CHAPTER 4

The Nature of the General Factor of Intelligence

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In the current chapter, we present an overview of our program of research on the relationship between working memory, executive attention, and intelligence. This line of work has culminated in a new theory of the positive manifold of intelligence and a corresponding new model of the general factor, *g*. We refer to this new framework as process overlap theory (POT) (Kovacs & Conway, 2016b). We present here an overview of POT and review initial empirical support of the theory. We conclude this chapter by addressing a series of questions posed by the editor.

When describing our research on intelligence, we find it useful to start with a description of the positive manifold, which refers to the pattern of all-positive correlations that is observed when a battery of mental tests is administered to a large, heterogeneous sample of people. Even when the battery of tests includes rather diverse tasks, such as a vocabulary test and a mental rotation test, the correlations observed among all tests tend to be positive. It is also true that, among this pattern of all-positive correlations, there are clusters of correlations that are stronger than others, and these clusters of strong correlations are thought to reflect what are known as group factors, representing broadly interpreted abilities. For example, a vocabulary test, a reading comprehension test, and a listening comprehension test might reveal relatively strong positive correlations within the positive manifold, and this cluster is thought to reflect a group factor that we might refer to as verbal ability. This pattern of all-positive correlations and clusters of particularly strong positive correlations is best explained by confirmatory factor analysis that includes a hierarchical general factor. That is, multiple group factors, such as verbal ability and spatial ability, account for the clusters of strong positive correlations, and a higher-order general factor, or *g*, accounts for the positive manifold.

The Cattell-Horn-Caroll (CHC) (McGrew, 2009) model nicely captures this factorial structure of intelligence (see Figure 4.1). The CHC

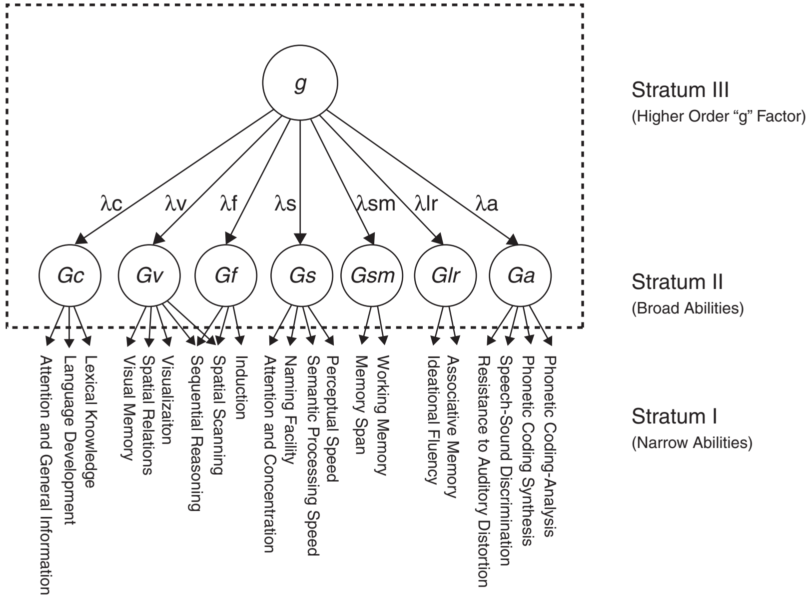

Figure 4.1 The Cattell-Horn-Carroll psychometric model of intelligence. Ovals represent latent variables. Directional arrows depict causality. *g*: general intelligence; Gc: crystallized knowledge; Gv: visual-spatial ability; Gf: fluid reasoning; Gs: processing speed; Gsm: short-term/working memory; Glr: memory retrieval; Ga: auditory processing; λ: Factor loading of each broad ability on *g*.

model consists of seven group factors, including fluid and crystallized intelligence, as well as a higher-order *g* factor, which represents general intelligence. We find the CHC model to be a useful description of the structure of intelligence but we take issue with the interpretation of the general factor as reflective of a general cognitive ability. According to POT, which we describe in more detail in the next section, the general factor is "not a thing," and therefore cannot have a causal influence on mental test scores.

Process Overlap Theory

POT is motivated by the theory of fluid and crystallized intelligence (Blair, 2006; Cattell, 1971; Horn, 1994; McGrew, 2009). This model makes a distinction between fluid reasoning and crystallized knowledge. Fluid reasoning is the ability to solve novel problems, the solution of which does not depend on previously acquired skills and knowledge. It is usually measured with tests that require inductive reasoning, such as Raven's Progressive Matrices. Crystallized knowledge, in contrast, depends on experience and existing skills, and is usually measured by tests of general knowledge or vocabulary.

