey Training School for Feeble-Minded Boys and Girls at Vineland, N.J. (Zenderland, 2001) and is perhaps most known for his study of the "Kallikak family" (Goddard, 1912) this work had little impact upon the blatantly racist discrimination policies enacted in the U.S. immigration act of 1923 (Mackintosh, 2011). Goddard should rather be remembered for being one of the first adapters of Binet and Simon's intelligence test (Goddard, 1908).

One of the most well known of the proponents of racial discrimination using intelligence tests who bemoaned the decrease in national intelligence that was due to immigration was perhaps Carl Brigham (1923) who emphasized racial differences in performance on the U.S. Army Alpha exam between "Nordic", "Alpine", "Mediterranean" and "Negroid". However, eight years later (Brigham, 1930) he dismissed his earlier studies by saying "that comparative studies of various national and racial groups may not be made with existing tests, and [this review shows], in particular, that one of the most pretentious of these comparative racial studies—the writer's own—was without foundation." In an unpublished paper from about 1934 he concluded that "The test scores very definitely are a composite including schooling, family background, familiarity with English, and everything else, relevant and irrelevant.The native intelligence hypothesis is dead." (p 16 Saretzky, 1982) Though Brigham's later retraction is admirable, it is still important to consider the damage his statements may have caused to more marginalized groups.

Albeit researchers like Goddard and Brigham eventually denounced their earlier work, "intelligence" is unfortunately often associated with the eugenics rhetoric that further dehumanized those already marginalized in the US during the 20th century. As descriptors like savage and comparisons to animals were normalized in every day language to distinguish marginalized individuals such as people of color or those with disabilities as "others" (Haslam, 2006), the word intelligence would also be commandeered and folded into this rhetoric. Although IQ tests were not used to make prejudicial policies, lobbying by eugenics groups would lead to legislation that would justify the subjection of individuals to sterilization on basis of "feeble mindedness" (Buck v. Bell 274 U.S. 200, 1927, Oberman, 2010). The dehumanization and removal of bodily autonomy from these individuals is unforgivable and it is not surprising that individuals repulsed by intelligence research often push back due to their familiarity and disgust with these cruel movements. However, it is important to recognize that these cruelties come from a different group of individuals than those interested in studying cognitive ability.

Admittedly, there are still those interested in debating racial differences in intelligence (see the featured debates in *Nature* (Ceci and Williams, 2009, Rose, 2009)). Nevertheless, we urge those engaging in intelligence research to reflect on how "...the uses made of scientific findings depend more on one's value system than on the facts discovered" (p 11, Eysenck, 1998). While we fully acknowledge the harm that some intelligence research has caused in the past, we should also recognize that not all modern critiques are as unbiased as they claim to be. (E.g., see Lewis, DeGusta, Meyer, Monge, Mann and Holloway, 2011, for a discussion of Gould's critique of Morton). This is especially true if we wish to engage and encourage those less interested in including measures of cognitive ability into their research on the importance of intelligence testing.

3. Reestablishing Trust Through Open Science

Despite intelligence tests' dark and controversial history, the study of intelligence is perhaps psychology's greatest success. The need to screen military recruits in World War I led to the development of a group intelligence test, the "Army Alpha" and "Beta" (for the illiterate) (Yoakum and Yerkes, 1920). The "Alpha" and "Beta" tests were used for rapid classification of the recruits' potential. Rather than using a history of schooling in elite East coast schools, the use of standardized tests derived from the "Alpha" allowed "Ivy League" colleges in the US to offer scholarships to students from around the country (Chauncey and Hilton, 1965). High scorers on similar tests were more successful candidates for training in the Army Air Force in World War II (Dubois, 1947). Ongoing research shows that using such ability tests as the Graduate Record Examination (GRE) allows graduate programs in all fields to select stronger candidates for graduate training (Kuncel, Hezlett and Ones, 2001, Kuncel, Credé and Thomas, 2007, Sackett and Kuncel, 2018). There are few occupations or outcomes that are not predictable by cognitive ability (Gottfredson, 1997).

