Working memory capacity and its relation to general intelligence

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Abstract:

Early investigations of working memory capacity (WMC) and reasoning ability suggested that WMC might be the basis of Spearman's g. However, recent work has uncovered details about the basic processes involved in working memory tasks, which has resulted in a more principled approach to task development. As a result, claims now being made about the relation between WMC and g are more cautious. A review of the recent research reveals that WMC and g are indeed highly related, but not identical. Furthermore, WM span tasks involve an executive-control mechanism that is recruited to combat interference and this ability is mediated by portions of the prefrontal cortex. More combined experimental–differential research is needed to understand better the basis of the WMC–g relation.

Article:

In the past decade, cognitive scientists have entertained the notion that working memory capacity (WMC) is the 'Factor X' that underlies individual differences in general intelligence (or Spearman's g) [1–5]. Much of the speculation on this topic has been motivated by a series of studies published in 1990 by Kyllonen and Christal [6], in which they demonstrated strong correlations between WMC and reasoning ability (r = 0.80–0.90). As impressive as these correlations were, Kyllonen and Christal themselves had serious reservations about the battery of WMC tasks used in their 1990 studies: 'We concede to a certain degree of arbitrariness in creating tasks according to such a broad and vague definition of their requirements, and readers may find fault with the way we operationalized the working memory factor. But without well-developed models of information-processing requirements of the tasks, we can only proceed with what is available.'

More recently, differential, experimental, and neuroimaging research projects have uncovered important details about the information-processing requirements of WMC tasks. The purpose of this paper is to review this recent progress, and in so doing, re-examine the relation between WMC and g in light of these new findings. The main points to emerge from the review are: (1) the creation of WMC tasks is a much more principled and much less arbitrary endeavor than it was in 1990; (2) WMC and g are indeed highly related, but are not the same construct; and (3) the basis of the WMC–g relation is most likely to be an executive-attention control mechanism, which is mediated by portions of the prefrontal cortex.

The research to be reviewed draws upon methodology from both the differential and experimental traditions of psychology [7]. Because the Kyllonen and Christal data provide an excellent point of departure for this review, we begin with a discussion of the differential approach. We then review experimental investigations into the basic processes contributing to the performance of WMC tasks and consider how those investigations inform the differential data. Finally, we review studies of the neural bases of WMC and g and consider how this work might further constrain theories of working memory, intelligence, and their relation. We conclude with problems that still exist with respect to the measurement of WMC and provide suggestions for future research.

Differential approach to the relation between WMC and g

The following review of individual differences studies of WMC and g (or general reasoning ability) is restricted to projects that used latent variable analyses (see Box 1). This criterion was adopted for two reasons. First, latent variables provide a cleaner measure of the construct under investigation and therefore these analyses

provide the clearest picture of the true relation between WMC and g. Second, the number of published papers containing at least one correlation between a single measure of WMC and a single measure of intelligence (or reasoning) is simply too large to be adequately summarized in a brief review.

Kyllonen and Christal developed the first latent variable analysis of individual differences in WMC and g, and demonstrated strong correlations (near unity) between WMC and reasoning ability (see also [8]). Our main concern here is not with the magnitude of the correlations but rather with the characteristics of the battery of their WMC tasks.

Box 1. Latent variable analyses

Latent variable modeling, also known as structural equation modeling (latent variable models with causal paths among latent variables), and confirmatory factor analysis (latent variable models without causal paths among latent variables) involves the administration of multiple measures for each hypothetical construct (e.g. working memory capacity, g) to a large number of subjects, typically 100 or greater. The observed measures, or tasks, are referred to as manifest variables. Latent variables are derived from the covariance among manifest variables that putatively measure the same construct. That is, latent variables represent variance that is shared among all the tasks that are being used to identify the construct. As such, the task-specific variance that is unique to each task is removed, resulting in a relatively pure measure of the latent construct of interest (see Figure I).

