Relations among fluid intelligence, sensory discrimination and working memory in middle to late childhood - A latent variable approach

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1. Introduction

Human mental abilities and individual differences thereof have been of central interest since the very early days of psychology as an empirical discipline. Research interest in the area has not only targeted intelligence in adulthood, interest in intelligence in childhood has equally been in the focus from very early on. The first test of intelligence, for example, was designed to assess mental abilities in children (Binet-Simon scale; Binet & Simon, 1905) and research on intelligence and individual differences in childhood is still a thriving field of enquiry today. However, even with more than a century of empirical research and a large number of models and theories, intelligence is still an elusive concept in both childhood and adulthood. In the domain of psychometric intelligence, contemporary views emphasize that it is a broad and multi-faceted concept embracing various aspects of information processing (Hunt, 2011). But the question of which mechanisms of information processing are more, respectively less essential when trying to explain individual differences in psychometric intelligence is still a strongly debated issue (Deary, 2012; Demetriou, Mouyi, & Spanoudis, 2008; Hunt, 2011). Different information-processing mechanisms have been suggested to be related to intelligence, including attention (e.g., Burns, Nettelbeck, & McPherson, 2009; Schweizer, Moosbrugger, & Goldhammer, 2005; Stankov, 1988), processing speed (e.g., Fry & Hale, 2000; Kail, 2007), sensory discrimination (e.g., Deary, Bell, Bell, Campbell, & Fazal, 2004; Meyer, Hagmann-von Arx, Lemola, & Grob, 2010; Troche & Rammsayer, 2009), and working memory (WM; e.g., Conway, Getz, Macnamara, & Engel de Abreu, 2011; Cowan & Alloway, 2009).

Of these variables, sensory discrimination ability is probably one of the oldest contenders for an explanation of individual variability in intelligence. At the start of the last century, Spearman (1904) reported an almost perfect correlation between a factor derived from performance on discrimination tasks (i.e., weight, hue, and pitch discrimination) and his general factor of intelligence (*g*). Research has since been able to confirm a close relationship between general discrimination ability (GDA) – a collection of sensory discrimination abilities quantified in different tasks and different modalities – and intelligence (Deary et al., 2004; Troche & Rammsayer, 2009). At the same time, WM has been shown to be strongly related to intelligence in both adults and children (Ackerman, Beier, & Boyle, 2005; Engel de Abreu, Conway, & Gathercole, 2010; Swanson, 2011), with some researchers suggesting that WM was the information-processing mechanisms that best predicts measures of psychometric intelligence (Cowan & Alloway, 2009; Oberauer, Schulze, Wilhelm, & Süß, 2005). Very few studies have looked at both of these variables simultaneously to try and understand how they are related to each other and to intelligence, and which of these variables is more important in terms of explaining individual differences in intelligence. In the present study, a latent variable approach will be presented, exploring the relationship between WM and GDA and their relative contributions to fluid intelligence in children, to help untangle the interplay and relationship of these two information processing variables with intelligence.

1.1 Definition of Key Concepts

Fluid Intelligence. The literature on intelligence offers various models and theories of psychometric intelligence. Recent models describe individual differences in intelligence with a fairly small number of dimensions of mental ability, referred to as factors, including for example, verbal ability and visuo-spatial reasoning (Hunt, 2011). One prominent factor in these models and theories is fluid intelligence. Fluid intelligence is generally considered to be the ability to deal with new and unusual problems, or in other words, the ability that allows individuals to flexibly adapt their thinking to new problems and situations (Cattell, 1963). Instruments that assess fluid intelligence are typically tests that assess deductive, inductive, and quantitative reasoning, where novel problems have to be solved or patterns detected (Hunt, 2011; Willis, Dumont, & Kaufman, 2011). For the present study, the Culture Fair Test

(Weiss, 2006), a test of fluid intelligence was chosen as a measure of intelligence. Reasons for this choice included (1) the wide use of such tests in studies of intelligence (see e.g., Conway et al., 2011), (2) the relatively culture-free stimuli that are used in such tests (Willis et al., 2011), and (3) the fact that some researchers have suggested that fluid intelligence and *g* are effectively equivalent (for a discussion of the issue see Hunt, 2011; Johnson & Bouchard Jr, 2005).

Sensory Discrimination. Interest in sensory discrimination was sparked at the end of the 19th century when Galton suggested 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). More recently, sensory discrimination ability has been defined as the ability to detect small differences between stimuli of the same modality (Deary, 1994) and in tasks used to assess sensory discrimination ability, participants are usually required to compare two stimuli that are presented one after the other (e.g., comparing the pitch of two tones; Troche & Rammsayer, 2009).

