CHAPTER SIX

PROCESS OVERLAP THEORY: HOW THE INTERPLAY BETWEEN SPECIFIC AND GENERAL MENTAL ABILITIES ACCOUNTS FOR THE POSITIVE MANIFOLD IN INTELLIGENCE

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Introduction: Experimental and differential psychology

The scientific study of individual differences in cognition and mainstream experimental psychology have been separated since the birth of modern psychology. Francis Galton's famous work on mental ability (Galton, 1869) was published a decade before Wilhelm Wundt established the first psychological laboratory, yet Galton had little influence on Wundt who was uninterested in individual differences. James McKeen Cattell, a PhD student of Wundt at the time, under the strong influence of Francis Galton and his theory of intelligence as sensory acuity, intended to change the topic of his dissertation to individual differences in mental ability. The idea was opposed by Wundt, hence only after submitting his thesis in 1866 could Cattell start working on his 'mental tests', which were published in 1890 (Fancher, 1985). Titchener, the main advocate of Wundtian psychology, opposed the application of the methods of experimental psychology to the study of individual differences even more strongly (Brody, 2000). The separation became permanent after Clark Wissler put Cattell's mental tests to an empirical test and found no correlation either between the tests themselves or with an external criterion of intelligence, university grades.

> "This study was enormously influential. (…) The results of the study were instrumental in ending the attempt to measure intelligence by the techniques initially advocated by Galton." (Brody, 2000, p. 17.).

Wilhelm Stern, the inventor of the IQ formula outlined a unified framework for experimental and differential psychology, but it did not turn out to be influential: in 1957 Lee Cronbach still lamented on the two distinct lines of research in scientific psychology, correlational and experimental (Cronbach, 1957). This distinction has been also referred to as general vs. differential psychology (Brody, 2000; Deary, 2001).

In this chapter the current status of this separation will be examined from a methodological perspective, with a focus on identifying domain-specificity in correlational and experimental psychology. This will be followed by a recent theoretical endeavour, process overlap theory, that purports to explain individual differences in intelligence on the basis of mechanisms identified by experimental psychology and neuroscience.

Modularity and intelligence 1: from mental architecture to individual differences?

In the past decades the doctrine of domain-specificity has become dominant in cognitive psychology and the localization of specific functions has been a central theme in neuropsychology and neuroscience. The idea of domain-specificity was expanded in Jerry Fodor's seminal book on the architecture of the mind (Fodor, 1983), which championed in articulating the concept of modularity. The central tenet of Fodor's theory of modularity is that the human mind is comprised of a general processing mechanism as well as domain-specific modules: specific processing mechanisms that react to specific kinds of stimuli only.

Fodor criticises 19th century "faculty psychology". He introduces a distinction between what he calls the horizontal and vertical systemization of the mind and argues in favor of the latter. By horizontal fractionation he means identifying domain-general systems that are separated according to the processes involved. For example, in this systemization memory and perception are separated, but the same memory processes are activated regardless of the nature of stimuli: we rely on the same cognitive system to remember the colour of the neighbour's dog, the date of Aristotle's birth or what our first day in school was like. According to Fodor, psychometrics, just like old faculty psychology, belongs to the horizontal tradition, and both are fundamentally wrong. Vertical systemization, on the other hand, is domain-specific: it focuses on the nature of the sensory information that serves as an input for the given system rather than on the processes involved. That is, a separate system is responsible for processing human faces, objects, or music, even if all these processes contribute to perception.

Besides domain-specificity, the other most important feature of modules, according to Fodor, is encapsulatedness, which means that modules are processing information independently, never in conjunction with other modules. Once processing is carried out each module provides output information for the general-purpose mechanism that all the modules feed into. In this chapter emphasis will be put on these two aspects of the concept of modularity, mostly ignoring other characteristics such as rapid and compulsory processing, computational nature, a lack of top-down control, innateness, etc.