The statistical goal of a latent variable model is to account for all the observed correlations among the manifest variables. Thus, the model produces what is called a reproduced correlation matrix based on the relations among manifest variables specified in the model. The reproduced correlation matrix is then contrasted with the observed correlation matrix. If they are similar then the model is thought to fit. Model fit is typically assessed with a chi-square test of independence, which tests whether the reproduced correlation matrix is independent of the observed correlation matrix. If the two are statistically independent, then the chi-square statistic is significant, and the model is considered to be a bad fit. In such a case, the model would need to be revised and then tested again. Model fit is also assessed via several fit indices, which range from 0 to 1, where 1 is considered a perfect fit [40,41]. Also, competing models can be tested and the difference in chi-square is assessed for significance; if the difference is significant then the better fitting model is preferred.
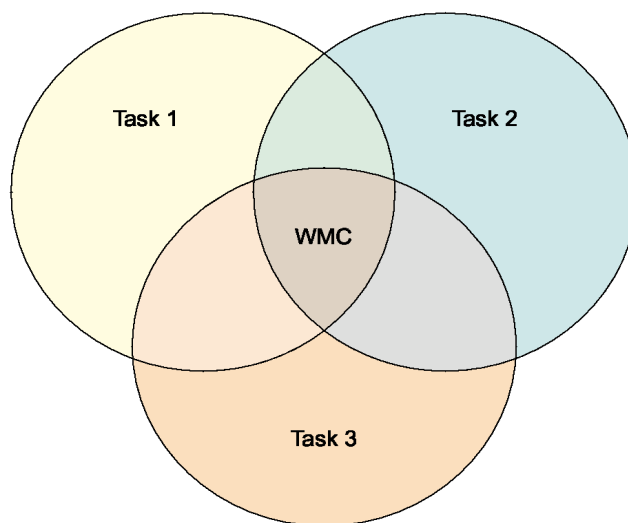
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Figure I. A venn-diagram of the relationship between three working memory capacity (WMC) tasks. The common variance represents the latent variable (e.g. WMC) when the task-specific variance is removed.

Kyllonen and Christal adopted a 'varied-content and varied-process' approach to selecting their battery of WMC tasks. As mentioned above, they did this because well-formulated theories of the task requirements of different WMC tasks did not exist. It therefore made sense to select a wide range of tasks, in terms of content and process, and derive a latent variable from the battery of selected tasks. The problem with this approach is that it is difficult to ascertain the key cognitive mechanisms underlying performance of the tasks contributing to the latent variable, which in turn makes it difficult to account for the covariation between WMC and g in terms of cognitive processes [5].

More recent research has provided some insight into the nature of WMC tasks, which allows for a more principled approach to task selection. For instance, one clear distinction among tests of immediate memory is between those tasks that require storage versus those that require storage plus some form of additional processing [9–12].

These two classes of tasks show differential patterns of deficits in different patient populations [13], they predict reading and listening comprehension in different ways [10,11], and they reveal different patterns of activation in neuroimaging studies [12] (see Box 2).

Engle and his colleagues exploited this distinction between simple span tasks and WM span tasks in their individual differences investigation of WMC and general intelligence [11]. They administered several simple span tasks and WM span tasks, as well as two figural/spatial tests of g, to a large sample of subjects. The first question addressed in the study was whether the battery of memory tests would be explained by a one- or two-factor latent variable model. If the WM span tasks indeed tap something different from the simple span tasks then a two-factor model would be best, and indeed, a two-factor model of the memory tasks fit the data better than a one-factor model. Furthermore, the latent variable derived from the WM span tasks served as a significant predictor of general fluid ability (r = 0.59) whereas the latent variable derived from the simple span tasks did not.

One potential problem with the Engle project is that the battery of WM tasks consisted solely of verbal WM span tasks. A more comprehensive approach was adopted by Süb and colleagues, who created a battery of tasks that included both verbal and non-verbal tasks and tests other than span tasks [14]. Also, they attempted to tap different signature functions of working memory, such as coordination, integration, updating, and switching. Despite the differences in task selection between the Engle project and the Süb project, the magnitude of the correlation between WMC and g was consistent (r = 0.59, r = 0.65, respectively).

The consistency of the WMC–g relation has been further supported by two other latent variable analyses, one by Ackerman and colleagues [15], who observed a strong correlation between WMC and g (r = 0.58) and another by Conway and colleagues (r = 0.60) [3], who also replicated Engle's null correlation between simple span and g. A crucial finding from these recent latent-variable studies is that WM span tasks, such as operation span (see Box 2), load on a separate factor from simple span tasks, such as digit span [3,11], suggesting that WM span tasks indeed reflect something different from simple span tasks. And, not only do WM span tasks load on a separate factor from simple span tasks, they predict g in a way that simple span tasks do not [3,11]. Thus, there is a boundary condition of sorts, in that one type of immediate memory task reveals stronger correlations than does the other. It is imperative then to understand the basic processes that contribute to the performance of WM span tasks.

