Accounting for individual differences in the development of verbal and visual short term memory processes in children

Koppenol-Gonzalez, Gabriela V.; Bouwmeester, Samantha; Vermunt, Jeroen K.

Published in:
Learning and Individual Differences

DOI:
10.1016/j.lindif.2018.01.007

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Learning and Individual Differences 66 (2018) 29–37

Contents lists available at ScienceDirect

Learning and Individual Differences

journal homepage: www.elsevier.com/locate/lindif

Accounting for individual differences in the development of verbal and visual short term memory processes in children

Gabriela V. Koppenol-Gonzalez[a,*], Samantha Bouwmeester[b], Jeroen K. Vermunt[a]

[a] Tilburg University, Department of Methodology and Statistics, P.O. Box 90153, NL-5000 LE Tilburg, The Netherlands
[b] Erasmus University Rotterdam, Department of Psychology, Education & Child Studies, P.O. Box 1738, NL-3000 DR Rotterdam, The Netherlands

A R T I C L E   I N F O

Keywords:
Short term memory
Development
Methodology
Transition analysis
Longitudinal

A B S T R A C T

In developmental research on memory, the model of working memory of Baddeley and Hitch (1974, Baddeley, 1986) is the theory most often referred to. This theory has played an important role in studies on human learning in general. However, it is not clear how the verbal and visual short term memory systems develop. In order to investigate this development, we argue that some important issues should be taken into account; a longitudinal research design and individual differences between children. The current study is a follow-up study in which we investigated the transitions that a subsample of 30 children made between verbal and visual processing during the course of one year. Our results showed that the children showed large variation in STM processes and did not move from one type of processing to another in a consistent manner. This implies that the development of the verbal and visual STM systems may be less predictable than expected based on the literature, stressing the importance to be cautious when individual differences between children are not taken into account.

1. Introduction

In memory research, the most robust and frequently used theory on memory processes is the model of working memory of Baddeley and Hitch (1974) and Baddeley (1986), proposing that working memory (WM) consists of three systems. The phonological loop and the visuospatial sketchpad are modality-specific short term memory (STM) systems, which are part of the central executive, a modality-independent WM system. The phonological loop is a system for storage and processing of verbal information and the visuospatial sketchpad is a system for storage and processing of visual and spatial information. More recently the episodic buffer has been added to the model; a fourth system to store information from the STM systems and long term memory in one episodic representation (Baddeley, 2000). Studies on the model of WM typically investigate the use of the phonological loop and the visuospatial sketchpad with different types of memory tasks and relate performance on these tasks to different types of outcomes such as language development, mathematical and reading ability, and more complex higher order cognitive functions (for an overview, see Baddeley, 2003; Jarrold & Towse, 2006; Zimmer, 2008). As such, the model of WM lies at the heart of many studies on learning in children.

Although the model of WM was initially developed based on adult studies (see Baddeley, 2003), developmental studies have shown that the same structure of memory systems can be assumed to exist in children from four years of age onward (Alloway, Gathercole, & Pickering, 2006; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Gathercole, Pickering, Ambridge, & Wearing, 2004). Developmental researchers have extensively applied this model to investigate the verbal and visual memory systems in children. However, the actual developmental pathway of the verbal and visual memory systems remains uncovered. Clarifying and understanding this developmental pathway would be beneficial for, among others, the design of educational methods focusing on children of different ages. It may be expected for example, that younger children benefit more from visual methods than verbal methods. However, if visual memory develops further as children grow older, and as such, continues to play a significant role in learning, visual educational methods should still be available for older children instead of being replaced by verbal methods. Whether this is the case can only be concluded after the actual development of the memory systems has been studied further.

Despite the similarities of memory systems in children and adults, there is a peculiar gap between findings of developmental studies and those of adult studies with respect to STM processes. Adult studies have shown that some participants use verbal and visual processing interchangeably depending on the type of task and that there are large individual differences with respect to the use of verbal and visual processing (Daneman & Carpenter, 1980; Della Sala, Logie, Marchetti, & Wynn, 1991; Logie, Della Sala, Wynn, & Baddeley, 2000). For instance,

* Corresponding author at: Erasmus University, Department of Psychology, Education & Child Studies, P.O. Box 1738, NL-3000 DR Rotterdam, The Netherlands.
E-mail addresses: koppenolgonzalez@fsw.eur.nl (G.V. Koppenol-Gonzalez), bouwmeester@fsw.eur.nl (S. Bouwmeester), j.k.vermunt@tilburguniversity.edu (J.K. Vermunt).

https://doi.org/10.1016/j.lindif.2018.01.007
Received 4 November 2016; Received in revised form 22 December 2017; Accepted 13 January 2018
1041-6080/

some adults use visual processing when memorizing verbal material such as words, while others do not (Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996). Developmental studies on children, however, seem to conclude that development 'ends' with the use of verbal STM. This idea can also be seen in educational settings where different teaching materials are used for young children (mostly visual) than for older children (mostly verbal). If verbal processing would indeed be 'the final stage' of STM development in children, then adults should also show predominantly verbal processing. However, studies like the ones described above, which take individual differences between adults into consideration, have shown otherwise.

We argue that more insights about the development of verbal and visual processes can be gained, provided that the limitations of the most common developmental approaches are highlighted and taken into account. Two of these limitations concern the use of cross-sectional research designs and the way of dealing with individual differences in memory processes between children. The aim of the current study is therefore, to account for these two limitations while investigating the development of the verbal and visual STM systems according to the model of Baddeley and Hitch (1974).