POT also builds upon research on the relationship between working memory and fluid intelligence. Working memory refers to the "the ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information processing" (Cowan, 2016). For example, to comprehend this chapter, you must maintain information in an accessible state and at the same time continue to process new words, phrases, sentences, and paragraphs. Measures of working memory capacity, such as complex span tests, require this type of parallel storage and processing. For example, in the operation span test, participants have to remember a list of words while also solving a series of mathematical operations. Complex span tests are therefore different from so-called simple span tests, such as digit span, letter span, or word span, in which participants simply have to recall a list of items. And in contrast to simple span tests, variance in complex span tests is primarily domain-general (Kane et al., 2004). Therefore, similar to intelligence tests, a general factor of working memory capacity can be extracted, and this factor correlates strongly with fluid intelligence (Kane, Hambrick, & Conway, 2005; Oberauer et al., 2005).

POT is also inspired by empirical results on the relationship between working memory and fluid reasoning. Specifically, our prior work suggests that whatever working memory tasks measure beyond simple storage correlates most strongly with fluid reasoning (Conway & Kovacs, 2013; Kovacs, 2010). Furthermore, the processes that working memory tasks measure, beyond storage, most likely reflect individual differences in the executive attention component of working memory (Engle & Kane, 2004; Engle et al., 1999; Kane et al., 2001; Kane & Engle, 2002).

The main premise of POT is that a battery of intelligence tests requires a number of domain-general processes, such as those involved in working memory and attention, as well as a number of domain-specific processes. Importantly, domain-general processes are required by the majority (but not all) of test items, whereas domain-specific processes are required less frequently, depending on the nature of the test (e.g., verbal vs. spatial). Such a pattern of overlapping processes explains the positive manifold and thus the general factor. POT is, in this respect, similar to Thomson's sampling model (Thomson, 1916), but is also different in crucial ways (Kovacs & Conway, 2016a).

The most important and novel aspect of POT, and its main divergence from Thomson's ideas, is that it proposes that the processes involved in test performance are non-additive. Since executive attention processes are involved in the majority of test items, individual differences in executive attention pose general limits on total performance, acting as a bottleneck and masking individual differences in more domain-specific processes.

Besides providing an account of the positive manifold, POT also explains a number of important phenomena observed in the study of human intelligence. The first such phenomenon is ability differentiation, which refers to the finding that cross-domain correlations are higher in samples with lower average ability and so *g* explains more variance in such samples. The second is the worst performance rule, the finding that worst performance on a test (e.g., slowest reaction times on a speeded test) is a better predictor of *g* than average or best performance. The third is that the more complex a task, the higher its correlation with *g*. Finally, through proposing that the positive manifold is caused by the overlapping activation of the executive attention processes that are involved in both working memory and fluid reasoning, the theory accounts for the central role of fluid reasoning in the structure of human abilities, and for the finding that the fluid reasoning factor (Gf) seems to be statistically identical or near-identical to *g* (Gustafsson, 1984).

POT is therefore able to explain why *g* is both population- and task-dependent, i.e., it explains the most variance in 1) populations with lower ability, 2) worst performance, and 3) cognitively demanding tasks. POT focuses on the limitations of executive attention processes in explaining *g*, and proposes an interaction between the executive demands of the task and the executive functioning of the individual. This is expressed in a formal mathematical model (a multidimensional item response model) that specifies the probability of arriving at a correct answer on a given mental test item as the function of the level of domain-specific as well as domain-general cognitive processes (see Kovacs & Conway, 2016b).

The most important consequence of the theory is that *g* is "not a thing" but instead is the consequence of a set of overlapping cognitive processes sampled by a battery of tests. Therefore the general factor is a *formative* latent variable (Bagozzi, 2007), and as such it can be thought of as an index of mental functioning. Scores on the general factor represent a summary statistic that can be used to predict various phenomena, ranging from everyday cognitive performance (e.g., academic achievement and job performance) to non-cognitive life outcomes (e.g., socioeconomic status or longevity). Thus POT does not deny the existence of *g*, but, contrary to the standard view, interprets it as an emergent rather than a latent property.