Cognitive-experimental investigations of the basic processes underlying WM span tasks

One way in which the processes that contribute to WM span tasks has been explored has been to contrast the cognitive contexts in which individual differences in WM span relate, and do not relate, to performance. For example, a large and diverse group of subjects are screened using WM span tasks, and individuals with greater WMC are compared with individuals with lesser WMC in different experimental contexts. Although it is not ideal to categorize a continuous variable in this fashion, the approach has been productive for conducting

exploratory research to identify experimental manipulations that do and do not interact with WMC (in fact, this is exactly the type of treatment by organism approach endorsed by Cronbach [7]).

Box 2. Memory span tasks

One clear distinction between tests of immediate memory is that between 'simple' (or short-term memory) span tasks and 'complex' (or working memory) span tasks (see Figure I). Simple span tasks, such as digit span or word span, involve the serial presentation of a list of to-be-recalled stimuli. The stimuli are presented individually, typically one per second, and at the end of a series, the subject is required to recall the list in correct serial order.

WM span tasks are very similar, in that they involve the serial presentation of a to-be-remembered list of stimuli. However, WM span tasks also consist of a secondary processing component. For example, the operation span task requires the subject to solve simple mathematical operations while remembering words for later recall [42]. The subject is presented with an operation–word pair and they are required

to read the operation aloud, say 'yes' or 'no' to indicate whether the given answer is correct or incorrect, and then say the to-be-remembered word aloud. After a series of operation-word pairs the subject is presented with a recall cue and instructed to recall all the words in correct serial order.

Several such span tasks have been developed, including the reading span task [10], the counting span task [43], as well as spatial span tasks [44]. Each of these tasks consists of a processing component (e.g. solving math problems) and a storage component (e.g. remembering words). Although the exact nature of the processing and storage components vary across different span tasks, each of these tasks reveals good reliability (Cronbach's alpha = 0.70–0.80) and all the tasks correlate well with one another (r = 0.40–0.60) [3,11].
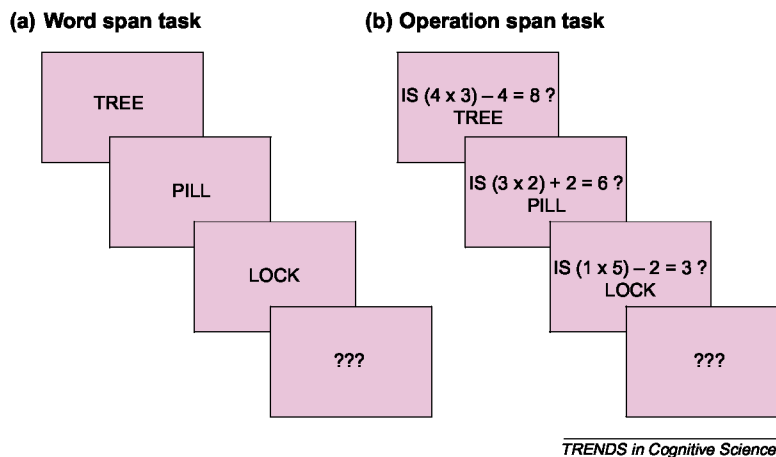

(a) Word span task

TREE

PILL

LOCK

???

(b) Operation span task

IS (4 x 3) – 4 = 8 ?
TREE

IS (3 x 2) + 2 = 6 ?
PILL

IS (1 x 5) – 2 = 3 ?
LOCK

???

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Figure I. Examples of **(a)** a simple span task (word span), in which serially presented material has to be recalled, and **(b)** a working-memory span task (operation span), in which the subject is given simple mathematical operations to solve at the same time as words to be recalled later.

The general conclusion from investigations that have adopted this approach is that WMC is related to performance in situations in which an executive attention control mechanism is needed to combat some form of salient interference, be it proactive interference, response competition, or habitual but inappropriate responses. For example, WMC is related to the speed and accuracy of retrieval of information from long-term memory (LTM), but only when a level of response competition is inherent in the task [16]. In a variant of the classic Sternberg memory-scanning paradigm, subjects committed to memory different sets of letters of varying set size (e.g. set 2 = R, W; set 6 = Q, T, P, S, F, K). In one condition, there was no overlap in set membership; that is, if a letter was a member of one set, it could not be a member of another set. In another condition, each letter was a member of two different sets. WMC was related to retrieval speed and accuracy in the overlap condition only. Specifically, the slope of the reaction-time/set-size function was steeper for individuals with lower WMC than for those with higher WMC. And importantly, the slopes did not differ at all between span groups in the no-overlap condition. Furthermore, for high WMC subjects, the slopes in the overlap and no-overlap conditions were equal, suggesting that high-WMC individuals did not allow the overlap manipulation to impair retrieval, whereas low-WMC individuals were negatively affected.