First of all, the developmental pathways of STM processes on its own right have barely been studied. As Ornstein and Haden (2001, p. 202) wrote strikingly: "*[…] it is as if researchers have focused on memory development and have not been concerned with the development of memory*." Indeed, when reviewing the literature, it becomes clear that many theories on memory have been developed until now (e.g., Anderson, 1976; Baddeley & Hitch, 1974; Henson, 1998; Luck & Vogel, 1997; Nairne, 1990; Oberauer, 2009; Page & Norris, 1998; Paivio, 1991; Yonelinas, 2002), but very few studies have focused on how memory processes develop in children. Moreover, most of these developmental studies use cross-sectional research designs (e.g., Baddeley, Gathercole, & Papagno, 1998; Camos & Barrouillet, 2011; Chuah & Mayberry, 1999; Conrad, 1971; Gathercole et al., 2004; Hitch, Woodin, & Baker, 1989; Kemps, De Rammelaere, & Desmet, 2000). However, when research questions concern the developmental changes in memory processes within individual children, cross-sectional studies fall short of providing an accurate answer.

In cross-sectional designs, developmental patterns in the use of memory processes between children are mostly described in terms of rough age boundaries. For example, until five years of age children have been found to rely on visual STM and hardly on verbal STM; from six years onward children have been found to start using additional verbal processing; and from 10 years onward children start showing performance levels on STM tasks resembling that of adults (Baddeley et al., 1998; Conrad, 1971; Gathercole, 1998; Gathercole, Adams, & Hitch, 1994; Gathercole et al., 2004; Hitch et al., 1989). The problem with such a description of development is that it does not give an explanation of *how* the verbal and visual systems develop. Especially the role of the visual STM system in the development of memory remains unclear. It seems that there are two possible explanations; either the development of visual STM stagnates around the age of six to become supplemented with the use of verbal STM (Hitch et al., 1989) or visual STM continues to develop after the age of six, but this development is difficult to detect because at the same time, children become more inclined to use verbal STM (Henry, Messer, Luger-Klein, & Crane, 2012; Riggs, McTaggard, Simpson, & Freeman, 2006). The latter implies that children are able to use visual processing at a higher level when they are older and therefore, older children may use visual processing in learning in a qualitatively different way than younger children.

We assign the difficulties with addressing these developmental issues both to the widely used cross-sectional designs, as well as to the focus on average scores. Because younger children not only rely more on visual STM but also show worse overall performance compared to older children, the cross-sectional approach using average scores leads to the intuitively logical conclusion that visual processing reflects a point in memory development that is inferior to verbal processing. However, adult studies provide strong evidence against this conclusion. Adult studies show that participants who use visual STM to process verbal stimuli do not perform worse than participants who use verbal STM (Logie et al., 2000; Saito, Logie, Morita, & Law, 2008). To put it differently, adults who process stimuli of memory tasks visually are not considered to be 'less developed' in terms of memory than adults who process the same stimuli verbally. Then why should we assume this is the case in children?

The next point is an important assumption underlying conclusions about the developmental pathway of children of a certain age based on average scores obtained from cross-sectional research designs. This is the rather strong assumption that the average score of children in a certain age group is a good representation of the performance of all the individuals in that age group, that is, the age groups are assumed to be homogenous. Subsequently, it is assumed that changes in average scores from one age group to another represents developmental changes of all the individual children. However, we argue that this assumption is questionable at the least. Children vary greatly in their memory performance (Henry et al., 2012; Koppenol-Gonzalez, Bouwmeester, & Vermunt, 2012; Palmer, 2000) and therefore, they may also vary greatly in the developmental pathways they follow.

In order to keep a priori assumptions about development to a minimum, we need a research design to meet two important criteria; it should account for individual differences and it should be longitudinal. Therefore, the research design should enable the identification of differences between children in terms of verbal/visual processing and performance, and it should detect how their STM use changes over time. Unfortunately studies that meet these criteria hardly exist. The few longitudinal studies on memory are mainly focused on specific memory skills as predictors of the development of other cognitive skills, such as reading acquisition (de Jong & van der Leij, 1999; Lervåg, Bråten, & Hulme, 2009; Perez, Majerus, & Poncelet, 2012), vocabulary development (Leclercq & Majerus, 2010), and academic achievement (Bull, Espy, & Wiebe, 2008). The general aim of the current study is to contribute to the literature on the development of memory processes according to the model of Baddeley and Hitch (1974) on the one hand, and to contribute to the literature on learning by accounting for individual differences between children in the use of verbal and visual STM, on the other hand.

2. Measuring the use of verbal and visual STM and individual differences

Assuming the model of WM of Baddeley and Hitch (1974), a very insightful method to distinguish between the use of verbal and visual STM processes is by manipulating the similarity of stimuli that are visual in nature (i.e., concrete pictures) but can easily be labeled verbally (i.e., existing words) (see e.g., Hitch et al., 1989; Logie et al., 2000; Poirier, Saint-Aubin, Musselwhite, Mohanadas, & Mahammed, 2007). When the visuospatial sketchpad is used to memorize pictures in a certain serial order (i.e., based on their visual features) and the pictures are visually similar, this similarity causes confusion leading to worse performance compared to the same situation with visually dissimilar pictures (Logie, 1995). Therefore, when pictures that are visually similar are recalled worse than pictures that are visually dissimilar, this can be assumed to indicate the use of visual STM. The same principle holds for pictures with labels that are phonologically similar (i.e., rhyme words). In this case, the phonological loop is used to verbally memorize the labels of the pictures. When the labels have to be recalled in a certain serial order and are phonologically similar, this will lead to confusion resulting in worse performance compared to the same situation with phonologically dissimilar pictures (Baddeley, 2003). Therefore, when pictures with phonologically similar labels are recalled worse than pictures with phonologically dissimilar labels, this can be assumed to indicate the use of verbal STM. This is specifically the case when memory for serial order is being called upon and, therefore, the position in which the stimuli are presented plays an important role in determining performance. In the current study, we applied this method by manipulated the similarity of nameable pictures to infer the use of verbal or visual STM in children instructed to memorize the pictures in a certain serial order.

