Sensory Discrimination, Working Memory and Intelligence in 9- and 11-Year Old Children

Annik E. Voelke* - annik.voelke@psy.unibe.ch
Stefan J. Troche - stefan.troche@psy.unibe.ch
Thomas H. Rammsayer - thomas.rammsayer@psy.unibe.ch
Felicitas L. Wagner - felicitas.wagner@psy.unibe.ch
Claudia M. Roebers – claudia.roebers@psy.unibe.ch

University of Bern, Switzerland

* Corresponding author (A. Voelke) at: Department of Psychology, University of Bern, Muesmattstrasse 45, 3000 Bern 9, Switzerland.

Phone Nr. +41 31 631 47 25

Fax Nr. +41 31 631 82 12

E-mail address: annik.voelke@psy.unibe.ch

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Abstract

More than a century ago, Galton and Spearman suggested that there was a functional relationship between sensory discrimination ability and intelligence. Studies have since been able to confirm a close relationship between general discrimination ability (GDA) and IQ. The aim of the present study was to assess whether this strong relationship between GDA and IQ could be due to WM demands of GDA tasks. A sample of 140 children (70 9-year-olds and 70 11-year-olds) was studied. Results showed that there was a significant overlap between WM, GDA and fluid intelligence. Furthermore, results also revealed that WM could not explain the relationship between GDA and fluid intelligence as such, but that it acted as a bottleneck of information processing, limiting the influence of GDA on the prediction of fluid intelligence. Specifically, GDA's influence on the prediction of intelligence was only visible when WM capacity was above a certain level.

Introduction

More than a century ago, on the eve of the development of the first intelligence test, Galton and Spearman suggested that there was a functional relationship between sensory discrimination ability and intelligence (Galton, 1883; Spearman, 1904). These ideas were, however, disregarded for almost a century, until they re-attracted research interest in recent years (Deary, 1994, 2012). Studies have since by and large confirmed a close relationship between general discrimination ability (GDA) – a collection of sensory discrimination ability in different tasks and different modalities – and IQ (e.g., Deary, Bell, Bell, Campbell, & Fazal, 2004; Troche & Rammsayer, 2009). These recent and Spearman's earlier findings are intriguing on two accounts. Firstly and looking at them from a practical perspective, if GDA could in fact be considered a good predictor of intelligence, this would provide researchers (and practitioners) with a simple, culture-fair indicator of mental abilities. Secondly, and from a theoretical perspective, high to very high correlations found between the two constructs are striking when one considers how differently they are measured. While GDA is measured using very simple tasks (e.g., comparing the pitch of two tones; Troche & Rammsayer, 2009), intelligence is measured using tasks requiring complex, sequenced and hierarchical information processing and problem solving skills (see e.g., Hunt, 2011).

It could be argued that due to the nature of the tasks used to assess sensory discrimination - comparing two very similar stimuli that are presented one after another - it is very likely that an individual's working memory (WM) capacity plays a crucial role for the association between GDA and IQ. WM is needed in many (simple) tasks where information has to be stored and processed simultaneously (Cowan & Alloway, 2009) – which is what is required for solving sensory discrimination tasks. Moreover, WM has repeatedly been found to be strongly associated with intelligence in adults (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999) and has also been shown to be central to intelligence in childhood (Cowan & Alloway, 2009). In other words, a possible theoretical explanation for the strong relationship between GDA and intelligence is that there is a significant overlap among GDA, IQ, and WM.

The aim of the present study was to assess whether the previously found correlations between GDA and intelligence could be replicated, and if so, whether GDA would be able to independently contribute to the prediction of intelligence after WM had been taken into account.

Sensory Discrimination and its Relationship to Intelligence

Sensory discrimination ability is the ability to detect small differences between stimuli of the same modality (Deary, 1994). It first garnered interest in research on intelligence more than a century ago, when Galton argued that “the only information that reaches us concerning outward events appears to pass through the avenue of our senses; the more perceptive the senses are of differences, the larger is the field upon which our judgment and intelligence can act” (Galton, 1883, p.19). Spearman following up on this idea, showed that there is a strong relationship between an unspecific general discrimination ability – derived from a battery of tasks assessing sensory discrimination in different modalities – and psychometric intelligence in children (Spearman, 1904). In fact, he found very high correlations between general sensory discrimination and general intelligence (r = .96 and r = 1.04; in his formulas, correlation coefficients greater than 1 were possible).