All of the studies just discussed were large scale assessment enterprises. They developed and used proprietary instruments that are difficult or expensive to use for academic research. The raw data are rarely available and we are forced to accept the results based upon summary statistics. This is in direct contrast with a growing movement in scientific research to have open methods and open data. By sharing one's methods of data collection and data analysis, as well as sharing the data, the general trust in the scientific enterprise will grow.

3.1. Open data

Part of engaging in open science involves sharing your data when possible. Strides with technology have made practice more approachable as researchers can rely on data repositories such as Open Science Framework, Dataverse, or GitHub. Although this practice has been adapted by funding institutions (National Institute of Health, National Sciencce Foundation) and required by some publishers, very few journals actually require researchers to share their data (Resnik, Morales, Landrum, Shi, Minnier, Vasilevsky and Champieux, 2019). Indeed there is a need to keep participants involved in research anonymous, nonetheless the field should consider how open data may increase trust in intelligence research. This trust relies on building a rapport about not only giving data back to the public at large, but being okay with others checking your work. It is understandable that some researchers may not be comfortable sharing their resources as they have their own questions planned for the data. In spite of this, our experience with sharing data (Condon and Revelle, 2015) has not only benefited our own work, but has inspired collaborations and also allowed others to pursue their own research interests (Dang and Wang, 2019, Fu, Zhang and Tao, 2020, Young, Keith and Bond, 2019).

3.2. Open materials

The idea of using and producing open measures and materials is nothing new, but is something that should be continually encouraged. It was very controversial when Lewis Goldberg (1999) introduced the International Personality Item Pool (IPIP) as "A Scientific Collaboratory for the Development of Advanced Measures of Personality and Other Individual Differences". Within two decades the IPIP has over 3,000 items that have been translated into at least 48 languages (Goldberg, 2018). This open source measure, along with others, have been further curated and extended to include approximately 10,000 items in an open database of individual differences (Condon, 2019). Beyond temperament, researchers have developed open source cognitive ability items. The International Cognitive Ability Resource (ICAR) (Condon et al., 2014) is to IPIP as ability is to temperament and has approximately 1,000 ability items for public.

4. Development of ICAR

The International Cognitive Ability Resource was developed to address the need for psychometrically valid tools that are well-suited for large-scale, remote data collection. This need is driven by the fact that nearly all existing tools are either insufficiently validated and/or encumbered by copyright protections – for decades, the resources needed to develop, validate, and maintain robust tools (and make a profit) have been supported by royalties and licensing fees. In this model, testing companies charge users of their proprietary content based on the number of tests administered and they limit the re-distribution of content. These limitations effectively prohibit large-scale un-proctored assessment, and delay the advancement of research on cognitive abilities.

The ICAR Project uses a different approach. Testing content has been developed by small teams of cognitive ability researchers and validated collectively across multiple waves and samples. Then, all testing content is maintained in the public-domain for non-commercial research purposes, allowing for subsequent validation by additional research teams and enabling the unlimited administration of content. In a companion piece to this article, we have discussed the data collection technique we refer to as Synthetic Aperture Personality Assessment (SAPA). Briefly, SAPA is a matrix sampling procedure where each individual receives a different set of overlapping test items. The data are Massively Missing Completely at Random (MMCAR) which allows for unbiased estimates of covariance structures between the items. As part of the larger SAPA-project (Revelle, Wilt and Rosenthal, 2010, Revelle, Condon, Wilt, French, Brown and Elleman, 2016), originally 60 and now close to 1,000 ability items have been administered to almost one million participants. Several types of ICAR content have been administered to online samples of more than one million participants. To support the competitive advantage of ICAR's public-domain status, test development procedures depend upon the algorithmic generation of testing content (aka rule-based item generation). This allows for large families of testing content to be developed – across a wide range of difficulty levels – reducing the need to restrict access to a small (proprietary) pool of questions. More information about these procedures can be found in previous studies (Condon and Revelle, 2014).