With regard to individual differences between children in the use of verbal and visual STM, previous studies have already applied interesting approaches. Palmer (2000) for instance, explored the individual scores of the children in her sample in terms of visual and phonological similarity effects, leading to four groups: Children using verbal STM, visual STM, both verbal and visual STM, and neither verbal nor visual STM. Next, by means of a cross-sequential design to investigate the development in the use of the different types of STM processes, Palmer (2000) found that the development of STM seemed to start with no specific type of processing, then moved to visual processing, then to a mixed type of verbal and visual processing, and finally moved to verbal processing. Adopting a similar approach as Palmer (2000) but accounting for some methodological issues, Henry et al. (2012) found a different type of developmental pathway in STM processes. Specifically, they found that although most of the older children seemed to use verbal processing, some of them also seemed to use visual processing. Moreover, the low performing children never used specific verbal or visual processing, while higher performing children always showed verbal and sometimes also visual processing.

Individual differences between children in the way they use verbal or visual STM during a serial order reconstruction task were also accounted for in another study (Koppenol-Gonzalez, Bouwmeester, & Vermunt, 2014). The responses on memory tasks with visually or phonologically similar stimuli were investigated by means of latent class analysis (LCA) in a sample of 210 children aged between 5 and 12 years. The focus was on the advantages of LCA as a way to avoid the dependence on average scores, that is, to avoid the underlying assumption that an average score is a good representation of the performance of all the individual children in a certain age group. These advantages were shown by comparing the conclusions that can be drawn about verbal and visual STM based on latent classes and based on a manifest grouping variable like age groups. This comparison showed that individual differences between children of the same age were detected and taken into account in a more meaningful way using the latent grouping variable than the manifest grouping variable.

Specifically, Koppenol-Gonzalez et al. (2014) used a person-centered approach to investigate whether subgroups could be distinguished showing differences in the use of STM systems. To this end, multiple models with an increasing number of latent classes were fitted to the data and it was found that the model with five latent classes showed the best balance between fit and parsimony (see Appendix A for details). The latent classes were distinguished based on a categorical latent variable representing the use of verbal or visual STM. Whether the children used verbal or visual STM was determined by the effect of the similarity of the stimuli (either visual or phonological), the effect of the serial position a stimuli was presented, as well as the interaction between similarity and serial position. This way, the performance of the children could be depicted in a serial position curve for the visually and phonologically similar memory tasks, facilitating the interpretation of the latent classes. Table 1 shows the interpretation of the latent classes adapted from Koppenol-Gonzalez et al. (2014).

The studies above have shown the presence of subgroups that can be distinguished in terms of verbal and visual STM within a heterogeneous sample. Furthermore, the interpretation of latent classes in terms of verbal and visual memory processes has been validated earlier by relating the latent classes' performance to external variables (Koppenol-Gonzalez et al., 2012). In the current study, we built on these previous results that were obtained with cross-sectional designs, by investigating the longitudinal changes in the use of STM processes over the course of one year.

Table 1
Characteristics of each latent class in the n = 210 sample at $t = 0$.

	Class 1	Class 2	Class 3	Class 4	Class 5
Proportion correct					
phon. sim.	0.28	0.30	0.65	0.68	0.99
vis. sim.	0.20	0.54	0.43	0.99	0.53
Interpretation	Lowest	Verbal-lower	Visual-lower	Verbal-higher	Visual-higher
Class size (*SE*)	0.33 (0.05)	0.22 (0.04)	0.19 (0.03)	0.10 (0.02)	0.16 (0.03)
M age (*SD*)	89 (24)	107 (25)	113 (25)	119 (21)	113 (23)

Note. phon; phonological, vis.; visual, sim.; similarity. Age is given in months.

2.1. Design and hypotheses

From the sample of children from the Koppenol-Gonzalez et al. (2014) study, we selected a subsample of children in the age range of 6 to 9 years because based on the WM theory, this is the age range in which memory development seems to go through the most changes (Baddeley et al., 1998; Conrad, 1971; Gathercole, 1998; Gathercole et al., 1994; Gathercole et al., 2004; Hitch et al., 1989). We investigated the changes in STM processes of this subsample by looking at their transitions between classes across four-month intervals. First, the children in the subsample performed the STM tasks three additional times and were assigned to one of the latent classes at each of the four measurement occasions based on the model parameters obtained with the larger sample. Then, using a transition model we examined the movements of the children across classes from one measurement occasion to the next. Since our approach is rather novel, it is hard to define any firm expectations about the results of the transition analysis. Therefore, the expectations outlined below are only tentative.

Based on previous developmental studies assuming the model of WM of Baddeley and Hitch, we might expect the younger children to belong in particular to a class showing visual processing. If they move to another type of processing during the year, this movement may be expected to be in the direction of a more verbal type of processing. Older children may be expected to have high probability to belong to a verbal processing class and to stay there during the subsequent measurements occasions. However, given the results of previous developmental studies accounting for individual differences in STM systems (Henry et al., 2012; Koppenol-Gonzalez et al., 2014; Palmer, 2000), the development of STM is not expected to be a smooth transition from visual to verbal processing. Rather, we expect more heterogeneity in the type of processing used by children of the same age than has been assumed until now. Some children may continue to use visual processing during the year or merely move to a class showing higher overall performance.

3. Method

3.1. Participants

In the current study, a subsample of 30 children was selected from the sample of 210 children from the study by Koppenol-Gonzalez et al. (2014). These children were selected from two primary schools in an urban area of the Netherlands. On the first measurement occasion at $t = 0$, the 210 children were aged 4;11 (4 years, 11 months) to 12;9 years and were on average 8;8 years old (104 months, *SD* = 26 months, 110 girls). The subsample of 30 children, who were selected from one primary school in an urban area of the Netherlands, was presented with the STM tasks three additional times (at $t = 1$, $t = 2$, and $t = 3$), with four-months intervals between each measurement occasion. Of these 30 children, 10 were first graders, 10 were second graders, and 10 were third graders (*M* age = 7;6, *SD* = 1;0, 15 girls). During the year, three boys moved to another school, so at the end of the data collection a total of 27 children remained (8 second graders, 9 third graders, and 10 fourth graders, *M* age = 8;7, *SD* = 1;0).[1] In total, we gathered data from 116 cases for the longitudinal part of the study (30 children with 4 time points minus the 4 time points of the drop-outs). All the children received a small reward such as postcards and stickers after participation.