Fodor claims that the roots of a vertical (i.e. modular) systemization of the mind can be found in Gall's phrenology. Gall's famous phrenological map, however, was actually constructed on the basis of individual differences data. Gall claimed that psychological differences in certain characteristics are correlated with morphological differences on the surface of the skull, which are in turn caused by differences in the parts of the brain that lie beneath those surfaces.

There is another version of the modularity hypothesis which claims that there is no general-purpose mechanism at all, the mind is entirely made up of domain-specific processes. This view, called 'massive modularity' (Sperber, 1994; Tooby & Cosmides, 1992) is shared by many evolutionary psychologists, but is sharply criticized by Fodor himself (Fodor, 2000).

When cognitive psychologists or cognitive scientists claim that something is modular they usually refer to double dissociation and rely on two sorts of evidence. The first comes from neuropsychological studies: an injury to one part of the brain results in the loss of an ability but leaves another intact, while an injury to a different part of the brain impairs the second ability but leaves the first intact. According to such evidence linguistic, spatial, and numerical cognition have been described as modular as all of them can be impaired without a decrease in performance in other areas.

The second comes from experimental studies and is based on interference. If participants have to solve two tasks in parallel and performance on one does not deteriorate with the onset of the other then the two tasks are considered to tap independent processes; if the two tasks interfere with one another, they are considered to tap the same process(es). For instance, such experiments were crucial for establishing the multi-component model of working memory (Baddeley & Hitch, 1974).

The concept of domain-specificity is indeed well supported by evidence from double dissociation. In fact, such evidence is crucial for modular theories about mental architecture. At the same time, the very concept of mental architecture is a universal one and as such is a within-individual account of cognition that cannot be automatically applied to the structure of between-individual variation. From a methodological perspective: double dissociation and experimental interference are appropriate pieces of evidence to fractionate at the within-individual level. Yet drawing direct inferences from such evidence to the structure of *individual differences* is, arguably, a fallacy. Take the following section, for instance, about a book on mental architecture:

> "One of the themes that emerged from part I of this book was the large number and the great diversity of different cognitive talents that are normally knit together to make up the intelligence of a real human. We saw this in the diversity of artificial networks that have been built to imitate one or other small aspects of human cognition, such as the ability to recognize faces, to read printed text, to see in three dimensions, to generate locomotion, to discriminate sounds, to discriminate emotions, and to discriminate grammatical sentences. We saw it again in the great variety of severe but isolated cognitive deficits that typically result from localized damage to various parts of the living brain.
>
> This diversity illustrates that **intelligence is not a one-dimensional commodity, something that varies only from greater to lesser**. Rather, the intelligence of any human has many dimensions, and **in a normal human population the scattered variation in cognitive ability within each of these dimensions will be considerable**." (Churchland, 1996, p. 253, bold added).

The argument essentially identifies separate – within-individual – cognitive systems and concludes that if they are independent then their variance must also be independent. Not only does this conclusion not necessarily follow from its premises, it actually seems to be directly contradicted by the – arguably – most replicated result in all of psychology: the positive manifold.

The positive manifold refers to the pattern of all-positive correlations that is observed when mental tests are administered to a large sample of people. Even when the tests include different domains such as in the case of a vocabulary test and a mental rotation test, the observed correlations are always positive. Overall, 40-50% of the between-individual variation in mental test scores is domain-general (Deary, Penke, & Johnson, 2010; Jensen, 1998).

This empirical finding will not be refuted by the logical analysis of within-individual evidence on modularity. In other words: the second half of the last sentence of the above quote ("in a normal human population the scattered variation in cognitive ability within each of these dimensions will be considerable") does not follow from the first half ("the intelligence of any human has many dimensions").

A dissociation of two processes in this sense is unrelated to the correlation between them (Kovacs, Plaisted, & Mackintosh, 2006). For instance, imagine if one measured different indicators of strength in both arms in a large sample (the strength of grip, the maximum weight one can lift, etc.). Measures of the strength of people's left arm will most probably correlate with those of the right arm, regardless of 1) people being able to do things with their arms in parallel (lack of interference in an experimental condition), or 2) people can lose only one of their arms in an accident with the other arm remaining intact (selective impairment due to injury).