4.1. Application of ICAR

The ICAR Team is an international consortium of social scientists that has received funding through a collaboration of funding agencies in the United States (NSF), Germany (DFG), and the United Kingdom (ESRC). Our shared goal for

ICAR development has been to encourage broader assessment of cognitive abilities, especially in applications that have not historically been able to afford the use of traditional tools. This includes a large proportion of research using online data collection methods in education, economics, psychology, biomedicine, and cognitive aging research.

The 19 types of ICAR content cover many domains of cognitive ability, including spatial, verbal, mathematical, and perceptual ability. More specifically, the tests include measures of two-dimensional and three-dimensional rotational ability, progressive matrices/matrix reasoning, propositional reasoning, figural analogies, verbal reasoning, letter and number series, abstract reasoning, emotion recognition, arithmetic, compound remote associates (aka the Remote Associates Test), face-detection (aka the Mooney Test), melodic discrimination, a perceptual maze task, and a situational judgment task. The extent of validation among these tests varies considerably – about half have been reported upon in a peer-reviewed publication. The best source of information about ICAR content (the "item types") is the online content repository (user registration is required). An older catalog of ICAR content from 2017 can be found on the project website http://icar-project.com/.

4.2. Why ICAR benefits open science

Previously mentioned, IPIP (Goldberg, 1999) transformed the way researchers would approach studying personality over the last two decades. It is our hope, that ICAR will not only help advance intelligence research, but open science overall. Similar to IPIP, ICAR has been cited as providing a valuable resource to psychology as the public-domain items have not only maintained their test validity, but inspired researchers to develop their own open source measures (Speer, Schwendeman, Reich, Tenbrink and Siver, 2019, Woike, 2019). Though we will go into greater detail about how the ICAR Project has enjoyed early success beyond our expectations later on, there are now about 1500 registered users of ICAR content from all of the disciplines listed above (and more); 45% are from North America and 40% from Europe. In the last three years (2017 to 2019), ICAR measures have been cited in more than 100 academic research articles. Importantly, the reporting of these results has served to validate the existing ICAR measures in several ways, including cross-validation against legacy (proprietary) tools, internal validation among the many different types of ICAR content, and cross-cultural validity. It has also helped to promote the development of new content. Starting with 4 types of content in 2014, the ICAR Project now hosts 19 types of content, with several additional types under development. As in other scientific fields, it seems that development in the public-domain has accelerated adoption and improvement of the framework relative to the development of copyrighted content.

Beyond the scope of encouraging researchers to develop and validate additional measures, the ICAR also largely outperforms proprietary tools as they are free and do not require researchers to have a clinical background. Specifically in considering how ICAR has benefited those studying cognitive ability, we found that a proportion of those using our measures were graduate students (e.g., Colalillo, 2018, Collmus and Landers, 2019, Lim, 2018, Rasmussen, 2018, Thompson, 2018, Young et al., 2019). Given the limited budget early career researchers often receive, we might extrapolate that one reason ICAR has been adapted into graduate work is due to either their cost saving nature or their ability to be used by those outside of clinical psychology. Contrasting this, outside of benefiting an individual's work, ICAR has also been used to help researchers understand larger methodological issues they might encounter when collecting data. For example, Rouse (2019) found no differences in cognitive ability between those listed with a Masters status on Amazon's Mechanical Turk to individuals ranked at lower payment tiers. The implications of such work are tremendous as they influence how other researchers might plan to collect their data. As ICAR also provides more flexibility to study design and works well in large samples, we wish to highlight how these characteristics might appeal to those interested in studying cognitive ability.