3.1.1. Ethics statement

In Dutch legislation the law on Medical-Scientific Research on Humans (in Dutch: Wet Medisch Wetenschappelijk Onderzoek met mensen, WMO) applies to studies in which people undergo a medical or physical intervention or in which certain behavior is required. This law serves to protect people from medical maltreatment and experimentation and states that although approval from an ethics committee is required for studies involving a medical or physical intervention, this requirement does not apply to certain behavioral studies. The current study was noninvasive, participation was on a voluntary basis, and the data were analyzed anonymously. The parents of all the children were informed about the study by writing and parental permission was acquired via the principal of the school.

3.2. Materials

The children were presented with the six STM tasks from the study of Koppenol-Gonzalez et al. (2014) on each measurement occasion. The materials and procedure in the current study are therefore identical to that study, but we will give a short description here. The tasks contained either visually or phonologically similar pictures, with list lengths of three, five, or seven items. In the current study, only the results for the seven-items lists are presented, because the three-items lists turned out to be too short to present meaningful results and the five-items lists gave similar results as the seven-items lists (see Appendix B for details). The STM tasks were serial order reconstruction tasks, with visually similar pictures consisting of pictures that had similar outlines and had labels that were phonologically dissimilar (see e.g., Poirier et al., 2007), or phonologically similar pictures with labels that were end-rhyme words and were visually dissimilar (Conrad, 1971).

Furthermore, the labels of all the pictures were matched for word length as much as possible, with most words consisting of one syllable. This way, the task demands of the tasks with phonologically and visually similar pictures were kept as constant as possible and only differed substantially in similarity. In an earlier pilot study (*N* = 14), it was checked whether children would use the intended labels, so the children in the experimental trials were not implicitly instructed to use verbal processing by rehearsing the intended labels before the experiment. The pictures used for the experimental trials were pictures that most children in the pilot study labeled with the intended end-rhyme words. None of those children were included in the present sample.

3.3. Procedure

The serial order reconstruction tasks were presented to the children individually on a 15.4-inch laptop in a quiet room in their school. First, the child received global instructions about the tasks, explaining that he/she would see a sequence of pictures and then would be asked to place the pictures in the same order that had been presented. Then, a practice trial was given, which could be repeated until the instructions were clear to the child. The practice trial had the same list length as the experimental trial, but the pictures were visually and phonologically dissimilar. Next, the child was presented with the experimental trial with, for example, the visually similar pictures. Before the next task with phonologically similar pictures was presented, the child again received a practice trial. This way, none of the children were successively presented with the visually and phonologically similar experimental pictures.

When the child was ready, the experimenter clicked a ‘start’ button. In the upper half of the screen there was a row of (3, 5, or 7) empty squares and during 2 s a picture was shown in each square. The pictures were shown one at a time, so with the presentation of each new picture the previous one disappeared. After the presentation of the pictures, all of the pictures appeared at the same time (in a row) in the bottom of the screen, in a different order than during the presentation. The child had to point out the pictures in their presented order and the experimenter placed the pictures in the empty squares. When the experimenter placed a picture in the square, the picture was not removed from the row in the bottom of the screen so the child could always choose between all of the presented pictures and was able to guess in case he/she did not remember the serial order of the presented pictures.

The children who were tested repeatedly every four months for a year, were presented with the same tasks, except that the serial order they had to reconstruct differed at each measurement occasion. Repeated presentation of the same pictures within one experiment is shown not to affect the phonological similarity effect (Coltheart, 1993). Moreover, many studies have repeatedly used the same pictures to investigate phonological and visual similarity effects with similar tasks (e.g., Hitch et al., 1989; Palmer, 2000; Poirier et al., 2007). Therefore, we assumed that the presentation of the same pictures after four, eight, and twelve months since the first measurement occasion at $t = 0$ would not affect the similarity effects we investigated at occasions $t = 1$, $t = 2$, and $t = 3$.

3.4. Statistical analyses

We used the software Latent GOLD 4.5 (Vermunt & Magidson, 2008) for the transition analysis in the current study. Because the transition analysis was based on the latent class analysis of the large sample of 210 children, a short explanation of this part of the analyses will follow first. The latent class model concerned a latent class logistic regression analysis (Vermunt & Magidson, 2005; Wedel & DeSarbo, 1994) to distinguish latent classes of children who used different types of STM processes, with the main focus on verbal and visual STM. The independent variable was a vector of dichotomous scores reflecting whether the child placed the pictures in the correct position (1) or not (0). The predictors were the similarity of the pictures (0 = phonological similarity and 1 = visual similarity), each serial position where the pictures were placed (1 to 7), and also an intercept reflecting the overall probability of a correct response.[2] The model parameters were estimated in terms of logistic regression weights, which are used for significance testing of the predictor values in each latent class, and the model parameters were estimated in terms of probabilities, which are used to interpret the predictor values in each latent class. The regression weights may therefore be used to calculate a probability and the probabilities may be used to calculate a regression weight. Based on the latent class analysis, five latent classes were distinguished as described above, reflecting the use of no specific verbal nor visual STM and low overall performance, verbal STM with low performance, visual STM with low performance, verbal STM with high performance, and visual STM with high performance (see also Table 1). Based on these results, we followed a number of steps in the current study.

First of all, the 30 children tested every four months for a year were assigned to one of the five classes estimated with the responses of the group of 210 children (at $t = 0$), including the 30 children of the

[1] In the transition model, the four time points with the missing values of these three children were included in the analysis in order to keep the correct structure of the data file (see Vermunt, Tran, & Magidson, 2008).