There are several possibilities for two different parts of the brain to be responsible for different domain-specific functions while performance on those tests can still correlate. One option is that there are certain parameters (e.g. neural conduction velocity, speed or accuracy of neural transmission, myelinisation, efficiency of glucose metabolism) that are common to these cognitive functions (Jensen, 1998). Another is that there are mutually beneficial interactions during development (van der Maas et al., 2006). A third possibility will be the focus of Section 4 in this chapter.

The quote above also highlights another important issue: the use of the very word *intelligence* in a within-individual and in an individual differences context. Not distinguishing these two conceptions necessarily leads to confusion as the two meanings are incommensurable. A modular mind can accommodate a general factor; or to be more precise, individual differences that are domain-general to a large extent are compatible with those differences appearing between people who have a modular mind. One cannot draw inferences directly from within-individual evidence on domain-specificity: such evidence is undeterministic to the structure of variation, which can *logically* be either domain-general or domain-specific, but *empirically* appears to be largely domain-general.

In his influential book Howard Gardner claimed that intelligence is not unitary, instead there are seven different and independent kinds of intelligences (Gardner, 1983). Gardner has since extended his list of intelligences (Gardner, 1999), but from the perspective of the current chapter the exact list or number of multiple intelligences is less interesting than the methods for separating them. Gardner has eight criteria which a specific ability has to satisfy in order to be considered an "intelligence".

1. "Potential isolation by brain damage.
2. The existence of idiots savants, prodigies, and other exceptional individuals.
3. An identifiable core operation or set of operations.
4. A distinctive developmental history, along with a definable set of expert "end-state" performances.
5. An evolutionary history and evolutionary plausibility.
6. Support from experimental psychological investigations.
7. Support from psychometric findings.
8. Susceptibility to encoding in a symbol system." (Gardner, 1983, p. 62-69.)

Apparently, Gardner's methods for separating "intelligences" show substantial overlap with the cognitive scientist's toolbox for studying mental architecture. The first criterion, potential isolation by brain damage, is basically equivalent to double dissociation based on selective impairment. The sixth criterion, support from experimental psychological investigations relates to interference between various tasks. As argued above: such pieces of evidence are sufficient to theorize about mental architecture, but are not directly relevant for differential psychologists who purport to identify the structure of mental abilities based on correlations between various mental tests. The existence of specific disorders falls under the same category: in the arm strength analogy this would be equivalent to a developmental disorder, instead of an accident, affecting only one of the arms.

Different developmental or evolutionary histories are also independent of the possible covariation between abilities. Human new-borns have a much higher head to body ratio than adults and in the course of development the head-body ratio substantially decreases. That is, the size of different parts of the body change independently: they have *distinctive developmental history.* But there is no a priori reason to suspect that this change affects the correlation between head and body size at any stage of development. Similarly, in the course of hominid evolution, the arm length to leg length ratio has decreased; the size of arms and legs changed independently, hence they have *different evolutionary histories*. Yet again, there is no a priori reason to expect that the correlation between the length of legs and arms have changed at any point.

What needs to be emphasized from the perspective of the current chapter is that Gardner's book is in fact more similar in its ideas and methods to Fodor's book on modularity then to standard works on human intelligence that focus on individual differences. In fact, due to his criteria, Gardner's book is more about mental architecture then about variation in intelligence; apart from his psychometric criterion, of course, but from that perspective three of his intelligences, linguistic, logical-mathematical, and spatial in fact do correlate.

Modularity and intelligence 2: from individual differences to mental architecture?

Psychologists studying individual differences in intelligence have applied the method of factor analysis to explore the structure of abilities responsible for performance on various mental tests. With the help of factor analysis, the large correlation matrices that consist of the inter-correlations of diverse cognitive tests can be simplified, assuming that the correlation between any two tests is the result of the tests' correlation with a "latent variable" which is not directly measurable.