Internal Consistency of POT

Kan, Van der Maas, and Kievit (2016) conducted a series of simulations to test whether a mathematical model of test performance, consistent with POT, would in fact generate a latent variable model consistent with the theory. They first created a specific version of the general mathematical model, which they then used in their simulation. Consistent with POT, fluid, verbal, and visuospatial reasoning were determined by a number of processes that each have a capacity, and the probability that a domain-general process is sampled was high (p = 0.50–0.60), while the probability that a domain-specific process is sampled was relatively low (p = 0.35).

Based on these equations and parameter settings, Kan and colleagues simulated test scores on three fluid intelligence tests, three verbal tests, and three visuospatial tests. The simulation resulted in a three-factor model in which all three factors were correlated and the correlations with the fluid reasoning factor were stronger than the correlation between the verbal and visuospatial factor. This is exactly what POT predicts. The results of the simulation are presented in Figure 4.2.

Besides providing evidence for POT, this simulation also demonstrates that it is possible for the positive manifold to emerge, and for a general factor model to be statistically appropriate even if there is no single process involved in all kinds of cognitive activities that a causal (non-formative) general factor could meaningfully represent.

Empirical Support of POT

One of the central claims of POT is that domain-general processes associated with working memory and executive attention will constrain performance on most items on most intelligence tests. To be clear, these processes are not essential for all items on all tests; for example, if one knows the definition of words on a vocabulary test, then working memory capacity will not constrain performance. But on most tests, and especially those that require fluid reasoning, working memory capacity and executive attention are vital. It therefore follows that scores on tests of

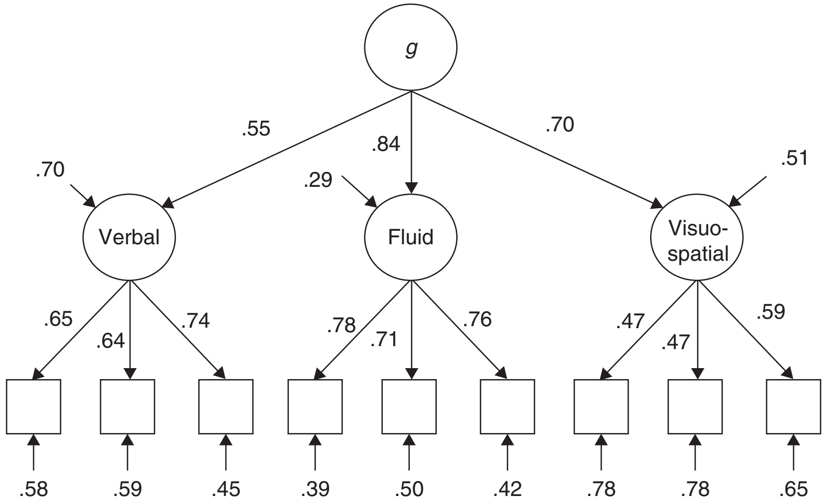

Figure 4.2 A latent variable model illustrating the results of a simulation by Kan et al. (2016). Ovals represent latent variables and squares represent manifest variables (representing nine simulated tasks, three for each construct). Directional arrows depict causality. *g*: general intelligence; Verbal: verbal ability; Fluid: fluid reasoning; Visuospatial: visuospatial ability.

working memory and executive attention should be strongly correlated (but not perfectly correlated) with fluid intelligence and the general factor of intelligence.

It is now well established that working memory capacity is strongly correlated with fluid intelligence. While some researchers have gone as far as to say that working memory capacity and reasoning are perfectly correlated (Kyllonen & Christal, 1990), two meta-analyses of latent variable studies investigating the relationship between working memory and fluid intelligence estimate that the correlation is somewhere between $r = 0.72$ to $r = 0.81$ (Kane et al., 2005; Oberauer et al., 2005). This estimate is consistent with a recent large sample study that found a correlation of $r = 0.77$ between the two constructs (Gignac, 2007).

According to the executive attention theory of individual differences in working memory capacity (Engle & Kane, 2004; Kane et al., 2001), the reason working memory and fluid intelligence are so strongly related is that both constructs rely to a great extent on executive functions, such as updating, inhibition, and task-switching. Therefore, measures of executive function should also be strongly related to fluid intelligence. Indeed, several recent latent variable studies have demonstrated strong correlations between executive attention and fluid intelligence (Engelhardt et al., 2016; Shipstead et al., 2014; Unsworth et al., 2014).

Editor's Questions

What Is Intelligence?