4.3. Flexibility of ICAR items

The utility of public-domain measures of cognitive ability has already been demonstrated across a wide range of applications and dozens of publications (see Table 1).Whereas some measures restrict researchers to use the same number of items or only offer one short form of their assessment, ICAR offers researchers autonomy in the items they select for their study. To date, researchers have ranged from using as few as four items (Choma and Hanoch, 2017) to as many as 60 items (Young et al., 2019). In addition to item selection, researchers are also not restricted by the number of ICAR domains they choose to use in their study. Rather, researchers can target the domains that relate most to their research. While a majority of the studies in Table 1 used the four domains of Matrix Reasoning, Three Dimensional Rotation, Letter and Number Series, and Verbal Reasoning, some studies used as few as one domain (Bates and Gupta, 2017, Rouse, 2019) and one study used five domains (Collmus and Landers, 2019). Further showcasing the flexibility of ICAR items, previous studies have focused on using domains they believe align with more classical definitions of fluid or crystalized intelligence (Zirenko, 2018) , while other studies have relied on administering questions from a specific domain (Andermane, Bosten, Seth and Ward, 2019, Jankovski, Zečević and Subotić, 2017, Liknaitzky, Smillie and Allen, 2017, Lim, 2018). Furthermore, studies have used varying amounts of ICAR domains to examine convergent (Irons and Leber, 2019, Kajonius, 2014, 2016) or discriminant validity (Chierchia, Fuhrmann, Knoll, Pi-Sunyer, Sakhardande and Blakemore, 2019, Connelly, Warren, Kim and Domenico, 2016, Weyhrauch, 2017) in their own measurement development.

Beyond the adaptability that ICAR offers in terms of item and domain inclusion, researchers can also aggregate what proportion of difficult items they wish to administer. This allows researchers that are concerned about observing either ceiling or floor effects in their study to target items they believe will be adequate for testing in their population of interest. In addition to the wide and growing diversity of content, most of the ICAR measures cover a broad range of ability, including items of high and low difficulty. This benefit stems from the use of rule-based item generation procedures as these enable the creation of increasingly difficult content through the combination of rules that are known to make the questions more or less difficult (Loe, Sun, Simonfy and Doebler, 2018). To illustrate this, let's consider a study which is interested in identifying respondents at the highest levels of ability (i.e., the top 1% or higher). The fact that most assessment tools contain content that is generally too easy for such assessments make them problematic for both respondents who may find them and test administrators whom who end up wasting resources on uninformative content. In psychometric terms, the Fisher Information curve of an easy item (assuming a two parameter logistic Item Response Theory model) will peak at medium or low ability, and the administration of such an item to a gifted respondent will not likely improve (that is, reduce) the standard error of the estimate of their ability.

In this example, the solution is to assess potentially gifted respondents on testing content with high Fisher Information at ability levels two or more standard deviations above the mean, though this is not always possible with proprietary tools of limited content. The ICAR framework already contains a relatively high proportion of this difficult content and allows for the rapid development of more, if needed. To demonstrate, we have completed a preliminary analysis of the content in a single domain (mental rotation), using one of the four original ICAR measures (three-dimensional rotation). Based on data from approximately 250,000 online respondents, Figure 1 a shows the test information function for a 66-item set, while Figure 1b shows considerable variability in difficulty among the items (indicated by the location and height of the peaks in the item informa-

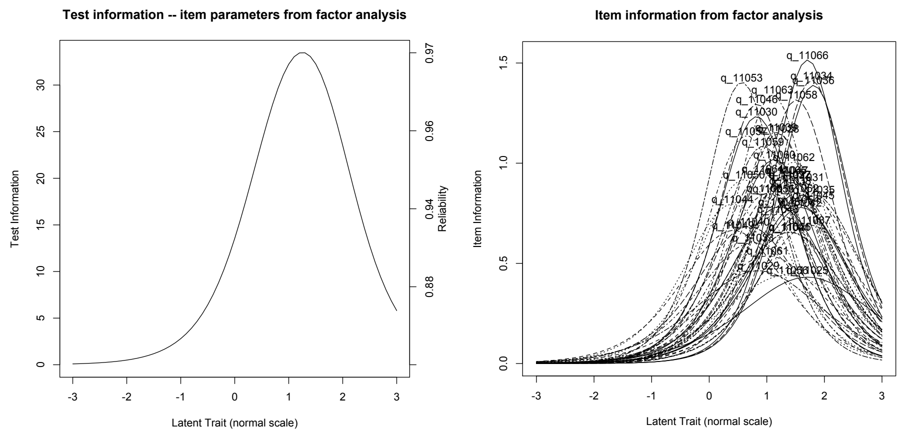

Figure 1: An example of the test information (and therefore reliability) as a function of a latent ability (left panel) and of item information (right panel).