As described in the introduction, Spearman (1904) proposed that there is a functional correspondence between *g* and GDA in children. More recent studies have been able to show a reliable relationship between intelligence and sensory discrimination for different modalities (Acton & Schroeder, 2001; Haldemann, Stauffer, Troche, & Rammsayer, 2011; Meyer et al., 2010; Stankov, Seizova-Cajić, & Roberts, 2001; Troche & Rammsayer, 2009). In most of these studies, single discrimination tasks correlated modestly with intelligence. When latent variables were derived from several sensory discrimination measures – reflecting the shared sensory variance, and thus GDA – the strength of the relationship increased. Troche and Rammsayer (2009), for example, found a correlation of $r = .64$ between GDA and intelligence in a sample of adults. Similarly, Deary and colleagues (2004) found correlations of $r = .68$ (in a sample of participants ranging from late childhood to adulthood with a mean age of 27 years and 2 months) and *r* = .92 (in a sample of children with a mean age of 12 years and 2 months) between GDA and *g*. Furthermore, Meyer and colleagues (2010) found that GDA and general intelligence correlated with *r* = .78 in children aged between 5 and 10 years. Some researchers have suggested that the strong relationship between GDA and intelligence may be due to neural substrates and their efficiency (Deary et al., 2004), but the actual reasons are still unclear today (Deary, 2012).

Working Memory. WM is an information process that is essential in many everyday life situations. It plays a central role in language development, reading, mathematics, reasoning, and problem solving (see e.g., Bjorklund, 2005; Cowan & Alloway, 2009; Henry, 2012). There is no single, well-agreed on definition of WM in the literature and there are many debates around the processes that are subsumed under the term WM. But while the available models and theories differ in important aspects (see e.g., Miyake & Shah, 1999), most experts of WM agree on a few basic principles. It is widely accepted that WM is a limited capacity system responsible for the maintenance of information and the simultaneous manipulation and processing of the same or different information over short periods of time (Baddeley, 2007; Conway et al., 2011; Cowan, 1999; Engle, Kane, & Tuholski, 1999; Hitch, 2006; Oberauer, Süß, Wilhelm, & Wittman, 2003). Recent research has shown that both storage and processing aspects of WM are influenced by multiple information processes including primary memory, attention control and secondary memory (Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014). Of these, attention control has recently garnered particular interest, and it has been suggested to be the most important aspect of WM (e.g., Carruthers, 2013).

Results from research on WM and fluid intelligence have shown a strong relationship between the two, both in adults (for an overview see Ackerman et al., 2005) and children (Engel de Abreu et al., 2010; Swanson, 2011; Tillman, Bohlin, Sorensen, & Lundervold, 2009). It has been proposed that WM is the information process that best predicts individual differences in intelligence scores (e.g., Oberauer et al., 2005), and some researchers have even suggested that intelligence and WM are effectively the same (Kyllonen & Christal, 1990). However, while most researchers agree that WM is an important component of intelligence, they still consider them to be conceptually different (e.g., Hunt, 2011; Oberauer et al., 2005).

Methods used to measure WM functioning can differ widely between studies. In line with other studies assessing the relationship between WM and fluid intelligence (e.g., Unsworth et al., 2014), we chose complex span tasks to represent WM in the present study. Complex span tasks are considered to represent WM as a multi-faceted system and to pick up variance from different processes subsumed in WM, such as attention control and short-term capacity (Unsworth et al., 2014). In these tasks, individuals are required to hold a piece of information in mind while manipulating or processing the same or different information (Conway et al., 2005).

1.2 Relationship between Sensory Discrimination, WM, and Intelligence

While there are ample studies assessing the relationship between fluid intelligence and WM or the relationship between sensory discrimination and intelligence (see Section 1.1 for examples), only very few studies have assessed sensory discrimination, WM, and intelligence in one single study. One of these is the study by Demetriou et al. (2008). The authors suggested a bottom-up model where lower-order perceptual and sensory processes affect the efficiency of higher-order cognitive processes. Consistent with this model, they found that individual differences in basic processes such as perceptual discrimination contributed to individual differences in higher level information processes such as WM, which in turn contributed to individual differences in psychometric intelligence. However, they only used one task to assess sensory discrimination ability, making it difficult to interpret the results at the level of a construct in the sense of GDA.

A more recent study (Voelke, Troche, Rammsayer, Wagner, & Roebers, 2013) assessed the contribution of GDA and WM to fluid intelligence in two age groups of children. The authors found that while WM explained substantial amounts of variance in fluid intelligence over and above GDA in both 9- and 11-year old children (an additional 20% and 11% of variance in the younger and older age group, respectively), GDA was not able to explain significant amounts of variance in fluid intelligence over and above WM (it explained an extra 2% of variance in both age groups). They argued that their results, in combination with results from various fMRI studies, showed that the relationship between GDA and fluid intelligence depends on WM functioning. However, because they used regression analyses, this did not allow them to estimate the structural relationship between the three constructs. Nonetheless, the results are interesting, as they reveal substantial amounts of shared variance at task level.