As discussed in the previous section, tests measuring cognitive abilities always show positive correlations and this phenomenon is referred to as the positive manifold; therefore factor analysis yields a strong general factor, *g*, that accounts for 40-50% of the variance. Yet 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 cognitive 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. This cluster, then, is thought to reflect a group factor that we might refer to as verbal ability. That is, in the literature of human intelligence, which traditionally focuses on individual differences, specific abilities are identified not through double dissociation, but by the covariance structure of tests with different content.

The analysis of large data sets demonstrated that a single general factor is insufficient to explain all of the variance since, for instance, verbal, spatial, and numerical tests correlate more strongly with one another than with tests tapping into other domains. Nor can the correlations between tests be accounted for by only specific factors because nearly half of the total variance in human abilities is cross-domain. The widely accepted three-stratum model acknowledges both *g* and specific factors at different levels of a hierarchy, where the correlation of group factors results in *g* (Carroll, 1993).

With respect to the "content" of factors, a widely accepted account is the model of fluid and crystallized intelligence (Cattell, 1971; Horn, 1994). In this model there are domain-specific as well as domain-general group factors, the most important of which are Gf (fluid intelligence) and Gc (crystallized intelligence). Gf is the ability to solve novel problems for which one cannot rely on already acquired skills or knowledge and is usually measured with tests of non-verbal, abstract reasoning. Tests that give loading on Gc measure previously acquired knowledge and typically consist of verbal material, such as vocabulary or reading comprehension. Other important factors of the model are Gv (visual-spatial), Gs (speed), Gsm (working memory). All factors are not created equal: Gf has a central role among cognitive abilities in the fluid-crystallized model and the correlation between Gf and *g* is perfect or near-perfect at the latent level (e.g. Gustafsson, 1984).

Johnson and Bouchard argued that the major flaw of the fluid-crystallized model is that it does not posit a general factor on the grounds that general factors extracted from different batteries are not the same (Johnson & Bouchard, 2005), yet large-scale analysis shows that general factors are in fact identical across batteries (Johnson, Bouchard, Krueger, McGue, & Gottesman, 2004). A more recent development, the Cattell-Horn-Carroll (CHC) model of mental abilities unifies the Cattell-Horn description of specific abilities, in particular Gf and Gc with Carroll's three-stratum model. CHC thus has the Cattell-Horn factors on the 2nd stratum and the correlation between 2nd stratum factors is explained with a 3rd stratum general factor, *g* (McGrew, 2009).

Besides CHC, however, there are other models of intelligence. For instance, Vernon proposed a model with *g* and broad second order factors: v:ed for verbal-educational abilities and k:m for kinaesthetic and mechanic abilities (Vernon, 1961). His group factors are, arguably, more domain-specific than the ones in the CHC model: whereas Gf and Gc are basically described by whether one has to deal with novel or already acquired information, v:ed and k:m are described by the domain they cover.

Importantly, all factorial models stem from the phenomenon that all correlations between mental tests are positive and that there are groups of tests, typically with similar content, for which the correlations are higher than the average correlation between all tests. While factor analysis is a useful statistic tool to identify patterns in complex correlational data, the interpretation of factors is problematic. Stevan Harnad for example compared the interpretation of factors to hermeneutics:

> "There is a huge hermeneutic component to psychometric analysis. The empirical part is the calculation of the correlations in the extraction of factors; the hermeneutic part is in interpreting the factors, figuring out what on earth they may mean." (Bock, 2000, p. 48.)

Not only the interpretation, but also the very status of factors as constructs is a matter of debate. The most extreme view is probably that factors are mere mathematical artefacts with no reality (e.g. Gould, 1996). This argument capitalizes on the claim that there are many different factorial solutions to a given correlation matrix that are mathematically equally tenable and therefore it is not possible to choose between solutions in an objective fashion. Hence any attempt to give psychological meaning to factors qualifies as "reification": factors do not have validity other than statistical and any particular factorial account is just one of the infinite factorial solutions of a given correlation matrix.

The ambiguity of factorial solutions is actually well known among psychometricians:

> "It is (…) clear that the rotated factors may take up any position in factor space and that accordingly, as has been argued, there is a virtual infinity of solutions. Since, as has been seen, these are mathematically equivalent there is no mathematical reason for choosing one rather than another." (Kline, 1991, p. 61.)

