Is Spearman's G determined by speed or working memory capacity?

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IS SPEARMAN'S G DETERMINED BY SPEED OR WORKING MEMORY CAPACITY?

Book Review of Jensen on Intelligence-g-Factor

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Abstract

According to Jensen, processing speed accounts for the relationship between working memory capacity (WMC) and general fluid abilities (gF). We argue that WMC, not speed, is the causal factor in the speed-WMC-gF relationship. Furthermore, we suggest that WMC, which reflects controlled attention capability, is the basis of gF.

Keywords

behavior genetics, cognitive modelling, evoked potentials, evolutionary psychology, factor analysis, g *factor, heritability, individual differences, intelligence, IQ, neurometrics, psychometrics, psychophyiology, skills, Spearman, statistics*

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1. The g Factor represents Jensen's (1998, 1999) lifetime commitment to the science of mental ability; it is impressive in its scholarship and scope. Jensen establishes that the general factor in cognitive ability is not a statistical artifact, it has practical validity, it is strongly related with psychological constructs born in the information processing approach to cognition, and it probably has some physiological and genetic basis.

2. Our particular interest is in Jensen's treatment of the information processing approach to g, specifically the relations among g, processing speed, and working memory capacity (WMC). We first outline Jensen's approach to the speed-WMC-g relationship and then demonstrate that it is incorrect. We then present evidence to support our own working hypothesis that WMC is the basis of Spearman's g. It is important for us to state at the outset that we favor Cattell's (1963) distinction between crystallized (gC) and fluid intelligence (gF), and that our arguments here pertain most closely to considerations of gF, and less so to gC.

3. There is abundant evidence, much of it reviewed by Jensen, that reaction time (RT) on elementary cognitive tasks (ECTs) is correlated with gF, with r's ranging from .2 0 to .60, depending on the number and kind of tasks employed. However, it is not at all clear what accounts for the RT-gF relationship. Jensen argues that processing speed is critical to gF because speed determines WMC, which in turn constrains global cognitive capability. According to his view, working memory has a limited capacity, both in terms of cognitive operations and content. Speed is therefore critical because: (1) faster processing allows more operations per unit time to proceed without overloading the system; (2) memory traces decay rapidly; and (3) rehearsal and storage take real time and so must compete. According to Jensen, then, a functionally above-average WMC actually reflects an above-average global processing speed (also see Kail & Salthouse, 1994; Salthouse, 1996).

4. We disagree. There are several empirical findings, some cited by Jensen himself, which cannot be reconciled with the notion that general speed is the underlying mechanism of WMC and general cognitive ability.

5. First, and somewhat amusing, is that rhesus monkeys (Macaca mulatta) show faster responses on ECTs than do human college students (Ms = 585 vs. 597), and that the monkeys also show substantially shallower RT slopes between simple-and complex-task RTs than do their Homo sapiens counterparts (Ms = 12 vs. 130 ms; Washburn & Rumbaugh, 1997)! Note, however, that the macaque intraspecies correlations between RT and a commonly employed measure of non-human "intelligence" are negative and similar in magnitude to those in the human literature (with r's ranging from -.44 to -.61). No monkey advantage over humans is ever found in WMC or short-term memory tasks. Clearly, these RT results should give pause to anyone proposing to rank intelligence of human races by "cognitive speed."

6. Second is the ubiquitous finding, reviewed by Jensen, that the correlation between RT and gF is larger when the ECT is "more complex," which really means when the ECT taxes memory and/or attention. If processing speed were linked to the general speed of neural transmission, then strong correlations should still be obtained in tasks without significant memory and attention demands, for such tasks obviously require neural transduction. Furthermore, ECTs in which the underlying processes can be automatized show decreasing RT variability and decreasing correlations with gF as practice proceeds (e.g., Ackerman, 1988; Rabbitt, 1997). These findings indicate that speed of controlled attentional processes, specifically, correlates with gF, rather than some general, biologically imposed speed limit in neural efficiency (which should actually be reflected best by automatized RTs). We are puzzled by Jensen's recognition of the contextual determinants of the RT-gF correlation, and his simultaneous insistence that

a global property of the entire nervous system (such as neural myelination) mediates it.