1.3 Developmental Perspective

Developmental psychologists have repeatedly suggested that cognitive functions follow differential developmental trajectories. This implies that different rates of development in cognitive functions are likely to result in changing interrelations, depending on the point in time of development when they are assessed (Bjorklund, 2005). Additionally, some authors have proposed a developmental fractionation or differentiation of cognitive functions during childhood and adolescence (Hitch, 1990; Logie & Pearson, 1997). In this line of thought, Demetriou et al. (2013) argued that in some phases of development, particular information processing mechanisms (such as WM) may be more important for changes in fluid intelligence than others. Their results supported this suggestion; they were able to show systematic changes in the relationships between processing speed, WM and fluid intelligence in children aged 4 to 16 years.

To be able to account for the possibility of differences in the relationship between GDA, WM, and fluid intelligence at different ages, we included a large age range in the present study, allowing us to test for possible age-dependent differences in patterns of interrelations.

1.4 The Present Study

In the present study, the interplay between GDA, WM, and fluid intelligence at the level of latent variables was investigated in middle to late childhood. Using latent variables and structural equation modeling (SEM), allows measurement errors to be minimized and task specific variances to be controlled for. Furthermore, the common features of tasks are pronounced by extracting the shared variances of the indicating tasks and using them for the estimation of the structural links among the latent variables. Compared to regression analyses, SEM allows the researcher to disentangle the relationships between the assessed constructs more precisely. To be able to extract latent variables for GDA, WM and fluid intelligence, several tasks were used for each construct. WM and GDA were each assessed with three tasks in different modalities, while fluid intelligence was assessed with a test made up of four subtests (CFT-20R; Weiss, 2006).

Previous literature in the area was used to guide model development for the SEM analyses. Because studies have shown that both GDA and WM are strongly related to intelligence (Ackerman et al., 2005; Deary et al., 2004; Engel de Abreu et al., 2010; Meyer et al., 2010; Swanson, 2011; Tillman et al., 2009; Troche & Rammsayer, 2009) and some researchers have suggested that WM and intelligence are essentially the same (Kyllonen & Christal, 1990), we first tested whether the theoretically derived three-factor model (with GDA, WM, and fluid intelligence as one factor each) could be assumed, or whether a two-factor model with either WM and fluid intelligence or GDA and fluid intelligence tasks loading onto one factor respectively, made more sense.

Additionally, due to the nature of sensory discrimination tasks – participants are presented with two stimuli of the same modality, one after the other – it is likely that some WM resource is activated during the tasks, since to be able to solve these tasks successfully, participants have to keep the first stimulus active while seeing or hearing the second stimulus and then making a decision. We tested whether the activation of WM resources was a main characteristic of sensory discrimination tasks or whether there was an overlap between WM and sensory discrimination but the tasks could be differentiated. To do this, we tested whether a model with GDA and WM loading onto the same factor would better fit to the data than a model with separate factors for these two constructs.

Then we tested a model which assumed WM and GDA to be dissociable sources of individual differences in fluid intelligence that could each predict unique variance in fluid intelligence (Model 1). Because of results of previous studies described in Section 1.2, a second model in which GDA and WM were related but GDA was not able to predict unique variance in fluid intelligence over and above WM (Model 2), was also tested.

2. Method

2.1 Participants

The sample consisted of 263 children (56.3% boys) ranging in age from 7 years 11 months to 12 years 9 months (mean age: 10 years 2 months, *SD* = 13 months). The sample used in the present study was drawn from a large study assessing sensory discrimination, WM and intelligence in childhood and adulthood (see Troche, Wagner, Voelke, Roebers, & Rammsayer, 2014 for adult data). The children were recruited through public schools in Switzerland. The study was approved by the local ethics committee and informed consent was obtained from all parents.

To test for age-dependent differences in patterns of interrelations we divided the sample into a younger age group representing middle childhood (*n* = 139) ranging in age from 7 years

11 months to 10 years 1 month (mean age 9 years 2 months, *SD* = 4 months) and an older age group representing late childhood (*n* =124) ranging in age from 10 years 2 months to 12 years 9 months (mean age 11 years 3 months, *SD* = 5 months). To test whether the results would change if the groups differed more strongly in age, we also tested the models with a young group (*n* = 138) ranging in age from 7 years 11 months to 9 years 11 months (mean age 9 years 2 months; *SD* = 4 months) and an old group (*n* = 92) ranging in age from 11 years 0 months to 12 years 9 months (mean age 11 years 6 months, *SD* = 4 months).