In the more than 100 years since then, the picture has not changed much. Recent studies assessing the association between GDA and intelligence have confirmed a close relationship, revealing high to very high correlations between the two constructs. In their study with adults, Troche and Rammsayer (2009) for example, found high correlations (r = .64) between GDA and intelligence, which they assessed using six subtests of reasoning from the Berlin model of intelligence structure (BIS; Jäger, Süß, & Beauducel, 1997). The tests used in the study included two tests with numerical content (continuing numerical series, estimating solutions of mathematical tasks), two tests with verbal content (recognizing semantic relations, marking one of four words that does not fit semantically) and two tests with figural content (recognizing figural analogies, completing a progressing string of figures). Similarly, Deary and colleagues (2004) found correlations of $r = .68$ (for participants aged between 13 and 62 years) and $r = .92$ (in a sample with a mean age of 12 years and 2 months) between general discrimination and general intelligence. In the study with the older sample, intelligence was assessed with 13 subtests of the Johnson O'Connor Research Foundation test battery (see e.g., Daniel, 1982) which included tests of spatial ability, numerical ability, memory, convergent thinking, divergent thinking, vocabulary and perceptual speed. In the younger sample, intelligence was assessed with the Mill Hill Vocabulary Test (Raven, Raven, & Court, 1982), the Cattell Culture Fair Intelligence Test (Cattell & Cattell, 1973) and an extended Digit Symbol Test from the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981). In addition, Meyer and colleagues (Meyer, Hagmann-von Arx, Lemola, & Grob, 2010) found that general discrimination and general intelligence correlated with $r = .78$ in children aged between 5 and 10 years. When the sample was split into smaller age bands, the correlations remained high in all age groups. Intelligence was measured using six tests from the Intelligence and Development Scales (IDS; Grob, Meyer, & Hagmann-von Arx, 2009). The IDS have their roots in a reconception of the Kramer Intelligence Test and were developed as a measure of general intelligence that could also provide a profile of six development domains, including cognition, language, mathematics and social-emotional competence. The six subtests used in the study were: phonological memory, visuo-spatial memory, auditory memory (retelling a previously heard story), conceptual reasoning, figural reasoning and selective attention. All 6 subtests belong to the profile of cognition (Grob et al., 2009; Meyer et al., 2010).

The above studies clearly show that GDA is related to intelligence. However, due to the very heterogeneous types of tests used to assess intelligence in the studies, it is difficult to draw any firm conclusion as to which aspects of intelligence contribute to this relationship.

WM and its Relationship to Intelligence

WM has been described as an essential cognitive function needed in many everyday life-situations. It plays a central role for language development (e.g., Archibald & Gathercole, 2006) and many higher order cognitive processes such as reading, mathematics, reasoning and problem solving (e.g., Cowan & Alloway, 2009; Swanson, 2011).

Most researchers would agree that WM is a limited-capacity system responsible for maintenance of information over short periods of time, and for the simultaneous manipulation and processing of information (e.g., Cowan & Alloway, 2009). However, there is still some disagreement as to the exact internal structure of WM. This can clearly be seen when comparing some of the most prominent models of WM. In his model, Baddeley (1986, 2000, 2007) for example, describes WM as being made up of multiple specialized components, that is, a central executive responsible for the control and processing of information and subsidiary slave systems (the phonological loop, the visuo-spatial sketchpad and the episodic buffer) responsible for the temporary storage of information. Cowan (e.g., 1999) on the other hand, describes WM in his model as being made up of a central executive that directs attention and controls voluntary processing as well as three memory components including long-term memory (LTM), activated parts of LTM and a subset of activated memory in the focus of attention and awareness where information is stored. Slightly different again, Engle and colleagues describe WM as consisting of a store in the form of LTM traces active above threshold, processes for achieving and maintaining this activation and controlled attention (Engle, Kane, & Tuholski, 1999). Despite the obvious differences between WM in the three models, there are also many similarities. All three models contain a component responsible for controlling attention and processing information and components responsible for storing information over brief periods of time. Emphasizing the commonalities even more, the storage components (the slave systems in the Baddeley model, activated memory in the focus of attention in the Cowan model and LTM traces active above threshold in the Engle et al. model) are often referred to as STM (see e.g., Engle, Kane et al., 1999; Engle, Tuholski et al., 1999; Henry, 2012).

In recent studies, WM has been found to be strongly related to intelligence in both adults (for an overview see e.g., Ackerman, Beier, & Boyle, 2005) and children (e.g., Belacchi, Carretti, & Cornoldi, 2010; Engel de Abreu, Conway, & Gathercole, 2010; Röthlisberger, Neuenschwander, Michel, & Roebers, 2010; Swanson, 2011¸ Tillman, Bohlin, Sørensen, & Lundervold, 2009). Studies have been able to show that the relationship between WM and intelligence holds true for both fluid intelligence (e.g., Ackerman et al., 2005; Belacchi et al., 2010; Engel de Abreu et al., 2010; Röthlisberger et al., 2010; Swanson, 2011; Tillman et al., 2009) and crystallized intelligence (e.g., Ackerman et al., 2005; Swanson, 2011; Tillman et al., 2009). Some researchers have even suggested that WM is the information-processing process that best predicts measures of intelligence (Kyllonen & Christal, 1990; Oberauer, Schulze, Wilhelm, & Süß, 2005).

As mentioned in the introduction, it is possible that the WM demands of GDA tasks contribute to the association between GDA and IQ. If tasks measuring GDA were reliant on a person's WM, this could explain the high correlations between GDA and intelligence.

The Present Study

The purpose of the present study was to explore how GDA and WM are related to intelligence in children and whether GDA is able to contribute to the prediction of intelligence independently of WM. To be able to interpret the results in terms of developmental progression or individual difference, two age groups – a younger age group (9-year-olds) and an older age group (11-year-olds) – were chosen for the study. It is well known that WM develops from early childhood at least through adolescence (Best & Miller, 2010) and that test scores on intelligence tests increase with age, at least through to adolescence (Ferrer, O'Hare, & Bunge, 2009). Although documentations of age-related changes in GDA are extremely rare, it is likely that GDA also improves with age.