[2] The regression model had the following form: $\text{logit } P(y = 1 | Class = x, Pos = r, Sim = s) = \beta_{0x} + \beta_{1xr} + \beta_{2xs} + \beta_{3xrs}$.

Learning and Individual Differences 66 (2018) 29–37

Table 2
Characteristics of each latent class in the n = 30 sample at t = 0.

	Class 1	Class 2	Class 3	Class 4	Class 5
Proportion correct					
phon. sim.	0.28	0.30	0.65	0.68	0.99
vis. sim.	0.20	0.54	0.43	0.99	0.53
Interpretation	Lowest	Verbal-lower	Visual-lower	Verbal-higher	Visual-higher
Class size (*SE*)	0.36 (0.09)	0.17 (0.07)	0.20 (0.07)	0.14 (0.06)	0.14 (0.06)
M age (*SD*)	88 (12)	90 (10)	98 (15)	94 (15)	91 (11)

Note. phon; phonological, vis.; visual, sim.; similarity. Age is given in months.

current sample. Note that in the sample of $n = 30$ we therefore do not speak of latent classes anymore but of manifest classes, because we used the parameters that were estimated with the larger sample of $n = 210$ to assign each of the 30 children to one of the five latent classes at $t = 0$. This model contained 210 observations using 14 scores per child, leading to 2940 replications (no missing values) to estimate the parameters.

Second, we estimated a model, again with the parameters that were estimated with the $n = 210$ sample, including all the subsequent time points of the $n = 30$ sample. This model contained 210 observations at $t = 0$ plus 30 observations at 3 different time points ($t = 1$, $t = 2$, $t = 3$) minus 4 time points because of drop-out, leading to a total number of 296 observations. This analysis resulted in probabilities for each of the 30 children in the current study to belong to each of the five classes based on their responses on the subsequent measurement occasions at $t = 1$, $t = 2$, and $t = 3$. At each time point, a child has therefore five probabilities which add up to 1 over the five classes. The class with the largest probability is the class that child is assigned to (class membership). Therefore, we obtained a sequence of class memberships per child representing the changes in the use of STM processes over the four different time points.[3] We used the sequences of class membership per child for the transition analysis based on the $n = 30$ sample with a total of 116 observations (4 subsequent time points per child excluding the 4 missing time points).

Third, in order to examine whether the classification of the 30 children at the subsequent time points was sufficiently accurate, our basic model was compared to a model assuming no classification errors. This no classification errors model assumes that each child has a probability of 1 to belong to one of the classes and a probability of 0 to belong to the other classes at each time point. If the classifications at the different time points are accurately enough (no difference with the model assuming no classification errors), we can continue working with the basic transition model instead of having to continue with a more complex transition model accounting for the classification errors (see Bakk, Tekle, & Vermunt, 2013; Vermunt, 2010).

Fourth, the changes in the use of STM processes were analyzed by estimating a transition model with parameters for class membership at $t = 0$, that is, $P(x_0)$, as well as for the transition to a certain class on measurement occasion t given the class membership on the previous measurement occasion t-1, that is, $P(x_t|x_{t-1})$. These transition probabilities are the probabilities of moving from one class on occasion t-1 to another class on occasion t. Note that we do not estimate latent classes at each time point with our $n = 30$ sample, we merely estimate the transition probabilities to the classes the children of the current sample were assigned to using the parameters estimated with the $n = 210$ sample.

Finally, our basic transition model was compared to two different models. One model was defined such that there were no transitions over time, meaning that we can test the hypothesis that the children remain in the same class over the course of one year. Specifically, we compare our basic model (with the estimated transitions) to a model in which the transitions from a certain class at t-1 to the same class at t are set to 1 and the transitions between different classes from t-1 to t are set to 0. The second model was defined in such a way that there was independence in the transition probabilities. This means that the probabilities of moving from one class at t-1 to all the other classes at t are set to be equal. Comparing this model to our basic model enables us to test the hypothesis that children have an equal probability to move to any of the classes over the course of one year.

With this approach, we aim to address as accurately as possible our research question whether children are more likely to move from visual processing to verbal processing, or whether they are as likely to move to verbal processing as they are to move to visual processing, in order to gain some more insight in the development of the verbal and visual STM systems.

4. Results

We assigned each of the 30 children to one of the five classes at $t = 0$ using the estimated parameters obtained with the $n = 210$ sample. Table 2 shows the distribution of the 30 children of the current study over the classes estimated with the $n = 210$ sample at $t = 0$. Comparison with Table 1 shows that the class sizes of the five classes was not exactly the same for the current $n = 30$ sample as it was for the $n = 210$ sample, but they are similar; for instance, in both samples, most of the children belonged to the lowest performing class without showing specific verbal or visual STM (class 1).

The assignment of the 30 children to one of the five classes at each subsequent time point was used for the transition analysis. Table 3 shows the fit indices of our basic model (i.e., each child has a certain probability for each of the five classes) and a model assuming no classification errors (i.e., each child has a probability of 1 for one of the classes). The comparison indicates that both models fit the data equally well. Therefore, we analyzed the transitions based on the basic transition model.

Table 4 shows the transition probabilities between the classes from t-1 to t and their corresponding *SE*s in order to decide whether a transition probability was significant. For the interpretation of the transitions between classes, we only focus on the significant transition probabilities ($p < .05$). When children belonged to the lowest performing class at t-1, they were likely to move to any of the classes on the next occasion t, except for the verbal and visual classes with high performance. Children coming from the verbal STM class with lower performance at time point t-1 were likely to move to any of the classes at the next time point t, except for the visual STM class with higher performance. Children coming from the visual STM class with lower performance were likely to move to the verbal STM class with lower performance, and so were the children coming from the verbal class with higher performance. Children coming from the visual class with higher performance were as likely to move to the verbal-lower class as they were to stay in the visual-higher class. This means that when a child is in a particular class at occasion t-1, it is hard to predict his or her class membership at occasion t, especially with respect to the use of specific verbal/visual STM processes.