2.2 Tasks

2.2.1 Assessment of Fluid Intelligence

Fluid intelligence was measured using the short version of the CFT 20-R (Weiss, 2006; reliability: .92). 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 paper-pencil test with time limits and can be administered either in a group or in an individual setting. The dependent measures used for this task were the number of correctly answered items in each of the four subtests.

2.2.2 Sensory Discrimination Tasks

Sensory discrimination ability was assessed with three tasks, an auditory and a visual duration discrimination task 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. Correct responding results in a decrease of the difference between the standard and the comparison stimulus and incorrect responding results in the task becoming easier as the difference between stimuli is increased. 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 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 trial 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 over 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 was clearly above threshold, but not dazzling. The stimuli consisted of a constant 100-ms standard interval and a variable comparison interval. 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. For the *auditory duration discrimination (aDD)* task, stimuli were white-noise bursts presented binaurally through headphones (Razer Orca) at an average intensity of 67dB. The stimuli consisted of a constant 100-ms standard interval and a variable comparison interval. 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 frequency 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.

2.2.3 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 simple sentences (e.g., “lions have four legs”, “cows can fly”). They were asked to judge whether each sentence made sense or not and to simultaneously remember the last word of each sentence. At the end of each trial, participants were asked to recall the last word from each sentence in the order 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). Children heard a mixed sequence of letters and digits. They were required to repeat the letters and numbers, beginning with the numbers in numerical order followed by the letters in alphabetical order. There were three trials per sequence length. The starting sequence consisted of one letter and one digit. If all three trials of a sequence were answered incorrectly, the task was ended; otherwise trial length was increased by one digit or letter. The total number of correctly answered trials (correctly recalled number-letter-sequences) was used as a measure of performance.

Patterns Memory (PM): Children completed an adapted version of the patterns memory task devised by Ang and Lee (2010). It consists of both 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 trained research assistants. There was no time limit to respond. The verification component of the task was not scored but children were not aware of this. 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.

2.3 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 the two sessions.

2.4 Statistical Analyses

Indicators of sensory discrimination were logarithmized to obtain normally distributed data and reverse scored so that higher values represent superior performance for all included variables. Structural equation modeling was done using AMOS 21 software (Arbuckle, 2012). Model fits were assessed as good when the chi-square probability was greater than .05, the comparative fit index (CFI) was greater than .95, the root-mean-square (RMSEA) smaller or equal to .06, the standardized root mean square residual (SRMR) smaller than .10 and the normed χ^2 below 2 (Garson, 2012; Hu & Bentler, 1999; Kline, 2011; Schweizer, 2010).

3. Results

3.1 Preliminary Analyses

Descriptive statistics for the variables included in the study are presented in Table 1. Table 2 presents Pearson correlations and partial correlations (controlling for age) for all variables. Against the background of the significant interrelations between the variables, confirmatory factor analyses (CFAs) were conducted testing whether a two-factor solution with either fluid intelligence as one factor and GDA/WM as one factor, or WM as one factor and GDA/fluid intelligence as one factor, or GDA as one factor and WM/fluid intelligence as one factor, respectively, would represent the data better than the theoretically assumed three-factor solution. The model fit for the first two-factor solution (WM and fluid intelligence/GDA) was unsatisfactory [χ^2 (34) = 82.918, $p < .001$, normed χ^2 = 2.44; CFI = .909; RMSEA = .07; SRMR = .06]. The model fit for the second two-factor solution (fluid intelligence and WM/GDA) was also unsatisfactory [χ^2 (34) = 76.02, $p < .001$, normed χ^2 = 2.24; CFI = .922; RMSEA = .07; SRMR = .06]. The model fit for the third two-factor solution (GDA and fluid intelligence/WM) was good [χ^2 (34) = 36.82, $p = .340$, normed χ^2 = 1.08; CFI = .995; RMSEA = .02; SRMR = .04], as was the model fit for the three-factor solution [χ^2 (32) =

32.88, p = .424, normed χ^2 = 1.03; CFI = .998; RMSEA = .01; SRMR = .04]. A chi-square difference test between the third two-factor model and the three-factor model was not significant [$\Delta\chi^2(2)$ = 3.95, p = .139]. The fit indices indicate that the two models are comparable. However, the fit indices for the three-factor model are very slightly better. Because this corresponds with the theoretical assumptions around WM and intelligence, we adopted a three-factor solution with fluid intelligence, WM and GDA as a factor for each the analyses reported below.