It is possible that the constructs do not develop at the exact same rate, and therefore lead to different contributions of both WM and GDA to intelligence at different ages. In other words, WM could have a stronger (or weaker) influence on intelligence than GDA in the younger compared to the older age group and GDA could have a stronger (or weaker) influence on the prediction of intelligence than WM in the older compared to the younger age group. Alternatively, the predictive power (or the relative impact) of WM and GDA to explain individual differences in intelligence may differ as a function of WM capacity. As Deary (2012) has recently outlined, more sophisticated skills in one basic information process may lead to stronger reliance on these processes, possibly attenuating the impact of other information processes. By including two different age groups this question could be addressed more systematically in the present study.

Sensory discrimination ability and working memory were each assessed with tasks using different modalities such as verbal, visuo-spatial, auditory or visual material. To be able to contribute to the untangling of the inconsistent results described above, and because studies of the relationship between WM and intelligence often focus on fluid intelligence, a test of fluid intelligence was used as a measure of intelligence in the present study. Fluid intelligence consists of the ability to solve new and unusual problems as well as the ability to reason in new situations (Hunt, 2011). It can be assessed with tests that are non-verbal and relatively culture-free (Willis, Dumont, & Kaufman, 2011).

Method

Participants

The sample consisted of 140 children (71 boys) ranging in age from 8.6 to 12.0 years. They were recruited through public schools in Switzerland. The sample was divided into a younger age group (N= 70) with a mean age of 9 years 2 months (*SD* = 4 months; range: 8 years 7 months to 9 years 8 months) and an older age group (N = 70) with a mean age of 11 years 4 months (*SD* = 4 months; range: 10 years 7 months to 12 years 0 months). The study was approved by the local ethics committee, and informed consent was obtained from all parents.

Tasks

Working Memory Tasks

Listening Recall (LR): Participants completed a translated and adapted version of the listening recall task from the Working Memory Test Battery for Children (WMTB-C; Pickering & Gathercole, 2001). In this task, participants heard a series of sentences. They were asked to judge whether each sentence made sense or not (e.g., "lions have four legs", "pineapples play football") and to simultaneously remember the last word of each sentence. At the end of each trial they were required to recall the last word from each sentence in the order that they were presented. There were 6 trials for each span length. The length of the first sequence was one sentence. When 50% of the trials were answered incorrectly the task was terminated, otherwise the length of the sequence was increased by one sentence. The total number of correctly answered trials (correct recall of the last word of each sentence) was used as the dependent variable.

Letter-Number Sequencing (LNS): Participants completed the letter-number-sequencing task from the German version of the Wechsler Intelligence Scale for Children (Petermann &

Petermann, 2008). In this task, children heard a mixed series of letters and digits. They were required to repeat these, with the digits in numerical order first and the letters in alphabetical order second. Each sequence consisted of three trials. The starting trials consisted of one letter and one digit. If a child answered all three trials incorrectly, the task was ended; otherwise trial length was increased by one letter or digit. The total number of correctly answered trials (correctly recalled letter-number series) was used as measure of performance.

Patterns Memory (PM): This task is an adapted version of the computerized patterns memory task devised by Ang and Lee (2010). It consists of a processing and a storage sub-task. For the processing part of the task, children were asked to verify a matrix equation made up of dots connected by lines. For the storage component, children had to remember the locations of two blackened squares in a 4x4 grid (see Figure 1). They were told to remember the grid and squares as a pattern. Each sequence consisted of matrix-equation-grid pairs in which a matrix-equation was presented followed by a grid with blackened squares. The children had 8s to verify the matrix equation (i.e. true or false) using external response buttons. The grid with two blackened squares was shown for 3s immediately after the children responded. After the last matrix-equation-grid pair of a sequence was shown, a screen with the recall cue (i.e. one of the patterns of the sequence, but with only one blackened square) appeared. The children then had to point to the location of the missing square on screen. Answers were recorded by the researcher. There was no time limit to respond. Each trial consisted of 6 matrix-equation-grid pairs. The length of the first trials consisted of two matrix equations with the corresponding grids. When 50% of the trials were answered incorrectly, the task was ended. Otherwise, the length of the sequence was increased by one matrix-equation grid pair. The total number of correctly answered trials (correctly recalled patterns) was used as the dependent measure.

Sensory Discrimination Tasks

Sensory discrimination ability was assessed with three tasks, an auditory and a visual duration and a pitch discrimination task. To quantify the individual discrimination performance, an adaptive psychophysical procedure, the weighted up-down method (Kaernbach, 1991), was applied. ‘Adaptive’ means that the differences in stimulus magnitude between the constant standard stimulus and the variable comparison stimulus are varied from trial to trial depending on the participant’s previous response. A correct response results in a decrease of the difference between the standard and the comparison stimulus, making the task more difficult; whereas an incorrect response results in an increase of the difference between the standard and the comparison stimulus, making the task easier. A detailed description of this procedure is given by Rammsayer and Brandler (2007). As an indicator of discrimination performance, the difference limen (DL), which is represented by half the interquartile range of the difference threshold [(75% threshold value – 25% threshold value)/2] was determined for each discrimination task as suggested by Luce and Galanter (1963). It is important to note, that with the DL as a measure of sensory sensitivity, the better the performance, the smaller the DL value.