As a final step we checked whether our basic model described above differs substantially from two types of restricted models; one model in which the class membership on one occasion is completely independent of the class membership on the next occasion and a model in which there are no transitions whatsoever. In the independence model we state that for all the children in a certain class at t-1, the probabilities to move to any of the other classes are equal. In terms of Table 4, this model would contain a probability of .20 in all the cells. In contrast, in the no transitions model we state that all the children in a certain class at t-1 stay in the same class on the next measurement occasion t. In terms of Table 4, this model would contain a probability of 1 in all the

[3] These class memberships per child may be saved in another data file (e.g., SPSS) for further analysis.

Table 3
Fit statistics of our basic transition model and the no classification errors model.

Model	Log-likelihood	N parameters	BIC	AIC3
Basic	−167.33	24	416.29	406.66
No classification errors	−166.94	24	415.51	405.88

Table 4
Transition probabilities between the classes from *t*-1 to *t*.

		t				
		Lowest	Verbal-lower	Visual-lower	Verbal-higher	Visual-higher
t-1	Lowest	0.32 (0.09)	0.40 (0.10)	0.16 (0.07)	0.08 (0.05)	0.04 (0.04)
	Verbal-lower	0.33 (0.09)	0.15 (0.07)	0.26 (0.08)	0.15 (0.07)	0.11 (0.06)
	Visual-lower	0.23 (0.12)	0.31 (0.13)	0.15 (0.10)	0.08 (0.07)	0.23 (0.12)
	Verbal-higher	0.16 (0.11)	0.58 (0.14)	0.01 (0.01)	0.16 (0.11)	0.09 (0.08)
	Visual-higher	0.11 (0.10)	0.33 (0.16)	0.11 (0.10)	0.11 (0.10)	0.33 (0.16)

Note. The probabilities sum up to 1 in each row, *SE*s are given in parentheses.

diagonal cells and a probability of 0 in all the off-diagonal cells.

Table 5 shows the fit statistics of these two models compared to our unrestricted (basic) model as shown in Table 4. The BIC and the AIC3 values indicate that the independence model shows the best balance between fit and parsimony and the no transitions model shows the worst balance between fit and parsimony, meaning that a model in which children may move to any class on the next measurement occasion represents our data better than a model in which children stay in the same class over the period of one year. Therefore, we have to interpret the specific transition probabilities in Table 4 with caution.

5. Discussion

In the current study, we investigated the development of STM according to the model of Baddeley and Hitch (1974), accounting for individual differences within children of a certain age in the use of verbal or visual STM over time. Although this study aimed at obtaining some insight into the development of STM processes, this development is not as stable in our sample during the course of one year compared to what may be expected based on the literature.

The latent class analysis based on the sample of 210 children yielded five subgroups of children reflecting the use of no specific verbal nor visual STM and low overall performance, verbal STM with low performance, visual STM with low performance, verbal STM with high performance, and visual STM with high performance (Koppenol-Gonzalez et al., 2014). Assuming the model of Baddeley and Hitch, all of these subgroups reflect exactly what the theory would predict; qualitative differences in STM reflecting either verbal or visual (modality-specific) systems. However, the results of the transition analysis on the subsample of 30 children in the current study showed that there was no systematic way in which the children moved from one type of processing to another over the course of one year. In fact, a transition model in which children are just as likely to move to any of the classes, showing a verbal type of processing, a visual type of processing, or low overall performance interchangeably, seemed a better representation of our data. It even seemed a much better representation than a model in which children continue to use the same type of processing over the course of one year.

Table 5
Fit statistics of the restricted models compared to our unrestricted model.

Model	Log-likelihood	N parameters	BIC	AIC3
Basic	−167.33	24	416.29	406.66
Independence	−177.08	8	381.37	378.16
No transitions	−5314.64	4	10,642.88	10,641.27

Our main conclusion is therefore that when examining the development of individual children avoiding a priori assumptions about development, it seems that the neat and logical pathway of children moving from the use of visual STM towards verbal STM, as described by many cross-sectional developmental studies, is actually not that neat. In that respect, children and adults may be more alike than previously thought; children too will vary in their responses and maybe even more so than adults because they are in different points along the developmental pathway of STM (see Siegler, 2007, for a similar point of view about cognitive processes in strategy use). Despite the fact that the model of WM of Baddeley and Hitch is a good framework for describing the verbal and visual STM systems, the current use of this model in the context of developmental studies on the STM systems, unfortunately, has not yet provided a clear framework. What the developmental pathway exactly is for the verbal and visual STM systems and how they relate to each other remains to be clarified. We state than in attempting to do so, we should take individual differences and our research designs into careful consideration.

In terms of learning our results may suggest that the distinction between verbal and visual STM on its own right should not be interpreted as a distinction in child characteristics related to a certain point in development. Therefore, it remains a difficult question whether specific types of learning methods (either verbal or visual in nature) should be applied in educational settings for children of certain ages. In the meantime, it seems that children should be considered flexible in the use of verbal and visual STM systems. They may switch between these systems depending on the task itself, the difficulty of the task, or other task demands.

Based on our results, we would recommend some points of improvement to take into consideration in future studies. First of all, a larger sample of children than our current sample should be longitudinally studied to draw conclusion about memory development and the effect on learning with more certainty. However, it can be questioned to what extent a larger sample size will generate clearer developmental pathways over time, because there seem to be considerable individual differences between children. It would nevertheless be very interesting to examine whether different developmental pathways exist in a very large sample. Second, future samples may contain children of a wider age range, who may be followed for more than one year. It is possible that our sample of 6- to 10-year-olds contained mostly children in a certain point of memory development that Palmer (2000) called the 'mixed type of verbal and visual processing' and maybe this mixed type of development explains our findings of different types of processing being used interchangeably. However, if the children in the current age range already showed unsystematic transitions, a sample containing children of a wider age range followed over a longer time period, may very well show even less systematic transitions. Nonetheless, it is certainly worthwhile to investigate this idea since there are little longitudinal studies on the development of memory.