3.2 Relationship between GDA, WM, and Intelligence

In a first step, the correlations between fluid intelligence, WM and GDA were investigated separately by means of structural equation modeling. Coefficients were r = .57 (p < .001) between fluid intelligence and GDA, r = .91 (p < .001) between fluid intelligence and WM, and r = .62 (p < .001) between GDA and WM, respectively. Next, a model (Model 1) assuming that WM and GDA each predict distinct portions of variance in intelligence was tested. Regression coefficients were computed from WM onto fluid intelligence and from GDA onto fluid intelligence, while GDA and WM were assumed to correlate. Age was used as a control variable, correlating with GDA and WM and regressing onto fluid intelligence. The model yielded a good model fit [$\chi^2(39)$ = 44.59, p = .248, normed χ^2 = 1.14; CFI = .991; RMSEA = .02; SRMR = .04]. All factor loadings on the latent variables were significant at p < .001. WM and GDA correlated significantly (r = .62, p < .001), and WM also predicted fluid intelligence (β = .88, p < .001), but GDA did not significantly predict fluid intelligence (β = .07, p = .590). In a next step therefore, the path from GDA to fluid intelligence was deleted, making the model more parsimonious. This Model 2, depicted in Figure 2, also yielded good fit statistics [$\chi^2(40)$ = 44.90, p = .274, normed χ^2 = 1.12; CFI = .992; RMSEA = .02; SRMR = .04].

3.3 Relationship across Development

To make sure that we were not overlooking differential relationships between the variables at different ages, we wanted to test whether the relations predicted above were the same for the younger children in our sample (representing middle childhood with a mean age of 9 years 2 months) and the older children in our sample (representing late childhood with a mean age of 11 years 3 months). Descriptive statistics for the variables included in the study split by age group are shown in Table 3 and Pearson correlations for all variables by age group are shown in Table 4. Results of MANOVAs for each group of variables (Table 3) showed that performance on the tasks increased significantly with age for all tasks included in the study. Furthermore, the effects seemed to be more pronounced for the intelligence tasks (η_p^2 varied between .11 and .15 for these tasks) than for the GDA tasks (η_p^2 between .06 and .14) and the WM tasks (η_p^2 between .05 and .13).

We also tested the factor solutions described in section 3.1 separately for the two age groups. Fit indices for the CFAs for each age group are shown in Table 5. The results indicated that for the younger age group, a two factor solution with GDA as one factor and fluid intelligence and WM combined as a second factor was the best solution. For the older age group on the other hand, the three-factor solution with a factor each for GDA, WM and fluid intelligence was the best solution. Because we wanted to test for invariance of the relationship between WM, GDA and fluid intelligence between the two age groups, we decided to continue with the three factor solution and the SEM models investigated previously for both age groups.

In a next step, we tested Model 2 without age as a control variable for both age groups separately. The model yielded good fit indices for the younger age group [$\chi^2(33) = 44.03$, $p = .095$, normed $\chi^2 = 1.33$; CFI = .951; RMSEA = .05; SRMR = .06] and for the older age group [$\chi^2(33) = 27.80$, $p = .724$, normed $\chi^2 = .84$; CFI = 1.00; RMSEA = .00; SRMR = .05]. All factor loadings on the latent variables were significant at $p < .05$. When the path from GDA to fluid intelligence was allowed, the fit indices were still good for both groups: $\chi^2(32) = 43.61$, $p = .083$, normed $\chi^2 = 1.36$; CFI = .949; RMSEA = .05; SRMR = .06, for the younger children, and $\chi^2(32) = 27.76$, $p = .681$, normed $\chi^2 = .87$; CFI = 1.00; RMSEA = .00; SRMR = .05, for the older children, respectively. However, the path itself did not reach significance in either age group (β = .10, $p = .527$ for the younger age group and β = .04, $p = .835$ for the older age group). A multiple-group analysis for measurement invariance showed that measurement invariance across both age groups could be assumed for the first model tested (Model 2 without age as a control variable), meaning the model applied to both groups equally well. The chi-square difference tests were neither significant when the factor loadings were constrained [$\Delta\chi^2(7) = 12.32$, $p = .091$], nor when the structural relations as well as the factor loadings were constrained [$\Delta\chi^2(8) = 14.26$, $p = .075$].

To investigate whether the similar findings and path coefficients in the two groups would change as a function of age group if the two groups differed more strongly in terms of age, a part of the sample was cut out for the following analyses only. The young age group now included children aged between 8 and 10 years and the old age group children aged between 11 and 13 years. The fit indices for the models (Model 1) tested with these age groups were good for both groups: $\chi^2(32) = 43.61$, $p = .083$, normed $\chi^2 = 1.36$; CFI = .949; RMSEA = .05; SRMR = .06, for the young age group and $\chi^2(32) = 31.02$, $p = .516$, normed $\chi^2 = .97$; CFI = 1.00; RMSEA = .00; SRMR = .06, for the old age group. But as before, while WM could significantly predict fluid intelligence, the path from GDA to fluid intelligence remained non-significant in both age groups (β = .10, $p = .527$ for the younger age group and β = .01, $p = .973$ for the older age group).