Gould's argument, however, is a fallacy, since the fact that there are an *infinite* number of factorial solutions does not imply that *any* factorial solution will do and that it is not possible to reject any of them. For instance, the set of natural numbers consists of an infinite amount of numbers. However, neither '-1' nor '0.5' are parts of the set of natural numbers. Similarly, even if there is an infinite number of mathematically equivalent factorial solutions it is still possible for a given factorial solution to not fit the data. Indeed, several models in the history of intelligence research have been discarded, including Spearman's original model of *g*, Thurstone's model of Primary Mental Abilities, or Guilford's Structure of Intellect model (Guilford, 1956; Spearman, 1904; Thurstone, 1938).

An investigation of possible ontological stances one can take regarding latent variables concluded that one must take a realist view in order for assumptions of latent variable modeling not to be violated (Borsboom, Mellenbergh, & van Heerden, 2003). So if they are not mere statistical artefacts in what sense can factors be interpreted as *real*? Are they equivalent to processes, mechanisms, etc.? Do they have a meaningful within-individual interpretation? In particular: can the general factor of intelligence (psychometric *g*) be identified as a within-individual domain-general construct (psychological *g*)?

If it can, then the following statement is valid: “Anna used his general intelligence to correctly answer items on both the inductive reasoning test and the mental arithmetic test.” This, however, is substantially different from saying that “If Anna performs better on the inductive reasoning test than most people it is very likely that she will perform better on the mental arithmetic test as well”. The latter statement leaves the possibility open that Anna in fact did not use the same general ability on the two tests and there is some other reason for the results to correlate. The positive manifold only translates to the second statement, not the first; in order to validate the first statement one has to review other kinds of evidence about fractionation at the universal (or individual) level. That is, the first statement is about mental architecture, not individual differences. As it was discussed in the previous section: the actual evidence from cognitive psychology and neuropsychology questions the validity of the first statement.

Whether *g* can be interpreted as a unitary construct has been controversial from an individual differences perspective, too: Kranzler and Jensen have had a prolific debate with Carroll on the subject (Carroll, 1991a, 1991b, 1993, Kranzler & Jensen, 1991a, 1991b, 1993). Kranzler and Jensen factor analysed various elementary cognitive tasks (such as various reaction time and inspection time measures) and found different “elementary cognitive factors”, many of which correlated with the *g* factor extracted from psychometric tests but not with each other. From these results they concluded that *g* is the result of several independent processes.

Carroll disagreed and claimed that the procedure used by Kranzler and Jensen could not extract pure factor scores. He therefore argued that the question could not be decided by the methods employed by Kranzler and Jensen. From the perspective of the present chapter it is worth looking at Jensen’s evaluation of the debate:

> “to show that the general factor involves individual differences in two independent processes, A and B, and is therefore not fundamentally unitary would require that individual differences in A and B be measured separately and that A and B are each independently correlated with the general factor of the psychometric tests. The more difficult condition to satisfy (…) is that it must be assumed that the empirical *g* factor scores derived from the tests are “pure” *g* uncontaminated by any non-*g* “impurities”. (…) [But] because it is virtually impossible to prove definitively that the *g* factor scores are “pure” in this sense, **the issue retreats from the scientific arena, and it then becomes a purely**

> **metaphysical question whether g is or is not unitary."** (Jensen, 1998, p. 261., bold added).

The last sentence is surprising: while it might indeed be impossible to fractionate *g* on purely psychometric grounds, it is arguably cognitive psychology, cognitive science, and neuroscience, rather than metaphysics that can shed light on whether *g*, a general account of between-subject variation, is the result of a single, unitary process or a number of independent processes. If, for instance, different tests load on *g* but performance on the tests can be dissociated as a result of selective impairment then it is unlikely that *g* is the result of a single, unitary process, psychometric evidence notwithstanding. Let us return to the analogy of the strength of the arms once more: if we find that our measures correlate very strongly, or even perfectly between the two arms it would still be incorrect to claim that "armness" is a unitary construct (i.e., humans only have one arm).