All tasks consisted of 64 trials, and each trail consisted of one standard and one comparison stimulus. The answers were logged by trained research assistants. After each response, visual feedback (a green ‘+’ for correct responses or a red ‘-’ for incorrect responses) was displayed. The instructions emphasized accuracy not speed.

Duration Discrimination Tasks: For the *visual duration discrimination (vDD)* task, stimuli were filled visual intervals generated by a red light emitting diode positioned at eye level of the participant. The intensity of the LED is clearly above threshold, but not dazzling. For the *auditory duration discrimination (aDD)* task, stimuli are white-noise bursts presented binaurally through headphones (Razor Orca) at an average intensity of 67dB. The stimuli in both tasks were a constant 100-ms standard interval and variable comparison intervals. The duration of the comparison interval varied according to the weighted up-down method. On each trial participants had to decide which of the two intervals was longer.

Pitch Discrimination (pD): In this task, the stimuli consisted of 500-ms sine waves that were presented through headphones (see above). The pitch of the constant standard tone was 440 Hz and the duration of the comparison interval varied according to the weighted up-down method. On each trial participants had to decide which of the two tones was of higher pitch.

Assessment of Fluid Intelligence

To measure fluid intelligence, the short version of the CFT 20-R (Weiss, 2006; reliability: .92) was used. The CFT 20-R is an adapted and revised version of Cattell's Culture Fair Intelligence Test. It consists of four subtests: series completion, classification (odd elements), matrix completion and topological reasoning (dot task). It is a timed paper-pencil test and can be administered either in a group setting or in an individual setting. The dependent measure used for this task was the aggregated score of the total number of correctly answered items in each of the four subtests.

Procedure

Children were tested three times over the course of 3 days to two weeks during school hours. In one of these sessions the CFT 20-R was administered in a small group setting (five to ten children). Testing of both sensory discrimination and working memory was split into two sessions due to the length of time it took to administer all the tasks. The order of tasks was randomized across and in between sessions, with working memory tasks and sensory discrimination tasks appearing in each of these two sessions.

Results

Preliminary Analyses

The means and standard deviations for all the variables assessed in the study are presented separately for the two age groups in Table 1. Significant differences between the two age groups, with the 11-year-olds always performing better than the 9-year-olds, were found for all of the variables except the LNS task (see Table 1). As a consequence and because we aimed to explore age-dependent patterns of interrelations between the included variables, the following correlation and regression analyses were conducted separately for both age groups.

To assess whether the working memory tasks and the sensory discrimination tasks could be compiled into composite scores, a principal component analysis with oblique rotation (oblimin) was conducted across the two age groups [KMO = .71, Bartlett's test of sphericity χ^2 (15) = 102.35, p <.001]. It showed that the six tasks loaded onto two factors (each with an Eigenvalue greater than 1), with the three sensory discrimination tasks loading onto one factor and the three working memory tasks loading onto the second factor (see Table 2). Together the two factors explained 54.9% of the total variance. Taking these results into account, z-scores of the sensory discrimination variables (aDD, vDD, pD) were added to form a composite score for GDA and z-scores of the working memory tasks (LR, LNS, PM) were added to form a composite score for WM.

Relationship between GDA, WM and Intelligence

All Pearson's correlations between the composite scores for WM and GDA and fluid intelligence were significant in both age groups. Correlations between WM and fluid intelligence were .51, $p < .001$, for the younger age group, and .38, $p = .001$, for the older age group. Correlations between GDA and fluid intelligence were .28, $p = .021$, and .24, $p = .048$ for the younger and older age group, respectively. Correlations between WM and GDA were .25, $p = .036$, for the younger age group, and .30, $p = .011$, for the older age group.

Hierarchical regression analyses were conducted to evaluate the contribution of both WM and GDA to fluid intelligence in the two age groups. In an initial model, WM was entered into the regression analysis in a first step, followed by GDA in a second step. Results are depicted in Table 3 and revealed that WM explained a significant amount of variance in intelligence in both the younger and the older age group. GDA did not explain significant amounts of variance in intelligence over and above individual differences in WM and this pattern of results held for both age groups.

In a second model, GDA was entered into the regression analysis first, followed by WM in a second step. Results showed that GDA predicted fluid intelligence in both the younger age group ($\beta = .28$, $p = .021$, $\Delta R^2 = .08$), and the older age group ($\beta = .24$, $p = .048$, $\Delta R^2 = .06$). WM was found to substantially contribute to the prediction of fluid intelligence over and above GDA in both the younger age group ($\beta = .47$, $p < .001$, total $R^2 = .28$), and the older age group ($\beta = .34$, $p = .005$, total $R^2 = .16$), explaining an additional 20% and 11% of the variance in intelligence in the younger and the older age group, respectively.

In a final step of analyses, differential predictions based on individual differences in WM (rather than individual differences in chronological age) were addressed. For these, the sample was split into two groups based on participants' WM capacity. This median-split grouping resulted in a lower WM capacity group ($N = 71$) and a higher WM capacity group ($N = 69$). Means and standard deviations for age, WM, GDA and fluid intelligence for the two groups are shown in Table 4. A hierarchical regression predicting intelligence where age was entered in a first step, followed by WM in a second and GDA in a third step was performed. Results are depicted in Table 5 and revealed that WM explained a significant amount of variance over and above age in both groups. Remarkably, GDA was able to explain an additional proportion of variance over and above that explained by age and WM in the higher WM capacity group, but not in the lower WM capacity group.