With respect to the STM tasks used, the amount of items that the children are presented with should be increased. For instance, a pool of more pictures could be used to present the children with a number of tasks with the same task demands (in terms of similarity and number of items) at one measurement occasion. This way, it can be investigated how consistent children are in their type of processing when executing multiple similar tasks on the same measurement occasion.

To conclude, in our attempt to improve the way in which the development of memory processes is studied, we have accounted for two important issues; taking individual differences between children of the same age into account and examining the development of STM processes over a longer period of time. Using this approach, we found that children can interchangeably use verbal or visual STM. Therefore, based on this study it is not possible to depict a clear-cut picture of a developmental pathway that all children of a certain age will follow. When accounting for individual differences and the developmental course of children, the development of the verbal and visual STM systems is not nearly as neatly as described in the literature based on studies that do not account for individual differences between children. The assumptions underlying these studies may need some questioning and where possible, too strong assumptions about memory development should be avoided. We recommend taking these issues into account, not only when conducting research but when interpreting research results as well. The results of the current study can be considered as a revelation of the difficulties with operationalizing, measuring, and interpreting cognitive constructs underlying human learning, especially the constructs as complicated as memory.

Appendix A. Fit indices of the 7-items model (Koppenol-Gonzalez et al., 2014)

N classes	Log-likelihood	N parameters	BIC	AIC3
1	−1893.36	14	3861.57	3828.71
2	−1722.98	29	3601.03	3532.96
3	−1666.17	44	3567.61	3464.33
4	−1627.27	59	3570.01	3431.54
5	−1603.74	74	3603.16	3429.47
6	−1584.51	89	3647.97	3439.07

Appendix B. Fit indices of the 5-items model (Koppenol-Gonzalez et al., 2014)

N classes	Log-likelihood	N parameters	BIC	AIC3
1	−1091.49	10	2236.46	2212.99
2	−953.97	21	2020.23	1970.94
3	−904.16	32	1979.43	1904.32
4	−862.09	43	1954.10	1853.17
5	−845.02	54	1978.79	1852.05
6	−830.93	65	2009.43	1856.87

Interpretation of the 5-items model (Koppenol-Gonzalez et al., 2014)

	Class 1	Class 2	Class 3	Class 4	Class 5
Proportion correct					
phon. sim.	0.41	0.99	0.99	0.99	0.51
vis. sim.	0.47	0.98	0.39	0.60	0.98
Interpretation	Lowest	Highest	Visual-lower	Visual-higher	Verbal-higher
Class size (*SE*)	0.22 (0.03)	0.38 (0.04)	0.07 (0.02)	0.12 (0.02)	0.21 (0.03)

Appendix C. Latent GOLD 5.0 syntax for the estimation of the classes for n = 30

```
options
  algorithm
    tolerance=1e-008 emtolerance=0,01 emiterations=0 nriterations=0;
  startvalues
    seed=0 sets=100 tolerance=1e-005 iterations=0;
  bayes
    categorical=1 variances=1 latent=1 poisson=1;
  montecarlo
    seed=0 replicates=500 tolerance=1e-008;
  quadrature  nodes=10;
  missing  excludeall;
  output
    iterationdetail parameters standarderrors=robust probmeans=posterior profile bivariateresiduals
estimatedvalues;
variables
  caseid pp_time_nr;
  dependent score nominal;
  select followup 1;
  independent itemPosition nominal, similarity nominal, time inactive;
  latent
    Class nominal 5;
equations
  Class <- 1;
  score <- 1 | Class + itemPosition | Class + similarity | Class + itemPosition similarity | Class;
{
here the 74 parameter estimates of the LCA of the n=210 sample were entered
}
```

Latent GOLD 5.0 syntax of the transition analysis (basic model) for n = 30

```
options
  algorithm
    tolerance=1e-008 emtolerance=0.01 emiterations=250 nriterations=50;
  startvalues
    seed=0 sets=10 tolerance=1e-005 iterations=50;
  bayes
    categorical=1 variances=1 latent=1 poisson=1;
  montecarlo
    seed=0 replicates=500 tolerance=1e-008;
  quadrature  nodes=10;
  missing  includeall;
  output
    parameters=effect standarderrors probmeans=posterior profile estimatedvalues;
variables
  caseid ppnr;
  select followup_first 1;
  dependent Class# nominal;
  independent time;
  latent
    Class nominal dynamic 5;
equations
  Class[=0] <- 1;
  Class <- (~tra) 1 | Class[-1];
  Class# <- (b~err) 1 | Class;

  b = -100;
```

References

Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visual short-term and working memory in children: Are they separable? *Child Development, 77*, 1698–1716.

Anderson, R. E. (1976). Short-term retention of the where and when of pictures and words. *Journal of Experimental Psychology: General, 105*, 378–402.

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews, 4*, 829–839.

Baddeley, A. D. (1986). *Working memory.* Oxford: Clarendon Press.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423.

Baddeley, A. D., Gathercole, S. E., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158–173.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Vol. Ed.), *The psychology of learning and motivation. 8. The psychology of learning and motivation* (pp. 47–90). New York, NY: Academic Press.

Bakk, Z., Tekle, F. B., & Vermunt, J. K. (2013). Estimating the association between latent class membership and external variables using bias-adjusted three-step approaches. *Sociological Methodology, 43*, 272–311.

Bayliss, D. M., Jarrold, C., Gunn, D. M., & Baddeley, A. D. (2003). The complexities of complex span: Explaining individual differences in working memory in children and adults. *Journal of Experimental Psychology: General, 132*, 71–92.