tion functions). The reliability of this measure is at or above .85, even as far as three standard deviations above the mean of difficulty. In addition to this example (which could be extended in order to identify content from most of the ICAR measures), members of the ICAR Team also have expertise in additional methods that could help to develop and scale assessments for respondents, including those based on frequency/count data produced by measures of processing speed and creativity (Doebler, Doebler and Holling, 2014, Forthmann, Gühne and Doebler, 2019).This freedom in item selection also allows researchers to find unique applications of ICAR items. Outside of using a high proportion of difficult items for standard cognitive ability testing, researchers have used these items to stress out or frustrate participants (Paulsen, 2018, Townsley, 2018).

4.4. Administering ICAR

The goal of item development for ICAR was to have many examplars of many types of items. Ideally, with the use of Automatic Item Generation, we could generate unique items for each participant, but that had a known structure (Blum and Holling, 2018). A further design consideration was to make the items “Google resistant”, that is, it would not be possible to do web searches to locate specific items and their answers. Thus, vocabulary or basic factual information items were not included. The items were meant to be delivered on cell phones or through web browsers.

In an effort to encourage diversity among the ICAR measures, no standard technological specifications have been adopted and a variety have been used. Most of the content has been developed for use on web-based apps, though approximately 10% of registered users express interest in administering paper-and-pencil equivalents, often in non-Western cultures. A limited number of measures have already been translated and/or administered in multiple languages. Most images make use of vector graphics (some are raster/png files); all are available for download as zip files and content loading is typically left up to the research team. In some cases, these research teams have included larger groups seeking to implement ICAR measures in apps that are built-for-purpose. Most prominently, this includes the Mobile Toolbox app, a large NIH-funded consortium led by Sage Bionetworks to develop mobile-based assessments for detecting cognitive impairment (https://sagebionetworks.org/research-projects/mobiletoolbox/). Others have adapted the ICAR items to more unique testing formats through "gamification" in order to make participants feel more engaged with the task (Collmus and Landers, 2019, Nikolaou, Georgiou and Kotsasarlidou, 2019).

Given the flexibility of item administration, some researchers inquire about standard instructions. Letter and Number Series items and the Verbal Reasoning items do not require instructions as the items are written as questions. Instructions for the Three Dimensional Rotation items are: "All the cubes below have a different image on each side. Select the choice that represents a rotation of the cube labeled X." Instructions for the Matrix Reasoning items are: "Please indicate which is the best answer to complete the figure below." No general instructions are needed for the test as a whole, though an important point for paper-and-pencil administration is that no instruments should be used to arrive at the correct answer (jotting in the margins, etc.), though this is more relevant for domains outside of the four item types previously specified. Though researchers often inquire about time limits, the ICAR measures are "power" tests so timing is not part of the administration or scoring. Still, in the interest of keeping administration moving, it can be useful to set an upper limit. If possible, we recommend piloting your study with a handful of participants in your target population. For something like the 16 item ICAR Sample Test, we recommend a maximum of 16 minutes for young adult participants (18-25 years old); the majority will be done in half that time. In the event that you are using a different set of items, you'll want to keep in mind that the spatial items (i.e. Three Dimensional Rotation) tend to take some participants much longer than other types. To our knowledge, those that have used our items in their studies range from not setting an upper limit to limiting administration of the items to as little as 10 minutes (Zhang, 2018).