Discussion

The main aim of the present study was to examine whether previously found links between GDA and intelligence could be explained in terms of WM, as correctly responding to GDA tasks may also rely on working memory resources. Specifically, we assumed that tasks measuring GDA make use of a person's WM and as WM has been shown to be strongly related to intelligence (e.g., Conway et al., 2002; Engel de Abreu et al., 2010; Swanson, 2011); this could explain the strong relationship between GDA and intelligence. Another major aim of the present study was to address the question of differential predictive power of GDA for individual differences in intelligence. That is, by including two age groups that differed in terms of their level of performance in WM and GDA both within and across age groups, age- and WM-capacity dependent analysis could be performed. The findings indicated that WM was a better predictor of fluid intelligence in both age groups and both WM capacity groups (high and low) compared to GDA. Furthermore, GDA did not predict fluid intelligence over and above WM in neither age group nor in the lower WM capacity group. GDA did, however, predict fluid intelligence over and above WM in the higher WM capacity group. These results suggest that GDA is related to fluid intelligence, but that its influence on the prediction of intelligence becomes only statistically reliable once WM capacity is above a certain level.

As to developmental progression in the tasks included, the analyses performed revealed that performance on the fluid intelligence test increased substantially with age. The older children also performed significantly better than the younger children in two out of the three WM tasks, namely letter-number-sequencing and patterns memory. Moreover, as predicted, sensory discrimination ability improved significantly between the younger and the older age group in all three tasks. As the absolute difference in chronological age between these two age groups was not very large (2 years), the documentation of reliable performance differences in the included tasks speaks for their reliability and sensitivity, an important prerequisite for the performed correlation and regression analyses.

With respect to the associations between GDA, WM, and intelligence, analyses revealed that WM as well as GDA were significantly correlated with fluid intelligence. This pattern of interrelations held in both age groups. This finding corresponds to previously reported results from studies with adults and children (e.g., Ackerman et al., 2005; Deary et al., 2004; Engel de Abreu et al., 2010; Meyer et al., 2010). However, while previous studies found high to very high correlations between GDA and intelligence (Deary et al., 2004; Meyer et al., 2010; Spearman, 1904), the present analyses revealed only moderate correlations between the two constructs in both age groups. Correlations further showed that WM and GDA were moderately inter-related in both age groups. Together, these results suggest that there is a significant amount of overlap between GDA, WM and fluid intelligence, that is, individuals who score high on intelligence tend to also score high on tasks of WM and GDA.

In order to assess the unique contribution of WM and GDA to fluid intelligence in the two age groups, regression analyses were performed. The results revealed that GDA and WM explained significant amounts of variance in fluid intelligence on their own. When the other predictor was taken into account however, only WM was able to explain significant amounts of variance in intelligence over and above GDA. In contrast, the contribution of GDA to the prediction of fluid intelligence over and above WM was negligible in both 9-year-olds and 11-year-olds. These results suggest that there is a significant and unique contribution of WM to fluid intelligence in children. It is possible, that the tasks used to measure GDA rely heavily on WM, therefore increasing the relative importance of WM. Sensory discrimination tasks in general require the participant to choose between two stimuli that are presented one after the other. To be able to solve the task, the participant has to be able to keep the first stimuli active while seeing or hearing the next stimuli, which is exactly what is required in WM tasks.

Results from studies assessing brain regions that are activated during sensory discrimination tasks reinforce this interpretation that both sensory abilities and WM abilities are used to solve sensory discrimination tasks (Livesey, Wall, & Smith, 2007; Nenadic et al., 2003). These studies show that some brain regions are only activated during specific tasks (e.g., the right putamen in duration discrimination tasks; Nenadic et al., 2003). Other regions, such as the right dorsolateral prefrontal cortex (DLPFC), which has previously been linked to WM (e.g., MacDonald, Cohen, Stenger, & Carter, 2000), are activated in various sensory discrimination tasks including duration, color and pitch discrimination (Livesey et al., 2007; Nenadic et al., 2003). Together, the results of these studies indicate that when solving sensory discrimination tasks, participants draw upon both sensory discrimination abilities as well as WM abilities.

In light of these results and the fact that WM is usually conceptualized as consisting of different components, some of which are responsible for processing of information and some others being responsible for storing information (e.g., see Baddeley, 2007; Cowan, 1999; Cowan & Alloway, 2009; Engle, Kane et al., 1999), it would be interesting to see whether sensory discrimination tasks involve both storage and processing or whether only one of the two components is used when these tasks are solved. On the task level, sensory discrimination ability (e.g., comparing the pitch of two tones) seem to correspond closer to simple span tasks used to assess storage aspects of WM (STM) than complex span tasks used to assess both storage and processing (see e.g., Engel de Abreu et al., 2010). It is plausible that solving sensory discrimination tasks only employs storage but not processing aspects of WM. However, to be able to assess whether this is in fact the case, both aspects of WM would have to be assessed separately in the same study, for example, by including both simple and complex span tasks.