Just like the cognitive scientist's toolbox underdetermines whether variation in cognitive abilities is domain-general or domain-specific, the psychometrician's toolbox underdetermines whether domain-general variation in cognitive abilities is the results of a single domain-general process. The architecture of cognition does not determine the structure of correlations between performance on various tasks and the latent variable structure of between-subject differences does not determine the architecture of cognition.

Therefore, a unitary domain-general cognitive mechanism is a sufficient but not necessary explanation of the positive manifold and is therefore not a necessary interpretation of *g*. In the next section a theory will be presented that actually does explain the positive manifold without postulating a unitary source of variance.

Finally, it is worth mentioning that the use of the expression *modularity* in both a within-individual and an individual differences context can be confusing, just like in the case of intelligence. Models of individual differences that emphasize group factors are sometimes referred to as modular and modularity is sometimes contrasted to *g* (e.g. Detterman, 1992). But a module in the cognitive scientist's sense (i.e., an encapsulated domain-specific processor) is not the same as a group factor, just like than the concept of general intelligence is not the same as *g*. Models focusing on domain-specific variance are not modular in the sense that modularity is traditionally used in cognitive science to describe mental architecture. It might be the case that there is an agreement between such within-individual and between-individual constructs. Such cases are referred to as ergodicity, but they are exceptions rather that the rule (Molenaar & Campbell, 2009). In the case of intelligence, it does not generally seem to be the case[1].

Process overlap theory

The most important feature of modularity is the "encapsulated" nature of modules: they are completely independent from one another with respect to information processing. The general assumption behind the concept of modularity is, therefore, that double dissociation is sufficient evidence to conclude that the tasks dissociated measure completely independent cognitive systems or modules.

Yet this is not the only reading of double dissociation; in fact double dissociation is arguably insufficient to claim complete functional independence. In the literature of memory research there has been a controversy between the systems vs. processes approach. From a methodological perspective the debate is about whether dissociation should be taken as evidence for postulating separate memory systems or whether such evidence is perfectly compatible with the existence of functionally overlapping processes:

> "Although on first appearances it may seem as if the difference between multiple processes and multiple systems is only terminological, it is in fact a fundamental difference. (…) multiple processes are construed as multiple steps in a stream of processing steps, not as comprising independent systems. Multiple systems operate independently of each other (they are similar to Fodorian modules) whereas multiple processes interact and combine to perform cognitive operations. (…) an alternative framework, *the components of processing framework*, developed by Morris Moscovitch, provides a more adequate framework that can resolve the conflict between the approaches. (…) different tasks may draw differentially upon different components in a processing system. **If two tasks can be dissociated** (…) **then there must be at least one component process that figures differently in the two tasks** (…). Within this framework, dissociations are no longer used to tease apart whole systems, but only differences in reliance on components within a larger system. It is here that the distinction between the systems and process approach becomes sharp." (Bechtel, 2001, p. 491-492, bold added).

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[1] With the probable exception of the cognitive concept 'fluid reasoning' and the psychometric group factor 'fluid intelligence' (Kievit, 2014).

A recent, process-oriented explanation of the positive manifold, called process overlap theory (POT, Kovacs & Conway, 2016) draws on the "components of processing" framework. It interprets evidence for dissociation (including neuropsychological, experimental, and developmental bases of dissociation) as ones fractionating processes rather than encapsulated and independent systems. That is, dissociated tests tap processes of which at least one is different, but not necessarily sets of completely different processes. Therefore the processes that are required for performance on different cognitive tests can overlap and can also be dissociated by brain injury etc. *at the same time*. Evidence for dissociation between domain-specific cognitive tests makes it difficult to interpret *g* as 'general intelligence', a unitary system that permeates all human cognition. But such evidence is compatible with an account of the general factor that explains the correlations between these domain-specific tests as the result of overlapping component processes. This is exactly what POT attempts.