4.5. Existing ICAR Research

The variety of ways ICAR items have been used over the last six years provides an exciting perspective to what cognitive ability testing can do for the scientific community. While many studies attempt to control for cognitive ability in their research, some have been more interested in examining how intelligence functions in a group setting (Bates and Gupta, 2017, Rowe, 2019), as well as more traditional research seeking to associate ICAR items with attentional tasks (Andermane et al., 2019), executive function tasks (Rautu, 2017), implicit learning (Thompson, 2018), cognitive reflection (Blacksmith, Yang, Behrend and Ruark, 2019), decision making (Farmer, Baron-Cohen and Skylark, 2017, Rouault, Seow, Gillan and Fleming, 2018), school achievement (Kirkegaard and Nordbjerg, 2015, Lugonja, Keleman and Subotić, 2018, Subotić, Lovrić, Gajić, Golubović and Sibinčić, 2019), and anchoring (Shu, 2018). Along with this, research has examined cognitive ability's relationship with personality coherence (Fournier, Dong, Quitasol, Weststrate and Di Domenico, 2018), personality regulation (Phillips, 2018), impression management (Roulin, 2016), self control (Townsley, 2018), ambiguity tolerance (Rautu, 2018, Jach and Smillie, 2019).

Equally important, studies have examined ICAR's relationship to the perception of leadership (Frick, 2017) and others (Rhoades, 2017), job performance (Rasmussen, 2018, Phillips, 2018), career interests (Elpers, 2018), and learning in higher education (Vermunt, Ilie and Vignoles, 2018). Studies have also sought to disambiguate cognitive ability from other individual differences like creativity (Karwowski, Dul, Gralewski, Jauk, Jankowska, Gajda, Chruszczewski and Benedek, 2016, Karwowski, Lebuda, Szumski and Firkowska-Mankiewicz, 2017, Karwowski, Jankowska, Brzeski, Czerwonka, Gajda, Lebuda and Beghetto, 2020, McKay, Karwowski and Kaufman, 2017, Zabelina, Friedman and Andrews-Hanna, 2019), frequency in selfie posting (Karwowski and Brzeski, 2017), perceived attractiveness (Talamas, Mavor and Perrett, 2016), parenting (Colalillo, 2018), empathy and emotion management (Evans, Hughes and Steptoe-Warren, 2019, Kajonius and Björkman, 2020, Vermunt et al., 2018), psychological symptoms and outcomes (Liknaitzky et al., 2017, Seow, Benoit, Dempsey, Jennings, Maxwell, McDonough and Gillan, 2019, Zhang and Goffin, 2018), and metacognition (Karwowski, Czerwonka and Kaufman, 2018).

Additional research has looked at cognitive ability's relationship with deviant behaviors including online criminal behavior (Treadway, 2017), its role in cheating (Cavanaugh, 2018), faking job credentials (Lortie, 2019), persuasiveness (Weiss, Lynam and Miller, 2018), susceptibility to "pseudo-profound bullshit" (Bainbridge, Quinlan, Mar and Smillie, 2019), and overconfidence in background knowledge or ability (Dunlop, Bourdage, de Vries, Hilbig, Zettler and Ludeke, 2017, Hood, 2015).

The measures have also been adopted for use in methodological research (Fu et al., 2020, Golino and Epskamp, 2017, Gillen, Snowberg and Yariv, 2019, Rouse, 2019, Young et al., 2019) and included in large-scale online data collection projects such as national panels (Krieke, Jeronimus, Blaauw, Wanders, Emerencia, Schenk, Vos, Snippe, Wichers, Wigman et al., 2016) and genetic association studies (Liu, Rea-Sandin, Foerster, Fritsche, Brieger, Clark, Li, Pandit, Zajac, Abecasis et al., 2017), with further inter-disciplinary work has been done in economics (Chapman, Dean, Ortoleva, Snowberg and Camerer, 2017, Chapman, Snowberg, Wang and Camerer, 2018, Goda, Levy, Manchester, Sojourner and Tasoff, 2019) and political science (Choma and Hanoch, 2017, Ludeke and Rasmussen, 2018, Rasmussen, 2016, Womick, Ward, Heintzelman, Woody and King, 2019) using ICAR items.