It is also possible that individuals try and rely more on WM when task difficulty increases. In other words, when task difficulty is increased and participants become uncertain as to which answer is the correct one (e.g., which tone is higher), they may rely more on WM to compare the two stimuli and to make a decision. If this was the case, individuals with better WM would succeed at solving the task more often than individuals with lower WM, again boosting the relative importance of WM. This interpretation was supported by the third regression analysis in the present study where the unique contribution of WM and GDA to fluid intelligence was assessed in lower and higher WM capacity groups, respectively. Children of both age groups were divided into a higher and a lower WM ability group according to their performance on the WM tasks. The results indicated that WM explained a significant amount of variance in fluid intelligence in both the lower and the higher WM capacity group. GDA, however, did not explain any significant variance in fluid intelligence over and above WM in the lower WM capacity group but was able to explain significant amounts of variance over and above WM in the higher WM capacity group. This differential pattern of prediction suggests that when WM capacity is low, GDA cannot predict fluid intelligence over and above WM. GDA can, however, predict fluid intelligence over and above WM when WM capacity is at a sufficiently high level. This interpretation can again be supported with results from studies looking at brain activation during task execution. Several studies have found that increased task difficulty (e.g., in auditory perception tasks; Lewandowska, Piatkowska-Janko, Bogorodzki, Wolak, & Szelag, 2010), resulted in greater activation of areas that have typically been related to WM processes, including the DLPFC (Lewandowska et al., 2010; Paus, Koski, Caramanos, & Westbury, 1998; Tregallas, Davalos, & Rojas, 2006).

The present study provides new evidence of the importance of WM in regards to the GDA – intelligence relationship in children. One limitation of the study is that WM was assessed using only complex span tasks. This meant that the relationship between the constructs could only be assessed in terms of WM as a whole, but not in terms of the subcomponents of WM (i.e., storage and processing). In a further study, WM should be assessed using both complex span tasks as well as tasks assessing only STM or storage aspects, to be able to make this differentiation. Additionally, it would also be interesting to see whether the present results also apply to other measures of intelligence (e.g., crystallized intelligence) or whether they are specific to the relationship between GDA and fluid intelligence. Furthermore, the differences in WM between the two age groups were not pronounced, and it was thus unlikely that the prediction patterns would vary substantially between the two age groups. Further studies using more age groups that target age- and WM-dependent predictions of intelligence using GDA are needed to help elucidate whether the present interpretations can be further supported.

Conclusion

The present study shows that there is substantial overlap between WM, GDA and fluid intelligence. The results indicate that GDA is indeed related to intelligence in children, but its influence on the prediction of fluid intelligence is dependent on WM capacity. WM seems to act as a bottleneck of information processing that limits the influence of GDA on the prediction of intelligence. The predictive power of GDA therefore, does not seem to stem from developmental progression, but rather appears to be due to individual differences in WM. Together, our results suggest that WM, despite not being able to fully explain the relationship between GDA and intelligence, certainly has a strong influence on it in children aged 9 and 11 years old.

References

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2005). Working memory and intelligence: The same or different constructs? *Psychological Bulletin, 131*(1), 30-60. doi: 10.1037/0033-2909.131.1.30

Ang, S. Y., & Lee, K. (2010). Exploring developmental differences in visual short-term memory and working memory. *Developmental Psychology, 46*(1), 279-285. doi: 10.1037/a0017554

Archibald, L. M. D., & Gathercole, S. E. (2006). Short-term and working memory in specific language impairment. *International Journal of Language & Communication Disorders, 41*(6), 675-693. doi: 10.1080/13682820500442602

Baddeley, A. D. (1986). *Working memory* (Psychology Series: No. 11). Oxford: Clarendon Press.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417-423. doi: 10.1016/S1364-6613%2800%2901538-2

Baddeley, A. D. (2007). *Working memory, thought, and action.* Oxford: Oxford University Press.

Belacchi, C., Carretti, B., & Cornoldi, C. (2010). The role of working memory and updating in Coloured Raven Matrices performance in typically developing children. *European Journal of Cognitive Psychology, 22*(7), 1010-1020. doi: 10.1080/09541440903184617

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development, 81*(6), 1641-1660. doi: 10.1111/j.1467-8624.2010.01499.x

Cattell, R. B., & Cattell, A. K. S. (1973). *Handbook for the Culture Fair Intelligence Test scale 2 forms A and B.* Champaign, IL: Institute of Personality and Ability Testing.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff, S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence, 30*(2), 163-183. doi: 10.1016/S0160-2896(01)00096-4

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62-101). Cambridge: Cambridge University Press.

Cowan, N., & Alloway, T. (2009). Development of working memory in childhood. In M. L. Courage & N. Cowan (Eds.), *The development of memory in infancy and childhood* (pp. 303-342). Hove, East Sussex, UK: Psychology Press.

Daniel, M. H. (1982). *A factorial study of reasoning tests.* (Technical Report 1982-6). Boston: Johnson O'Connor Research Foundaton.

Deary, I. J. (1994). Sensory discrimination and intelligence: Postmortem or resurrection? *The American Journal of Psychology, 107*(1), 95-115. doi: 10.2307/1423292

Deary, I. J. (2012). Intelligence. *Annual Review of Psychology, 63*, 453-482. doi: 10.1146/annurev-psych-120710-100353

Deary, I. J., Bell, P. J., Bell, A. J., Campbell, M. L., & Fazal, N. D. (2004). Sensory discrimination and intelligence: Testing Spearman's other hypothesis. *The American Journal of Psychology, 117*(1), 1-19. doi: 10.2307/1423593

Engel de Abreu, P. M. J., Conway, A. R. A., & Gathercole, S. E. (2010). Working memory and fluid intelligence in young children. *Intelligence, 38*(6), 552-561. doi: 10.1016/j.intell.2010.07.003

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102-134). Cambridge: Cambridge University Press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General, 128*(3), 309-331. doi: 10.1037/0096-3445.128.3.309

Ferrer, E., O'Hare, E. D., & Bunge, S. A. (2009). Fluid reasoning and the developing brain. *Frontiers in Neuroscience, 3*(1), 46-51. doi: 10.3389/neuro.01.003.2009

Galton, F. (1883). *Inquiries into human faculty and its development*. London: Macmillan.