POT is also strongly motivated by the sampling model of Godfrey Thomson. Thomson, a contemporary of Spearman, demonstrated mathematically that the positive manifold could emerge not only without a single underlying general intelligence but even without a single process being common to all of the tests. He proposed that different mental tests tap a large number of independent processes, some of which are common to more than one test. According to Thomson the correlation between different tests is caused by the overlap of the independent processes necessary to solve the tests; the larger the overlap, the larger the correlation. Using random data (he threw dice) Thomson was able to show that the positive manifold can be explained both by postulating a single general ability or a large number of independent processes (Thomson, 1916). A more recent analysis confirmed that from a statistical perspective one cannot decide between the sampling model and the *g* model, both are sufficient to account for the positive manifold (Bartholomew, Deary, & Lawn, 2009).

POT also builds upon research on the relationship between working memory and fluid intelligence. Working memory refers to:

> "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).

Measures of working memory capacity, such as complex span tests, require this type of parallel storage and processing. For example, in the symmetry span test participants have to remember spatial locations, the presentation of which is interrupted by images where symmetry judgments have to be made. Complex span tests are therefore different than so-called simple span tests, such as digit span, in which participants simply have to recall a list of items.

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: two meta-analyses of latent variable studies investigating the relationship between working memory and fluid intelligence estimate that the correlation is somewhere between $r = .72$ to $r = .81$ (Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süss, 2005).

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, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2002). According to the executive attention theory of individual differences in working memory capacity (Engle & Kane, 2004; Kane et al., 2001), working memory and fluid intelligence correlate strongly because both constructs rely to a great extent on executive functions, such as updating, inhibition, and task-switching. Indeed, several recent latent variable studies have demonstrated strong correlations between executive attention and fluid intelligence (Engelhardt et al., 2016; Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014)

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). Therefore, domain-general processes associated with working memory and executive attention will constrain performance on most items on most intelligence tests, whereas individual differences in specific processes will impact a narrower range of tests. Such a pattern of overlapping processes explains the positive manifold and thus the general factor as well as the domain-specific clusters of intercorrelated tests that result in group factors. Indeed, the first simulations that tested the theory confirmed POT (Kan, van der Maas, & Kievit, 2016; Kovacs, Conway, Snijder, & Hao, 2018): the positive manifold did emerge from the interplay of domain-specific and domain-general processes postulated by POT (see also McFarland, 2017, for a different but raleted simulation).

POT is similar to Thomson’s sampling model (Thomson, 1916), but is also different in crucial ways (Kovacs & Conway, 2016). 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. Therefore the correlation between two tests is not linearly related to the ratio of overlapping 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 (e.g., slowest reaction times) 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 (i.e., 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 (Kovacs & Conway, 2016).

Conclusions

In this chapter it has been argued that domain-specificity bears different meanings in differential psychology and in cognitive/experimental psychology. In the former it relates to finding that individual differences in tests with characteristic content (e.g. spatial or verbal) typically correlate more strongly with one another than with tests that have different content. In the latter it means that the mind can be fractionated into processors of specific content through double dissociation.

These two ways of identifying specificity in cognition do not necessarily translate to one another. That is, the general factor of intelligence does not necessarily translate to a domain-general problem solving mechanism and specific cognitive abilities in the differential sense are not the same as modules. It has been argued that a large part of incommensurability stems from the interpretation of double dissociation as evidence for completely independent cognitive systems responsible for the processing of domain-specific information.

Moscovitch's *component process model* of memory provides a different interpretation, one that is more compatible with domain-general variance in human mental abilities than a strongly modular approach to mental architecture:

> Given the emphasis on dissociations, it is easy to lose sight of the fact that these components, though isolable in principle, are typically highly interrelated. The components' function is determined not only by their internal organization but also by the network of connections to other components. (Moscovitch, 1992, p. 265.)

The most important consequence of POT 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 performanc) 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. Should the theory endure further tests it might eventually fulfil its main purpose: to explain variation in cognitive abilities by accounting for actual test performance with the interplay of general and specific cognitive processes that are identified by cognitive psychology and neuroscience.

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