5. Future Directions

One of our long-term goals when developing the ICAR measures has not yet been attempted — to encourage more holistic, empirical studies of the structure of cognitive abilities. Inspired by the work of legendary cognitive ability researchers, including Carroll (1993, 2005), Cattell (1943), Horn and Cattell (1982), Eysenck (1982), Horn and McArdle (2007) and Vernon (1965) we have tried to develop a new paradigm for assessing ability. This is the paradigm of open science. With the contributions of many different researchers, the original 4 lower level factors of ICAR as discussed by Condon and Revelle (2014) have grown to the 19 measures now available. Queries of the adequacy of the Carroll-Horn-Cattell (CHC) vs the VPR model (Johnson and Bouchard, 2005, Vernon, 1965) or some other structure are hiding in the shadows of the limitations of measurement. To address this question with sufficient authority, an even wider selection of item types is needed than are currently available. We hope that in the coming years researchers continue to join us on this endeavor and continue using ICAR items.

5.1. Item generation

A problem with any set of test items, particularly from an open source repository, is item security. Despite out best efforts to keep the items secure, copies of them have appeared on the internet. A solution to this problem is to create unique items for every participant through the use of Automatic Item Generators. Items can either be prepared “on the fly” that are unique for each individual, or large sets of items can be created with known properties. Some progress has made in generating arithmetic reasoning (Loe et al., 2018), figural analogies (Blum and Holling, 2018, Leon and Revelle, 1985), and perceptual mazes (Loe and Rust, 2017) and the ICAR group is continuing this effort.

In the process of item development it is possible to create new items and validate them against the existing set of items. As the number of domains has grown it has become possible to search for areas that are not yet well covered, as well as to validate new forms of existing sets. By taking advantage of our SAPA methodology, we have been able to sample from both new and old items in order to acquire the necessary statistics for the new items. This has been done in particular with our 3 dimensional rotation items where it was possible to use factor extension techniques to locate newer items in the space of the previous items. Figure 1 shows an example of this factor extension from the original ICAR items into a larger set of 3D rotation items.

5.2. Future items

One form of items that is intentionally missing given our concern for item security is that of vocabulary. In an unsupervised web session, it is trivial to use search engines to solve vocabulary problems. Creating a set of vocabulary items with known item difficulties can be done by using previous research. Presentation of small samples of these items in supervised situations would be possible. We hope to have such as set in the future.

5.3. What we'd love to see

Reflecting on the research already completed using the ICAR items, we are beyond thankful for everyone that has joined us in looking at cognitive ability with public-domain items and we hope that researchers continues their momentum in including intelligence tests within their studies. Notwithstanding our gratitude, there are areas that we believe should be targeted by future work. This includes researchers using more than just the 16 item ICAR Sample Test (Condon and Revelle, 2014) as there are now close to 1,000 ability items. Additionally, we would be interested in expanding the use of ICAR items into both young children, older adults, or elderly adult samples. As the median age of the participants for the 60 item validation study was 22, we believe further validation of the items in these sample populations would further benefit their psychometric properties. As researchers looks for ways to identify gifted students (Wai and Worrell, 2016), ICAR may benefit public education programs. Furthermore, as some studies using ICAR found associations between the items and working memory, ICAR may offer a unique opportunity to develop public-domain cognitive decline measures. While these are only a selection of ideas, the possibilities are endless and we look forward to seeing the field expand. We welcome suggestions from all and hope to expand the number of cooperating researchers.

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Table 1: Studies that have used ICAR.