Grob, A., Meyer, C. S., & Hagmann-von Arx, P. (2009). *Intelligence and Development Scales (IDS). Intelligenz- und Entwicklungsskalen für Kinder von 5-10 Jahren*. Bern, CH: Huber.

Henry, L. (2012). *The development of working memory in children.* London: Sage.

Hunt, E. (2011). *Human intelligence*. Cambridge: Cambridge University Press.

Jäger, A. O., Süß, H.-G., & Beauducel, A. (1997). *Berliner Intelligenzstruktur test form 4.* Göttingen, D: Hogrefe.

Kaernbach, C. (1991). Simple adaptive testing with the weighted up-down method. *Perception & Psychophysics, 49*(3), 227-229. doi: 10.3758/BF03214307

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity?! *Intelligence, 14*, 389-433. doi: 10.1016/S0160-2896(05)80012-1

Lewandowska, M., Piatkowska-Janko, E., Bogorodzki, P., Wolak, T., & Szelag, E. (2010). Changes in fMRI BOLD response to increasing and decreasing task difficulty during auditory perception of temporal order. *Neurobiology of Learning and Memory, 94*(3), 382-391. doi: 10.1016/j.nlm.2010.08.005

Livesey, A. C., Wall, M. B., & Smith, A. T. (2007). Time percpetion: Manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia, 45*, 321-331. doi: 10.1016/j.neuropsychologia.2006.06.033

Luce, R. D., & Galanter, E. (Eds.). (1963). *Discrimination* (Vol. 1). New York: Wiley.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*, 1835-1838. doi: 10.1126/science.288.5472.1835

Meyer, C. S., Hagmann-von Arx, P., Lemola, S., & Grob, A. (2010). Correspondence between the general ability to discriminate sensory stimuli and general intelligence. *Journal of Individual Differences, 31*(1), 46-56. doi: 10.1027/1614-0001/a000006

Nenadic, I., Gaser, C., Volz, H.-P., Rammsayer, T., Häger, F., & Sauer, H. (2003). Processing of temporal information and the basal ganglia: new evidence from fMRI. *Experimental Brain Research, 2003*, 238-246. doi: 10.1007/s00221-002-1188-4

Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H.-M. (2005). Working memory and intelligence - their correlation and their relation: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin, 131*(1), 61-65. doi: 10.1037/0033-2909.131.1.61

Paus, T., Koski, L., Caramanos, Z., & Westbury, C. (1998). Regional differences in the effects of task difficulty and motor ourput on blood flow response in the human anterior cingulate cortex: a review of 107 PET activation studies. *NeuroReport, 9*(9), R37-R47. doi: 10.1097/00001756-199806220-00001

Petermann, F., & Petermann, U. (2008). *Hamburg-Wechsler-Intelligenztest für Kinder IV (HAWIK-IV).* Bern, CH: Huber.

Pickering, S. J., & Gathercole, S. E. (2001). *Working memory test battery for children (WMTB-C).* London: Psychological Corporation.

Rammsayer, T. H., & Brandler, S. (2007). Performance on temporal information processing as an index of general intelligence. *Intelligence, 35*(2), 123-139. doi: 10.1016/j.intell.2006.04.007

Raven, J. C., Raven, J., & Court, J. H. (1982). *Mill Hill Vocabulary Test.* London: Lewis.

Röthlisberger, M., Neuenschwander, R., Michel, E., & Roebers, C. M. (2010). Exekutive Funktionen: Zugrundeliegende kognitive Prozesse und deren Korrelate bei Kindern im späten Vorschulalter. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 42*(2), 99-110. doi: 10.1026/0049-8637/a000010

Spearman, C. (1904). "General intelligence", objectively determined and measured. *American Journal of Psychology, 15*(2), 201-293. doi: 10.2307/1412107

Swanson, H. L. (2011). Intellectual growth in children as a function of domain specific and domain general working memory subgroups. *Intelligence, 39*(6), 481-492. doi: 10.1016/j.intell.2011.10.001

Tillman, C. M., Bohlin, G., Sørensen, L., & Lundervold, A. J. (2009). Intelligence and specific cognitive abilities in children *Journal of Individual Differences, 30*(4), 209-219. doi: 10.1027/1614-0001.30.4.209

Tregallas, J. R., Davalos, D. B., & Rojas, D. C. (2006). Effect of task difficulty on the functional anatomy of temporal processing. *NeuroImage, 32,* 307-315. doi: 10.1016/j.neuroimage.2006.02.036

Troche, S. J., & Rammsayer, T. H. (2009). Temporal and non-temporal sensory discrimination and their predictions of capacity- and speed-related aspects of psychometric intelligence. *Personality and Individual Differences, 47*(1), 52-57. doi: 10.1016/j.paid.2009.02.001

Wechsler, D. (1981). *Manual of the Wechsler Adult Intelligence Scale – Revised.* New York: Psychological Cooperation.