4. Discussion

The aim of the present study was to explore the relationship between sensory discrimination, working memory and fluid intelligence in children between 7 and 12 years of age. Previous studies have shown that both WM and sensory discrimination ability are strongly related to intelligence, but studies assessing how these three variables relate to each other are rare. In the present study, a latent variable approach was chosen to assess the relationship between the three variables on the level of the underlying psychological construct.

CFAs showed that GDA, WM and fluid intelligence could be considered to be separate constructs. Nevertheless, all three latent variables were substantially correlated with each other and both GDA and WM were positively related to fluid intelligence. The SEM analyses showed that while WM was able to predict variance in fluid intelligence above and beyond GDA, GDA was not able to explain significant amounts of variance in fluid intelligence neither in the whole sample, nor in the younger or older age group.

In the literature, there have previously been suggestions that intelligence and WM are essentially the same (e.g., Kyllonen & Christal, 1990). Because Pearson correlations showed high correlations between WM and fluid intelligence tasks, we performed CFAs to test whether we could assume two separate constructs or whether we were in fact assessing one construct with different tasks. For the whole sample, both a two-factor model with fluid intelligence and WM combined and a three-factor model with fluid intelligence, WM and GDA as three separable factors showed comparable fit indices. In the younger age group, the two factor-model with fluid intelligence and WM loading onto the same latent variable showed the best fit, whereas in the older age group, the three-factor model with fluid intelligence, WM and GDA as three separate factors showed the best fit. These results indicate that WM and fluid intelligence seem to overlap substantially at younger ages, making it difficult to empirically separate them. But as children grow older, WM and fluid intelligence develop at different rates, and while still overlapping to a large degree, become separable, revealing that they are indeed two different constructs. These results confirm the idea of a developmental fractionation (see e.g., Hitch, 1990) and suggest that over the course of development, information processes become increasingly differentiated and specific.

Our use of complex span tasks to represent WM does not allow us to conclude which specific processes subsumed under WM are responsible for the strong correlations found between WM and fluid intelligence, nor the developmental differentiation discussed above. Complex span tasks are considered to reflect WM as a multi-faceted construct that comprises several important processes, including attention control, primary memory and secondary memory (Shipstead et al., 2014; Unsworth et al., 2014). It is possible that only one of these processes (e.g., attention control) is responsible for the findings in the present study, or that more than one give rise to individual differences in WM, its development and consequently to its relationship with fluid intelligence. Further researcher will clarify this issue.

The above interpretations, that WM and fluid intelligence develop differentially, were also supported by the results of the age group comparisons for all variables studied. The results showed that performance on all tasks increased significantly with age. This is in line with previous research showing that WM and fluid intelligence are still developing at this age (Best & Miller, 2010; Ferrer, O'Hare, & Bunge, 2009). In contrast, there is very little previous research on the development of GDA in this age group. A comparison of the size of these effects indicated that performance on fluid intelligence seemed to increase more strongly than performance on tasks of WM and GDA. The findings that the constructs develop at different rates, corresponds to the findings of the CFAs above, where the relationship between WM and fluid intelligence changes with development.

Moving a step away from the immediate interpretation of the data, the results of the CFAs may also point to differences in the functional and structural characteristics of the three constructs. While WM and fluid intelligence differentiated with age – from loading onto the same factor in the younger age group to forming two separate factors in the older age group – GDA was found to constitute a separate factor in the younger age group already. Some researchers, especially from a neo-Piagetian perspective, have suggested that intelligence is made up of WM and acquired processing structures (see e.g., Pascual-Leone & Johnson, 2005). It is possible that an age-related increase in the number and the weight of such acquired processing structures supports – at least in part – the differentiation of WM and fluid intelligence found in this study. Consequently and from this theoretical perspective, the fact that GDA was a separate factor already in the younger age group may suggest that GDA is not being influenced by these acquired processing structures, at least not to the same extent: the functional and structural characteristics of GDA may be more resistant against such experience based changes in development.