The conclusion derived from these empirical findings was that WMC is related to an executive attention ability, which supports the active maintenance of goal-relevant information in the face of interference. This attention ability is most critical in interference-rich conditions because correct responding cannot be achieved via automatic spreading activation among memory representations, or via habitual responding. In interference-rich conditions, such automatic activation or habitual responding leads to errors and, therefore, must be suppressed.

This general conclusion is supported by other LTM studies finding WMC to predict encoding and retrieval success under conditions of proactive interference [17–20].

Similar conclusions have been drawn from research on 'low-level' attention tasks that require little by the way of memory, per se, such as dichotic listening [21], Stroop color-naming [22], visual orienting [23], and negative priming [24]. As an example, we will consider just one of these studies here – visual orienting. The pro-saccade task is perhaps one of the simplest cognitive tasks available. In fact, it can hardly be described as 'cognitive' at all. The subject's task is to orient to a visual cue presented in their periphery, typically a flashing stimulus. In some cases subjects are also required to detect a target that is subsequently presented in the same location as the cue (in the simplest case subjects only make an eye-movement, in which case performance is monitored using an eye-tracker). The anti-saccade version of the task is much more difficult. Here, subjects must make an eye-movement in the opposite direction of the visual cue. This is difficult because orienting to a flashing stimulus in the periphery is a reflexive response. Thus, in the anti-saccade task the habitual orienting response must be suppressed to make the correct, controlled eye-movement in the opposite direction.

Consistent with the memory-retrieval data discussed earlier, WMC is related to anti-saccade but not to pro-saccade performance: Individuals with greater WMC are less likely to make erroneous saccades, and are faster to make correct saccades and to correct erroneous ones, than are individuals with lesser WMC. In the pro-saccade task, individuals with high and low WMC are just as likely, and just as fast, to make the correct orienting response and to detect the target (if required).

In conclusion, investigations into the basic processes that contribute to WM span tasks suggest that they critically tap an executive attention-control process recruited in situations where an inappropriate yet highly accessible response must be selected against in favor of the appropriate response.

Neuroimaging studies of WMC and g

The distinction between tasks that require storage versus those that require storage and some form of processing can also be found in the neuroimaging literature [12]. For instance, several studies have shown that storage-only tasks reveal activation primarily in areas related to the content of the to-be-remembered material (e.g. Broca's area for verbal material, right-hemisphere pre-motor cortex for spatial material) [12], whereas storage-plus-processing tasks reveal content-specific activation but also domain-free activation in areas such as dorsolateral prefrontal cortex (DLPFC) and anterior cingulate (ACC) [12,25,26]. Indeed, recent theories and models of prefrontal function suggest that WMC, executive attention, and g are all highly related constructs, all heavily reliant upon the DLPFC [27,28].

Indirect evidence in support of the notion that WMC, executive attention, and g share a common neurological basis comes from localization studies. As mentioned above, investigations into the brain regions invoked by WMC tasks, for example, suggest that DLPFC and ACC are involved. Importantly, the same conclusion has been drawn from the literatures on localization of executive attention and g [28] . However, this evidence remains indirect because little attempt has been made to determine whether variation in behavioral performance on tasks that purportedly tap these constructs is mediated by variation in brain activity within these regions.

A recent study has examined the extent to which behavioral correlations are mediated by brain activity as measured by fMRI [29]. In the study, 48 subjects performed Ravens Advanced Progressive Matrices (RAPM), a measure of g, outside the fMRI scanner and then performed the n-back task, a measure of WMC, inside the scanner. The n-back task is a continuous performance test in which individual stimuli (typically letters or words) are presented in rapid succession and the subject must indicate whether the current stimulus matches the one presented n-back in the stream, and n varies, typically from 1–3. N-back is thought to tap WMC because it involves not only the storage of the last n presented stimuli, but also the continuous updating of n stimuli, which involves the deletion of stimuli presented more than n back in the stream. Moreover, some trials within the n-back task are thought to require more executive attention than others. For example, in a 3-back task, the second B in B-R-B-X is referred to as a 'lure' trial because it matches a recently presented stimulus but does not match

the one presented three back. Indeed, in the 3-back task, control foils were rejected more accurately than lure foils (accuracy = 96% versus 75%, respectively) [29].