Intelligence researchers rarely agree on a definition of intelligence (Sternberg & Detterman, 1986). However, most definitions refer to a "general mental capability," or "general intelligence," or something similar. As discussed, POT rejects the notion of a general ability that permeates all of cognition; hence we reject this family of definitions.

In fact, our definition of intelligence is twofold. Our primary focus is on abilities that, unlike *g*, can be substantively interpreted. This, together with the functional overlap of processes in cognitive performance that POT proposes, translates to the following definition:

> Intelligence is a system of separate abilities, some of which are domain-general, such as fluid reasoning, working memory, and executive attention, while others are domain-specific, such as verbal, spatial, or numerical skills. Each ability is in fact the result of a set of processes that are activated in an overlapping fashion by cognitive activity, such that many of the processes involved in working memory are also tapped to some extent by tests that purportedly measure domain-specific cognition.

Second, however, our model also includes *g*, albeit as a kind of index rather than a casual factor. This aspect of POT invokes the infamous definition by Edwin Boring (Boring, 1923), which recently gained new support (Van der Maas, Kan, & Borsboom, 2014), and which claims that *intelligence is what tests of intelligence measure*. If intelligence tests do not *measure* *g* per se, but rather *g* is the result of measurement, there is substantial flexibility in what kind of abilities one can include in intelligence. This is the reason we did not specify a list of specific abilities (like Thurstone's Primary Mental Abilities) in our definition.

Intelligence can be composed of different abilities for different "purposes," making the construct largely dependent on the cultural context in which one is trying to achieve success (Sternberg & Grigorenko, 2004). Having said that, we find it important to emphasize that fluid intelligence, as well as the overlapping constructs of working memory and executive attention, appear to be tremendously important cognitive skills in modern Western societies (e.g., Raven, 2000; St Clair-Thompson & Gathercole, 2006).

How Is Intelligence Best Measured?

It is important to consider the goal of measurement when choosing an appropriate assessment tool. Intelligence is best measured using a diverse battery of tests that can provide a profile-type assessment, highlighting individual strengths and weaknesses. A diverse set of tests is optimal if the goal is the diagnosis of learning disabilities because it allows for the detection of anomalous scores.

If, however, the goal of assessment is to predict a more specific outcome, then a narrow range of tests may be more appropriate. If the circumstances only allow a rough and ready evaluation of one's cognitive abilities, or if for some reason a single overall estimate is sufficient, a test of fluid intelligence is probably the best solution, as the fluid intelligence factor (Gf) is statistically near-identical to *g* (Gustafsson, 1984; Matzke, Dolan, & Molenaar, 2010); therefore tests of fluid reasoning tap central aspects of the variation in cognitive abilities. Finally, from a technical perspective, the best method for the measurement of cognitive abilities is *computerized adaptive testing* (Kovacs & Temesvari, 2016; Van der Linden & Glas, 2002; Weiner & Dorans, 2000).

The rise in popularity of websites like Lumosity and Cogmed raises another important related question: **can intelligence be measured through video games?** Angeles Quiroga and colleagues (2015) found that scores on the general factor derived from video games were very strongly correlated with scores on the general factor derived from the intelligence tests ($r = 0.93$). This is an exciting finding because it suggests that *g* scores can be reliably obtained from games. This obviously makes assessment more fun for the participants, but it presents other benefits as well; the use of games for assessment allows for repeated measurements and the tracking of performance relative to one's own baseline.

How Is Intelligence Best Developed?

In the past decade, online training programs, or "brain games," such as Lumosity, CogniFit, and Cogmed, have become incredibly popular. These websites claim to provide broad and general cognitive enhancement. Despite these claims, a recent independent review of "brain training" websites is rather pessimistic. Their conclusion: "we find extensive evidence that brain-training interventions improve performance on the trained tasks, less evidence that such interventions improve performance on closely related tasks, and little evidence that training enhances performance on distantly related tasks or that training improves everyday cognitive performance" (Simons et al., 2016). This is consistent with a recent meta-analysis of working memory training experiments, which provides evidence for near transfer but "no convincing evidence" for far transfer (Melby-Lervåg, Redick, & Hulme, 2016). Overall, our current state of knowledge does not seem to substantiate the strong claims of the marketers of such products, and careful future research is needed for such methods to be validated.