Sensory discrimination tasks, as discussed in the introduction, may activate WM resources due to the fact that they require participants to choose between two stimuli that are presented one after the other. For the focus of the present study, that is, the relationship between sensory discrimination, WM and fluid intelligence, it is important to know whether this activation of WM resources is substantial. If GDA tasks essentially measured WM functioning, this could significantly influence the relationship between the three assessed constructs. The correlation analyses showed significant overlap between some WM and GDA tasks. But the results of the CFAs indicated that WM and GDA tasks could not be considered to measure the same construct. That is, individual differences in performance on GDA tasks were not only due to WM functioning, but also other aspects; most likely individual differences in the ability to make fine discriminations in sensory perception.

Because of the results indicating that WM, GDA and fluid intelligence are different constructs and that WM and fluid intelligence differentiate with age, we chose to proceed with the three-factor model for the further analyses with all age groups, assuming that while highly connected, WM and fluid intelligence are separate constructs; or in the words of Earl Hunt (2011): "… the two are not identical, either in the sense of being perfectly correlated with each other statistically or in the sense of being conceptually identical." (p. 159). Looking more closely at the tasks used to assess WM and fluid intelligence in the present and other studies, this conclusion also makes sense. To be able to solve WM tasks correctly, participants are primarily required to hold information in mind and repeat it in the same or different form, while to be able to solve fluid intelligence tasks correctly, reasoning on top of storage and manipulation is required.

Hunt's statement cited above also corresponds with the results found in the correlation analyses of the latent variables. They showed that fluid intelligence and WM were substantially but not perfectly correlated with each other. The strength of the correlation found in the present study was on the high end of previously found correlations (Conway et al., 2011). GDA and fluid intelligence were also significantly correlated, but less strongly than fluid intelligence and WM. The correlations were lower than the ones found in previous studies. However, the strength of correlations found in previous studies also differed, with some studies finding very high correlations (r = .92; Deary et al., 2004) and others finding correlations between $r = .64$ and $r = .78$ (Deary et al., 2004; Meyer et al., 2010; Troche & Rammsayer, 2009). Whether these differences in strength of correlations are due to the fact that the present study focused on fluid intelligence only, or whether there were differences in the measurement of sensory discrimination or fluid intelligence that influenced the results is unclear at this stage.

The results of the correlation analyses suggest that there is a significant amount of shared variance between GDA, WM, and fluid intelligence. When the data was analyzed using SEM, the results showed that while the links between WM and fluid intelligence and WM and GDA were statistically significant, the link between GDA and fluid intelligence was not (see Figure 2). This means that while WM was able to explain significant amounts of unique variance in fluid intelligence, GDA was not able to do so. When we assessed both Models 1 and 2 with a younger age group (mean age 9 years and 2 months) and an older age group (mean age 11 years 3 months), the data showed that the results did not differ for the two groups and that Model 2 (without age as a control variable) was preferred in both age groups. More specifically, we were interested in the link between GDA and fluid intelligence and whether its strength would differ between different age groups. The results showed that the link remained non-significant in both groups, while the links between WM and GDA, and WM and fluid intelligence remained significant. Furthermore, the pattern of results remained the same when we split the groups differently while checking whether the results would change as a function of age group. When we split the sample so that the younger group included children aged 8 to 10 years and the older group included children aged 11 to 13 years, the link between GDA and fluid intelligence remained non-significant in both age groups, while the links between WM and GDA and WM and fluid intelligence remained significant. We concluded that there are no changing interrelations among the three constructs between the ages of 7 and 12 years.

The results of the SEM analyses correspond to earlier findings in the area (Demetriou et al., 2008; Voelke et al., 2013). Demetriou et al. (2008) found results supporting their proposal of a bottom-up model of intelligence in which lower-order cognitive functions such as sensory discrimination (which they called perceptual discrimination) affect higher order cognitive functions such as WM, which then in turn affect reasoning. Voelke et al. (2013), on the other hand, found that GDA was not able to predict variance in fluid intelligence over and above WM in two groups of children (aged 9- and 11- years). When they assessed the variables in two groups with different WM capacity (high vs. low) independent of age however, they found that when WM capacity was high, GDA was able to predict variance in fluid intelligence over and above that explained by WM. They interpreted these results as showing that GDA was related to intelligence in children, but that its influence on fluid intelligence was dependent on WM capacity.

Mathematically, Model 2 in the present study matches both interpretations. The model can show a bottom-up model like the one described by Demetriou et al. (2008), in which GDA influences WM, which then influences fluid intelligence, but it can also show that the relationship between GDA and fluid intelligence depends on WM functioning. With the present design of the study, it is not possible to determine which of the two interpretations is correct. But against the background of results from fMRI studies, which will be outlined below, we lean towards the second interpretation of the results as an explanation for the relationships found.