More importantly, significant correlations were observed between RAPM, n-back, and activity in DLPFC and ACC. In fact, the correlation between RAPM and event-related activity to lure trials was particularly striking (r = 0.54) and remained significant even when performance on non-lure trials was partialled out. Finally, the correlation between lure performance and RAPM was almost completely accounted for by lure-trial activity in DLPFC. That is, the percent-signal-change in DLPFC associated with lure trials accounted for 92% of the covariance between lure performance and RAPM, suggesting that the WMC/executive attention/g relation is mediated by activity in DLPFC.

Future issues: the current range of WMC tasks is still too wide

It is clear that the creation and selection of WMC tasks is more principled today than it was in 1990. However, the fact remains that a wide range of tasks are still being used to measure WMC and it is not clear how all these tasks relate to one another or to g. Here we consider tasks other than WM span and call for future research that addresses (1) the basic processes involved in these tasks, and (2) the relation between these tasks, WM span tasks, and g.

One problem with WM span tasks is that they clearly require processes above and beyond WMC or executive control. For example, operation span recruits mathematical ability [30], reading span involves verbal ability [31], and strategy-training has been shown to improve scores in WM span tasks [32] (however, differential skill and strategy-use does not affect the correlation between WM span and higher-order cognition [30,33,34]). Although no task is process-pure, it does seem possible to create measures of WMC that are less contaminated by other cognitive skills and strategies than WM span tasks. In a recent review, Cowan [35] argued that the limitation on immediate memory and attention can be estimated if the stimuli are presented in a manner that eliminates the possibility of strategy recruitment, such as grouping or rehearsal. According to this perspective, the signature of WM tasks is not the extent to which they require storage and processing but rather how well they prevent the recruitment of domain-specific skills and strategies.

For example, consider the visual-array comparison task [36]. In the task, an array of colored squares is presented briefly, followed by an inter-stimulus interval, followed by a second array that is identical or similar to the first. One square in the second array is marked by a circle, and if the two arrays were different, the difference was in the color of the encircled square. The key manipulation is the number of squares presented in the arrays. When the array is small (i.e. 4 or fewer), same/different judgments are very accurate. However, accuracy deteriorates when the array size is greater than 4, suggesting that approximately 4 independent locations can be actively maintained in immediate memory without the aid of a grouping or rehearsal strategy and, therefore, that this task provides an estimate of WMC.

Cowan [35] reviewed several tasks with similar characteristics to the visual-array comparison task and found a consistent capacity estimate of around 4 ± 1. Thus, it is possible that these tasks tap the limit that others have referred to as WMC. However, it is not clear how these tasks relate to other WM tasks, such as WM span tasks, how stable and robust individual differences are in these tasks, or how these tasks relate to measures of complex cognitive ability, such as g.

Another class of tasks used to measure WMC is the n-back task [37–39]. As mentioned above, n-back tasks are widely used in neuroimaging studies, being preferred over WM span tasks in the fMRI environment because their presentation and response requirements are less complex. Most n-back tasks, like the one described earlier, not only challenge memory maintenance, but also contain lure trials, which are stimulus matches n — 1 or n + 1 back. It is particularly difficult to reject these lure trials because familiarity comes into conflict with the task goal [29]. One intriguing possibility is that performance on lure trials is related to WM span performance (given the findings that span is particularly important under conditions of interference). However, at this point little

work has been done to examine the relation between n-back, other measures of WMC, and higher-order cognitive tasks.

Conclusion
In summary, several recent latent variable analyses suggest that WMC accounts for at least one-third and perhaps as much as one-half of the variance in g. What seems to be important about WM span tasks is that they require the active maintenance of information in the face of concurrent processing and interference and therefore recruit an executive attention-control mechanism to combat interference. Furthermore, this ability seems to be mediated by portions of the prefrontal cortex.

Although progress has been substantial in recent years, much more work remains to be done, particularly with respect to the measurement of WMC. Specifically, experimental task analyses need to be conducted on all the different types of WMC tasks that are currently being used in the field. And, latent variable analyses of different WMC tasks need to be conducted to determine the relationship among different WMC tasks and between these tasks and g.

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