7. Third, the standard deviation of an individual's RT distribution predicts gF better than does the median of the RT distribution. More specifically, individuals' worst trial" RTs are more strongly related to gF than their "best trial" RTs (e.g., Larson & Alderton, 1990). That is, the fastest responses from low-gF individuals' RT distributions are actually as fast as the fastest responses from high-gF individuals' RT distributions. Low-gF individuals, however, produce more RTs in the extremely "slow" tail of the RT distribution than do high-gF individuals. Again, these findings indicate that individual differences in some fixed lower bound of neural speed cannot determine individual differences in gF.

8. Instead, considerations of attentional control will ultimately explain the greater RT variability shown by lower-gF subjects, as such variability reflects a deficit in sustaining attention to the essential requirements of a task. Low-gF subjects, who on our view are relatively distractable (e.g., Engle, Kane & Tuholski, 1999), will show fluctuations in readiness for responding when a target is presented. Therefore, on some trials, the task goals and requirements will simply not be active in working memory and so must be retrieved from long-term memory. Responding will therefore be slower on those particular trials and consequently, overall variability for low gF subjects will be higher. Furthermore, the unpredictability of the warning signal in ECTs only increases the importance of sustained attention to performance. On a typical ECT trial, a 1 s warning signal precedes a random interval of 1 to 4 s before the target stimulus appears. A venerable research literature indicates that as the time between a warning signal and stimulus onset increases from 1 to 4 s, response times tend to increase as the subject's ability to sustain set and predict target onset decreases (see Niemi & Naatanen, 1981; Teichner, 1954). Individual differences in sustained attention, then, must substantially contribute to ECT performance and variability.

9. Evidence from our own labs is also inconsistent with the notion that speed drives the relationship between WMC and gF. Before discussing the evidence it is necessary to describe how the WMC construct is typically measured. According to the information processing approach, the function of working memory is to store or maintain information in the service of concurrent processing (Baddeley & Hitch, 1974). The first WMC instrument developed under this theoretical framework was the "reading span" task (Daneman & Carpenter, 1980), which requires subjects to read series of sentences for comprehension and also to remember the last word of each sentence for later recall. The number of sentences per series typically varies from 2-6 when testing healthy adults. The largest series for which subjects can recall all the final words is taken as their capacity, or "span." In similar tasks, such as operation span (Turner & Engle, 1989) and counting span (Case, Kurland, & Goldberg, 1982; Conway, Cowan, Bunting, Therriault, & Minkoff, 1999; Engle, Tuholski, Laughlin, & Conway, 1999), subjects engage in mathematical or counting processes while simultaneously storing unrelated words or digits. Scores on such working memory span tasks are highly intercorrelated, and predict a broad range of cognitive capabilities such as SAT, Raven's Progressive Matrices, and Cattell's Culture Fair Test scores, language and reading comprehension, vocabulary learning, bridge playing, and computer programming (see Engle, 1996).

10. According to Jensen's speed framework, the time spent on the processing component of the span task, that is, reading, solving equations, or counting, should account for the predictive validity of these tasks. That is, processing speed should drive the correlations between span and more complex measures of ability such as gF and aptitude tests. It does not. Several studies demonstrate that time spent on the processing component of the span task does not account for any variance in these correlations (Conway & Engle, 1996; Conway, Tuholski, & Engle, 1998; Engle, Cantor, & Carullo, 1992; also see Cowan, 1998).

11. Beyond the empirical evidence, there is a fundamental conceptual difference between Jensen's view

of WMC and our own. According to Jensen, "short-term memory (STM) comprises primary memory (PM) and working memory (WM)," where PM is a, "short-term passive holding station," and WM, "is also the temporary stage from which information is transferred into long-term semantic memory" (quotes from p. 252). From these definitions we cannot understand what distinguishes among short-term memory, working memory, and primary memory. What is clear, however, is that Jensen views WMC in terms of content. That is, capacity is defined as the number of bits maintained at any moment in time. We argue, in contrast, for a clear distinction between working memory and STM, and we view STM, but not WMC, in terms of content.