At the same time, most studies on training have focused on adults, in particular the elderly. The verdict on such studies does not necessarily transfer to children, whose brains are much more plastic and for whom such training might therefore be more beneficial. Indeed, it seems possible to improve executive attention in children with targeted interventions (Diamond et al., 2007; Thorell et al., 2009). Besides, regardless of the efficiency of recent cognitive training programs, there is a well-established brain-training method aimed particularly at children that clearly has the capability of raising intelligence: it is called education (Cahan & Cohen, 1989; Nisbett, 2009).

What Are Some of the Most Interesting Empirical Results from Your Own Research and Why Are They Important to the Field?

The most important result of our own research is process overlap theory, a new explanation of the more-than-a-century-old problem of the positive manifold (Kovacs & Conway, 2016b). In terms of empirical results, the most relevant findings from our own research concern the relationship between working memory and fluid intelligence and between working memory and executive attention. We have contributed to the now large literature demonstrating a strong relationship between working memory capacity and fluid intelligence (e.g., Conway et al., 2002; Conway & Kovacs, 2013; Engle et al., 1999; Kane et al., 2001, 2005), and we have provided empirical support for the executive attention theory of individual differences in working memory capacity, demonstrating that working memory capacity is related to the performance of attention tasks that have minimal memory demands (e.g., Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001; Conway et al., 1999). All of these empirical results are important in the current context because POT is influenced, to a great extent, by the executive attention theory of working memory.

We have also demonstrated that the processes that working memory tasks measure beyond pure storage and retrieval are most strongly related to fluid reasoning and least strongly to crystallized intelligence and processing speed (Conway & Kovacs, 2013; Kovacs, 2010).

Finally, as a work in progress, our preliminary results suggest that ability differentiation also takes place in working memory capacity, meaning that the correlations between domain-specific working memory tasks are stronger when overall capacity is lower and thus the general working memory capacity factor explains more variance in populations with lower working memory capacity (Kovacs, Molenaar, & Conway, in progress). This result can greatly inform debates about the domain-generality of working memory capacity.

What Do You See as the Most Important Educational or Social Policy Issue Facing the Field of Intelligence Today?

In our view, the most important educational issue facing the field of intelligence is the need to educate society with regard to the science of intelligence. That is, we intelligence researchers need to do a better job communicating our work to a broader audience. Mackintosh (2014) provides several compelling arguments as to why we all should be teaching a course on intelligence. We argue that such courses should be taught not only in psychology departments, but also in schools of education.

Besides, the field of education should move toward more evidence-based policies and interventions, and a dialog with researchers of cognitive ability should be an important milestone. All too often, ideas become fashionable among educators without thorough research having demonstrated their validity with prior evidence. For instance, the concept of learning styles seems to be immensely popular, even though there seems to be no solid evidence to back up the utility of matching teaching styles accordingly (Pashler et al., 2009; Rogowsky, Calhoun, & Tallal, 2015). Similarly, the so-called 10,000 hour rule has received enormous hype, even though the empirical evidence is far from univocal (Macnamara, Hambrick, & Oswald, 2014).

What Are the Most Important Questions about Intelligence that Future Research on Intelligence Should Address?

According to the United Nations 2015 report on aging, older persons are expected to account for more than 25% of the populations in Europe and in North America by 2030 (United Nations Department of Economic and Social Affairs Population Division, 2015). Therefore, one of the most important questions that future research on intelligence should address is **how do components of intelligence decline with age?** It is clear that some components of intelligence, such as fluid reasoning and processing speed, demonstrate sharp declines with age, while other components, such as crystallized intelligence, remain relatively stable and might even peak quite late (Hartshorne & Germine, 2015). An important area for future research is gaining a better understanding of the cognitive aging process and exploring ways in which declines in ability can be prevented or slowed.

As discussed before, one of the most important questions to be addressed by future research is whether intelligence can be enhanced through cognitive training. Finally, an ever-important question, which our own recent work addresses, is one of the most fundamental questions about intelligence: **what is the nature of *g*?** According to POT, *g* is "not a thing," but instead is a summary statistic. It remains to be seen whether such a view of *g* is correct, but if it is, that has implications for how the science of intelligence should proceed. For example, if *g* is nothing but a summary statistic, then the search for the neural basis of *g* is meaningless. Likewise, if *g* is just a summary statistic, then the search for general intelligence genes is also meaningless. In their commentary on process overlap theory, Kan and colleagues (2016) put it this way: "if a constructivist conceptualization of the higher order factor is most appropriate, this informs and constrains our search for neural and genetic antecedents: The most fruitful path in such cases would be to focus on those lower order variables that do allow for a realist, causal interpretation." We couldn't agree more.

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