FMRI studies looking at brain regions that are activated during specific cognitive tasks can give interesting insights into how the cognitive processes tapped in the present study may be related. Studies looking at the activation during sensory discrimination tasks have shown that certain brain areas are only activated during specific sensory discrimination tasks (e.g., the right putamen in duration discrimination tasks; Nenadic et al., 2003) while other regions, such as the areas in the dorsolateral prefrontal cortex (DLPFC), that have previously been linked to WM (see e.g., MacDonald, Cohen, Stenger, & Carter, 2000) are activated during various sensory discrimination tasks, including pitch, color, auditory duration, visual duration, and intensity discrimination (Ferrandez et al., 2003; Livesey, Wall, & Smith, 2007; Nenadic et al., 2003). These results show that brain areas that are considered to be fundamental for WM functioning (DLPFC; see e.g., Barbey, Koenigs, & Grafman, 2013; Owen, 2000; Smith & Jonides, 1999) are also activated in a wide variety of sensory discrimination tasks, supporting the assumption that some WM resource is activated during sensory discrimination. It is possible that this activation of WM represents a functional link between different kinds of sensory discrimination tasks, making it a feature of a latent GDA variable. Considering that the relationship between intelligence and sensory discrimination relies on the common variance of sensory discrimination tasks (single sensory discrimination tasks do not correlate well with intelligence, but GDA does), the results of the above studies support the interpretation that the relationship between intelligence and GDA may be due to WM functioning. Nevertheless, the results of the CFAs in the present study showed that WM does not fully explain the link between different kinds of sensory discrimination tasks. There appear to be other aspects of sensory discrimination, most likely related to perception, that are common to all sensory discrimination tasks. Yet, the results of the present study indicate that these aspects are not able to explain variance in fluid intelligence, at least not over the top of WM.

In summary, while GDA may be able to explain significant amounts of variance in fluid intelligence under certain circumstances (e.g., when WM capacity is high; Voelke et al., 2013) the present results together with results from fMRI studies indicate that the relationship between GDA and fluid intelligence depends in large parts most likely on WM functioning. Which aspect of WM functioning (e.g., attention control, short-term capacity, etc.) are important for the relationship cannot be determined from the present results.

4.1 Strengths, Limitations and Future Directions

Strengths of the present study include the size of the sample, as well as the use of SEM for the analyses. By using SEM, measurement errors and task specific problems are reduced and the common features of tasks are more pronounced, resulting in a purer measure of the construct of interest. It allows for explicit testing of models and lets researchers disentangle the relationships between assessed constructs more precisely.

Moreover, a comparatively wide operationalization of GDA was used in the present study, making it more suitable to be interpreted in terms of *general* discrimination ability. However, the breadth of tasks included could still be expanded. While auditory duration discrimination, pitch discrimination, and visual duration discrimination are used in the present study, other sensory modalities and processes are not included. Further tasks that could be included in future studies include color discrimination (Acton & Schroeder, 2001), loudness discrimination (Troche & Rammsayer, 2009), as well as texture and shape discrimination (Stankov et al., 2001).

In terms of WM theory, the study focused on theories that emphasize the simultaneous maintenance and processing of goal relevant information as the most important aspect of WM. This, unfortunately, meant that other aspects of WM outside of these theories were essentially overlooked, including, for example, the coordination or relational integration of ongoing information processing proposed by Oberauer and colleagues (see e.g., 2003; 2008). According to Oberauer and colleagues, this function is responsible for building new relations between elements and to integrate these relations into structures. Assessing how this relational integration function is affected by sensory discrimination (or vice versa) could provide an interesting area of future investigation.

Additionally, it is possible that the models of prediction would differ more strongly between age groups if the ages studied were further apart. Last but not least, future studies should also try to assess whether the present interpretations of the data – that the relationship between GDA and intelligence depends on WM functioning – can be supported or whether a bottom-up model should be favored after all.

4.2 Conclusion

In the present study, results are presented supporting the interpretation that the strong relationship found previously between GDA and intelligence depends on WM functioning. Interpreted from an individual differences perspective, the results show that WM is more essential than GDA when trying to explain individual differences in fluid intelligence in childhood. Interpreted from a developmental perspective, the results show that performance on GDA, WM and fluid intelligence tasks increase with age and that WM and fluid intelligence, while not being separable in middle childhood, develop at different rates, becoming more separable with age. But despite this differential development, the relationship between GDA, WM and fluid intelligence does not change between the ages of 7 and 12 years.

It seems that in the context of the search for information processes that underlie individual differences in intelligence, that what "… reaches us … through the avenue of our senses…" and "… the more perceptive the senses are of differences…" (Galton, 1883, p.19) (i.e., sensory discrimination) is important, but what really counts in terms of fluid intelligence is how we hold and manipulate information (i.e., WM) once we have received and assessed it.

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