12. According to our view, STM is purely a storage system, its capacity determined by practiced skills and strategies, such as rehearsal and chunking. In contrast, working memory is a more complex system incorporating the STM storage component as well as a controlled-attention component. Importantly, the controlled-attention component, and not storage capacity, is primarily what is shared between WMC and gF. Empirical support for this comes from a latent variable analysis of the relations among short-term memory capacity (STMC), WMC, and gF (Engle, Tuholski et al., 1999). Engle et al. administered several memory tasks and two tests of gF (Raven's Progressive Matrices and Cattell's Culture Fair test) to 133 undergraduates. Some measures were traditional STMC storage tasks, such as simple word span, in which words were presented one per second and then immediately recalled. The putative WMC tasks were reading span, operation span, and counting span. Consistent with the idea that the attention component of WMC is important to higher-order cognition, the latent variable derived from the WMC tasks was a significant predictor of the gF latent variable (path coefficient = .59), whereas the latent variable derived from the STMC tasks was not. Furthermore, when the variance common to the WMC and STMC latents was removed from the WMC-gF relationship, the WMC-gF path remained strongly linked to gF. A subsequent study using WMC, STMC, processing speed, and gF tasks, found an even stronger relation between WMC and gF (path coefficient = .98!), but no significant link between processing speed and gF (Conway et al., 1999; for related results see Kyllonen, 1996; Kyllonen & Christal, 1990; Larson & Saccuzzo, 1989).

13. But what is the essence of WMC? That is, what drives performance on tasks like reading span, operation span, and counting span, and what do these tasks have in common with tasks that are highly g-loaded, such as Raven's and Cattell's? According to our framework (see Conway et al., 1999; Engle, Kane et al., 1999; Engle, Tuholski et al., 1999; Kane, Bleckley, Conway, & Engle, in press), individual differences in WMC reflect the ability to engage controlled attention. That is, they reflect the ability to maintain activation to a representation in the face of interference or distraction. Therefore, working memory capacity is not "capacity" per se, but rather the ability to control activation. Supporting evidence is diverse and derives from a decade of work exploring individual differences in WMC (for a review, see Engle, Kane et al., 1999). We will briefly describe only two relevant studies here.

14. Initial evidence that attentional regulation of working memory is more important than either "capacity" or speed came from an investigation of individual differences in retrieval from long-term memory (Conway & Engle, 1994). Simply put, high and low WMC individuals differed in memory retrieval speed only under specific conditions. Subjects memorized sets of letters, with the number of letters in each set varying from 2 to 8 (e.g., 2-RW; 4-BGKT). After memorizing all sets to criterion, subjects performed a verification task in which a set cue -letter pair (e.g. 2-R, or 2-T) was presented and the subject had to indicate quickly and accurately whether the pair had been studied or not. The key manipulation in these experiments was the level of interference incorporated into the to-be-learned materials. In one experiment, each letter was a member of two different sets, thus introducing a level of response competition into the task (e.g., 2-RW; 4-BGRT). In another condition, each letter was a member of only one set, thus reducing response competition. Individuals measured to have high WMC on the operation span task responded more quickly and accurately on the verification task than did individuals with lower WMC, but only in the interference condition. High and low span subjects

performed equivalently in the no-interference condition, even across tests of large set sizes! This pattern of results suggests that the sheer capacity and sheer speed of the information processing system are not important to WMC differences. Rather, the attentional regulation of activation and interference resistance is critical.

15. Kane et al. (in press) showed that operation span performance is related to controlled visual orienting, even outside of a "memory-task" context. High and low span subjects performed both a pro- and anti-saccade task. In the pro-saccade task, subjects were presented with a fixation cue in the middle of a computer screen, followed by a blinking visual cue in the left or right periphery. The cue attracted attention so the subject could identify a subsequent target stimulus in that location. Thus, performance simply required reflexive orientation to a visual cue and identification of a target. In contrast, in the anti-saccade task, subjects saw the same fixation and peripheral cues, but the target was presented in the location opposite the cue. Therefore, subjects had to suppress reflexive orienting and shift attention in the opposite direction. Low span individuals performed as quickly and accurately as high span individuals in the pro-saccade task. However, in the antisaccade task, high spans identified targets much faster than low spans. High spans also produced fewer reflexive eye movements (in error), and they were much faster to correct eye movement errors when they did occur. Thus, when actively maintaining task goals was critical to combating interference from salient cues, high spans outperformed low spans, again suggesting that high WMC individuals have better control over attention al location.

16. In conclusion, we applaud Jensen's scholarly compilation of evidence to sup port the reality and importance of the general factor in cognitive ability. However, it is not speed that underlies the relations among information processing parameters and gF, as Jensen proposes; rather, it is WMC. Furthermore, we propose that WMC, which reflects controlled attentional ability, is the basis of general fluid abilities.

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