Study #	Authors	ICAR tests	# of items
1	Andermane et al. (2019)	MR	11
2	Bainbridge et al. (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
3	Baret (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
4	Bates and Gupta (2017)	MR	11
5	Bergh and Lindskog (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
6	Blacksmith et al. (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
7	Cavanaugh (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
8	Chapman et al. (2017)	MR, 3DR	6
9	Chapman et al. (2018)	MR, 3DR	6
10	Chierchia et al. (2019)	MR, 3DR, LSN, VR	Not disclosed
11	Choma and Hanoch (2017)	MR, 3DR, LNS, VR	4
12	Colalillo (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
13	Collmus and Landers (2019)	MR, 3DR, LNS, VR, PM	Not disclosed
14	Connelly et al. (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
15	Dunlop et al. (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
16	Elpers (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
17	Erceg, Galic and Bubić (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
18	Evans et al. (2019)	LNS, VR	25
19	Farmer et al. (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
20	Fayn, Silvia, Dejonckheere, Verdonck and Kuppens (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
21	Fournier et al. (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
22	Frick (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
23	Fu et al. (2020)	ICAR16 (MR, 3DR, LNS, VR)	16
24	Gillen et al. (2019)	MR	5
25	Goda et al. (2019)	MR, 3DR, LNS	5
26	Golino and Epskamp (2017)	ICAR60 (MR, 3DR, LNS, VR)	60
27	Hood (2015)	MR, 3DR, LNS, VR	40
28	Irons and Leber (2019)	MR	Not disclosed
29	Jach and Smillie (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
30	Jankovski et al. (2017)	PM	30
31	Kajonius and Björkman (2020)	ICAR16 (MR, 3DR, LNS, VR)	16
32	Kajonius (2014)	ICAR16 (MR, 3DR, LNS, VR)	16
33	Kajonius (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
34	Karwowski and Brzeski (2017)	MR, 3DR, LNS, VR	30
35	Karwowski et al. (2016)	MR, 3DR, LNS	30
36	Karwowski et al. (2017)	MR, 3DR, LNS, VR	30
37	Karwowski et al. (2018)	MR, 3DR, LNS, VR	15
38	Karwowski et al. (2020)	MR, 3DR, tasks that required reasoning	26
39	Kirkegaard and Bjerrekær (2016)	MR, 3DR, LNS, VR	5
40	Kirkegaard and Nordbjerg (2015)	ICAR16 (MR, 3DR, LNS, VR)	16
41	Krieke et al. (2016)	MR, 3DR	35
42	Liknaitzky et al. (2017)	VR	Not disclosed
43	Lim (2018)	MR	11
44	Liu et al. (2017)	MR, VR	46
45	Lortie (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
46	Ludeke and Rasmussen (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
47	Lugonja et al. (2018)	MR	11
48	McKay et al. (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
49	Nikolaou et al. (2019)	MR	11
50	Paulsen (2018)	ICAR16 (MR, 3DR, LNS, VR)	16

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Study #	Authors	ICAR variables used	# of items
51	Phillips (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
52	Rasmussen (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
53	Rasmussen (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
54	Rautu (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
55	Rautu (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
56	Rhoades (2017)	MR, VR, LNS	24
57	Rouault et al. (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
58	Roulin (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
59	Rouse (2019)	VR	Not disclosed
60	Rowe (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
61	Seow et al. (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
62	Shu (2018)	LNS, VR	20
63	Subotić et al. (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
64	Talamas et al. (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
65	Thompson (2018)	MR, LNS	20
66	Thurston (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
67	Townsley (2018)	MR, 3DR	8
68	Treadway (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
69	Van Geert, Orhon, Cioca, Mamede, Golušin, Hubená and Morillo (2016)	ICAR16 (MR, 3DR, LNS, VR)	16
70	Vermunt et al. (2018)	MR, 3DR, LNS, VR	12
71	Weiss et al. (2018)	LNS, VR	8
72	Weyhrauch (2017)	ICAR16 (MR, 3DR, LNS, VR)	16
73	Womick et al. (2019)	MR, 3DR, LNS, VR	12
74	Woznyj, Banks, Dunn, Berka and Woehr (2020)	ICAR16 (MR, 3DR, LNS, VR)	16
75	Young et al. (2019)	ICAR16, ICAR60 (MR, 3DR, LNS, VR)	16, 60
76	Zabelina et al. (2019)	ICAR16 (MR, 3DR, LNS, VR)	16
77	Zhang and Goffin (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
78	Zhang (2018)	ICAR16 (MR, 3DR, LNS, VR)	16
79	Zirenko (2018)	MR, 3DR	35

Note. ICAR= International Cognitive Ability Resource, ICAR16= 16 item ICAR Sample Test, ICAR60= 60 item ICAR test, LNS= Letter and Number Series, MR= Matrix Reasoning, PM=Progressive Matrices, 3DR= Three Dimensional Rotation, VR=Verbal Reasoning.