Weiss, R. H. (2006). *CFT 20-R. Grundintelligenztest Skala 2*. Göttingen, D: Hogrefe Verlag.

Willis, J. O., Dumont, R., & Kaufman, A. S. (2011). Factor-analytical models of intelligence. In R. J. Sternberg & S. B. Kaufman (Eds.), *The Cambridge handbook of intelligence* (pp. 39-57). Cambridge: Cambridge University Press.

Table 1

Mean and Standard Deviations for all Variables assessed by Age Group

Variable	Age group	Range	*M (SD)*	*t*(138)	*p*
Age (in years)	1	8.56– 9.70	9.16 (.29)	-40.772	.000
	2	10.62 – 12.00	11.34 (.34)		
CFT 20-R	1	12 – 38	27.49 (6.03)	-5.814	.000
	2	18 – 48	33.57 (6.34)		
aDD	1	8.70 – 62.30	25.35 (13.06)	4.662	.000
	2	7.15 – 45.10	17.12 (6.87)		
pD	1	32.00 – 132.48	75.74 (22.93)	2.142	.034
	2	15.90 – 130.05	67.00 (25.29)		
vDD	1	18.75 – 96.88	45.13 (15.05)	2.912	.004
	2	13.00 – 82.50	37.76 (14.90)		
LR	1	6 – 20	14.53 (2.80)	-1.492	.138
	2	7 – 24	15.29 (3.19)		
LNS	1	3 – 21	16.13 (3.00)	-3.313	.001
	2	10 – 23	17.67 (2.48)		
PM	1	1 – 12	5.54 (3.20)	-2.468	.015
	2	1 – 17	6.96 (3.57)		

Note. Age group 1 = younger age group; age group 2 = older age group. CFT 20-R = Culture Fair Intelligence Test; aDD = auditory duration discrimination task; pD = pitch discrimination task; vDD= visual duration discrimination task; LR = listening recall; LNS = letter-number-sequencing; PM = patterns memory.

Table 2

Factor Loadings for Principal Component Analysis of Working Memory and Sensory Discrimination Tasks

	Rotated factor loadings	
Tasks	Sensory discrimination	Working memory
aDD	**.820**	-.129
pD	**.611**	.240
vDD	**.731**	-.008
LR	.020	**.798**
LNS	.272	**.640**
PM	-.123	**.658**

Note. Factor loadings > .40 are in boldface. aDD = auditory duration discrimination; pD = pitch discrimination; vDD = visual duration discrimination; LR = listening recall; LNS = letter-number sequencing; PM = patterns memory

Table 3

Results from Hierarchical Regression Analyses Investigating the Independent Contributions of Measures of Working Memory and Sensory Discrimination to Fluid Intelligence for the Two Age Groups.

Predictor variables	Younger age group					Older age group				
	β	*B*	*SE B*	ΔR^2	*Tolerance*	β	*B*	*SE B*	ΔR^2	*Tolerance*
Step 1										
WM	.51***	.62	.13	**.26*** **	1.00	.38**	.50	.15	**.15** **	1.00
Step 2										
WM	.47***	.57	.13		.94	.34**	.44	.15		.91
GDA	.16	.19	.13	.02	.94	.13	.17	.15	.02	.91
Total R^2				.28					.17	

Note. WM = working memory, GDA = general sensory discrimination ability.

** $p < .01$, *** $p < .001$

Table 4

Mean and Standard Deviations for Age, WM, GDA and Fluid Intelligence for the High WM Capacity and Low WM Capacity Group

	Lower WM capacity		Higher WM capacity	
Variable	*M*	*SD*	*M*	*SD*
Age	10.40	1.17	10.09	1.09
WM	-1.55	1.40	1.74	1.24
GDA	-.33	2.23	.45	1.93
Intelligence	28.7	6.80	32.41	6.50

Note. WM = working memory, GDA = general sensory discrimination ability.

Table 5

Results from Hierarchical Regression Analyses Investigating the Independent Contributions of Measures of Working Memory and Sensory Discrimination to Fluid Intelligence for Lower and Higher WM Capacity Groups.

Predictor variables	Lower WM capacity					Higher WM capacity				
	β	*B*	*SE B*	ΔR^2	*Tolerance*	β	*B*	*SE B*	ΔR^2	*Tolerance*
Step 1										
Age	.49***	1.17	.25	**.24*** **	1.00	.43***	1.09	.28	**.19*** **	1.00
Step 2										
Age	.47***	1.13	.24		1.00	.42***	1.05	.27		1.00
WM	.28**	.58	.20	**.07** **	1.00	.28**	.62	.23	**.08** **	1.00
Step 3										
Age	.47***	1.13	.24		1.00	.42***	1.05	.25		1.00
WM	.28*	.56	.21		.91	.25*	.55	.22		.99
GDA	-.01	-.01	.13	.00	.91	.30**	.42	.14	**.09** **	.99
Total R^2				.31					.36	

Note. WM = working memory, GDA = general sensory discrimination ability.
* $p < .05$ ** $p < .01$, *** $p < .001$

Figure 1: Schematic Representation of a Trial from the Patterns Memory Task.