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical

achievement at age 7 years. *Developmental Neuropsychology, 33*, 205–228.
Camos, V., & Barrouillet, P. (2011). Developmental change in working memory strategies: From passive maintenance to active refreshing. *Developmental Psychology, 47*, 898–904.
Chuah, Y. M. L., & Mayberry, M. T. (1999). Verbal and spatial short-term memory: Common sources of developmental change? *Journal of Experimental Child Psychology, 73*, 7–44.
Coltheart, V. (1993). Effects of phonological similar and concurrent irrelevant articulation on short-term-memory recall of repeated and novel word lists. *Memory & Cognition, 21*, 539–545.
Conrad, R. (1971). The chronology of the development of covert speech in children. *Developmental Psychology, 5*, 398–405.
Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450–466.
Della Sala, S., Logie, R. H., Marchetti, C., & Wynn, V. (1991). Case studies in working memory: A case for single cases? *Cortex, 27*, 169–191.
Gathercole, S. E. (1998). The development of memory. *Journal of Child Psychology and Psychiatry, 39*, 3–27.
Gathercole, S. E., Adams, A., & Hitch, G. J. (1994). Do young children rehearse? An individual-differences analysis. *Memory & Cognition, 22*, 201–207.
Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*, 177–190.
Henry, L. A., Messer, D., Luger-Klein, S., & Crane, L. (2012). Phonological, visual, and semantic coding strategies and children's short-term picture memory span. *The Quarterly Journal of Experimental Psychology, 65*, 2033–2053.
Henson, R. N. A. (1998). Short term memory for serial order: The start-end model. *Cognitive Psychology, 36*, 73–137.
Hitch, G. J., Woodin, M. E., & Baker, S. (1989). Visual and phonological components of working memory in children. *Memory & Cognition, 17*, 175–185.
Jarrold, C., & Towse, J. N. (2006). Individual differences in working memory. *Neuroscience, 139*, 39–50.
de Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: Results from a Dutch latent variable longitudinal study. *Journal of Educational Psychology, 91*, 450–476.
Kemps, E., De Rammelaere, S., & Desmet, T. (2000). The development of working memory: Exploring the complementarity of two models. *Journal of Experimental Child Psychology, 77*, 89–109.
Koppenol-Gonzalez, G. V., Bouwmeester, S., & Vermunt, J. K. (2012). The development of verbal and spatial working memory processes: A latent variable approach. *Journal of Experimental Child Psychology, 111*, 439–454.
Koppenol-Gonzalez, G. V., Bouwmeester, S., & Vermunt, J. K. (2014). Short-term memory development: Differences in serial position curves between age groups and latent classes. *Journal of Experimental Child Psychology, 126*, 138–151.
Leclercq, A., & Majerus, S. (2010). Serial-order short-term memory predicts vocabulary development: Evidence from a longitudinal study. *Developmental Psychology, 46*, 417–427.
Lervåg, A., Bråten, I., & Hulme, C. (2009). The cognitive and linguistic foundations of early reading development: A Norwegian latent variable longitudinal study. *Developmental Psychology, 45*, 764–781.
Logie, R. H. (1995). Working memory. *Visuo-spatial working memory* (pp. 63–73). Hove, UK: Lawrence Erlbaum Associates, Publishers.
Logie, R. H., Della Sala, S., Laiacona, M., Chalmers, P., & Wynn, V. (1996). Group aggregates and individual reliability: The case of verbal short-term memory. *Memory & Cognition, 24*, 305–321.
Logie, R. H., Della Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *The Quarterly Journal of Experimental Psychology, 53A*, 626–646.
Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279–281.
Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition, 18*, 251–269.
Oberauer, K. (2009). Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition, 37*, 346–357.
Ornstein, P. A., & Haden, C. A. (2001). Memory development or the development of memory? *Current Directions in Psychological Science, 10*, 202–205.
Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105*, 761–781.
Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology, 45*, 255–287.
Palmer, S. (2000). Working memory: A developmental study of phonological recoding. *Memory, 8*, 179–193.
Perez, P. M., Majerus, S., & Poncelet, M. (2012). The contribution of short term memory for serial order to early reading acquisition: Evidence from a longitudinal study. *Journal of Experimental Child Psychology, 111*, 708–723.
Poirier, M., Saint-Aubin, J., Musselwhite, K., Mohanadas, T., & Mahammed, G. (2007). Visual similarity effects on short-term memory for order: The case of verbally labeled pictorial stimuli. *Memory & Cognition, 35*, 711–723.
Riggs, K. J., McTaggard, J., Simpson, A., & Freeman, R. P. J. (2006). Changes in the capacity of visual working memory in 5- to 10-year-olds. *Journal of Experimental Child Psychology, 95*, 18–26.
Saito, S., Logie, R. H., Morita, A., & Law, A. (2008). Visual and phonological similarity effects in verbal immediate serial recall: A test with Kanji materials. *Journal of Memory and Language, 59*, 1–17.
Siegler, R. S. (2007). Cognitive variability. *Developmental Science, 10*, 104–109.
Vermunt, J. K. (2010). Latent class modeling with covariates: Two improved three-step approaches. *Political Analysis, 18*, 450–469.
Vermunt, J. K., & Magidson, J. (2005). *Latent gold 4.0 user's guide.* Belmont, Massachusetts: Statistical Innovations Inc.
Vermunt, J. K., & Magidson, J. (2008). *Latent gold 4.5.* Belmont, Massachusetts: Statistical Innovations Inc.
Vermunt, J. K., Tran, B., & Magidson, J. (2008). Latent class models in longitudinal research. In S. Menard (Ed.). *Handbook of longitudinal research: Design, measurement, and analysis* (pp. 373–385). Burlington, MA: Elsevier.
Wedel, M., & DeSarbo, W. A. (1994). A review of recent developments in latent class regression models. In R. P. Ragozzi (Ed.). *Advanced methods of marketing research* (pp. 352–388). Cambridge, MA: Blackwell.
Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441–517.
Zimmer, H. D. (2008). Visual and spatial working memory: From boxes to networks. *Neuroscience and Biobehavioral Reviews, 32*, 1373–1395.