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Review article

Visuospatial working memory in specific language impairment: A meta-analysis

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ABSTRACT

We conducted a meta-analysis of the data from studies comparing visuospatial working memory (WM) in children with specific language impairment (SLI) and typically developing (TD) children. The effect sizes of 21 studies (including 32 visuospatial storage tasks and 9 visuospatial central executive (CE) tasks) were identified via computerized database searches and the reference sections of the identified studies. Meta-analyses and moderator analyses were conducted to examine the magnitude of the differences in visuospatial storage and CE, and their relation to the inclusion criteria used for SLI and the age of the children. The results showed significant effect sizes for visuospatial storage ($d = 0.49$) and visuospatial CE ($d = 0.63$), indicating deficits in both components of visuospatial WM in children with SLI. The moderator analyses showed that greater impairment in visuospatial storage was associated with more pervasive language impairment, whereas age was not significant associated with visuospatial WM. The finding of deficits in visuospatial WM suggests domain-general impairments in children with SLI. It raises questions about the language-specificity of a diagnosis of SLI. Careful attention should thus be paid to both verbal and visuospatial WM in clinical practice, and especially in those children with pervasive language impairments.

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1. Introduction

There is growing evidence that non-linguistic factors may contribute to the problems associated with specific language impairment (SLI) and that the impairment may therefore not be exclusively linguistic (Bishop, 2006). One factor that has been implicated is working memory (WM) (Archibald & Gathercole, 2006a; Bishop, 2006; Montgomery, Magimairaj, & Finney, 2010). Many studies have focused on the verbal domain of children's WM. Results regarding the visuospatial domain are ambiguous at best (Alloway & Archibald, 2008; Archibald & Gathercole, 2006a; Montgomery et al., 2010). However, if children with SLI also exhibit deficits in visuospatial WM, this would implicate more general limitations, thus challenging the specificity of SLI. In the present study, we therefore conducted a meta-analysis of the results of studies that have specifically compared visuospatial WM of children with SLI and their typically developing (TD) peers.

1.1. SLI and working memory

While the language of the majority of children develops more or less automatically, there are also children who show marked problems and delays. When the problems of the children can be characterized as a selective failure to make normal language acquisition progress without further evidence of underlying intellectual, neurological, social, or emotional impairments, then a diagnosis of specific language impairment (SLI) is usually made (Bishop, 2002, 2006). This impairment affects different aspects of the children's language including phonological, morphological, lexical and grammatical aspects. In many children, moreover, the linguistic profile can change over time (i.e., with age and development); changes can then be seen to occur both within and across the different aspects of language (Bishop, 2006; Leonard, 1998).

WM refers to the structures and processes used to temporarily store and manipulate information. WM can be conceptualized somewhat differently (Courage & Cowan, 2009; Engle, Tuholski, Laughin, & Conway, 1999; Miyake & Shah, 1999), but the most frequently adopted conceptualization for research on the WM of children with SLI to date has been the multicomponent model of Baddeley (Baddeley & Hitch, 1974; Baddeley, 2003, 2012). In this model, a central executive (CE) system is assumed to be linked to three subsystems: a phonological loop, a visuospatial sketchpad and an episodic buffer. The phonological loop and visuospatial sketchpad are so-called slave systems and responsible for the temporary storage of verbal and visuospatial information, respectively. The episodic buffer is a relatively recent addition to the model and assumed to entail a multidimensional representational system that binds information from different sources together to form chunks of information for further processing (Baddeley, 2003). The CE system coordinates and controls the activities of the subsystems. It has limited attentional capacity and thus requires "attentional control."

Engle et al. (1999) have previously suggested that WM capacity is limited by the ability to control attention and that the ability to control attention might, in fact, entirely explain the individual differences observed in WM capacity. In the Embedded-Processes model of Courage and Cowan (2009), moreover, WM is assumed to reflect the activation of information from long-term memory that is in the focus of attention. Both these views are in line with the Baddeley's model (2003, 2012) in which attentional control is part of the CE system, but focus more specifically on the executive and attentional aspects of WM.

Findings from different studies show strong links between WM limitations and SLI (Archibald & Gathercole, 2006a; Bishop, 2006; Montgomery et al., 2010). Increasing evidence indicates that the WM problems exhibited by children with SLI are diverse and may therefore involve different components of the WM system (i.e., storage and CE) (Montgomery et al., 2010). The storage component of WM can be evaluated by tasks that require serial recall of information. Verbal versions involve the retention of words, digits or letters, whereas visuospatial versions involve visual patterns or figures. The CE component is generally evaluated by tasks that require significant processing activity in addition to storage, typically using complex memory span tasks. An commonly used example of a verbal complex memory span task is listening span, in which children have to make a judgment about the meaning of each of a series of sentences, and additionally have to remember the last word of each sentence in sequence.

Most studies of the problems in different components of WM exhibited by children with SLI have focused on the verbal domain. A widely accepted account of the deficits associated with SLI, for example, is the phonological storage deficit hypothesis and the underlying assumption that verbal storage limitations lead to SLI (Archibald & Gathercole, 2007; Baddeley, 2003; Bishop, 1996; Coady & Evans, 2008; Gathercole & Baddeley, 1990). Much of the relevant evidence comes from studies of nonword repetition (i.e., the repetition of unfamiliar or nonexistent words that thus require phonological processing on the part of the child). A 16q chromosomal abnormality has even been linked to such poor nonword repetition in children with SLI and led to the suggestion that this specific verbal storage limitation might be a phenotypic marker of SLI (SLI Consortium, 2004). In addition to these constraints on verbal storage capacity, substantial deficits have been reported for verbal CE. Children with SLI are even more severely and consistently impaired on verbal complex memory tasks than on straightforward verbal storage tasks (Archibald & Gathercole, 2006a, 2006c; Ellis Weismer, Evans, & Hesketh, 1999; Marton & Schwartz, 2003).

In contrast to the findings for deficits in the verbal domain of WM, however, the results regarding the visuospatial domain are much less consistent. There is as yet no consensus regarding the role of visuospatial WM in the speech and language of children with SLI, for example, but several authors continue to assume that the WM deficits of such children are limited to verbal WM. This is because children with SLI and their TD peers have been found to perform similarly on visuospatial WM tasks. Age-appropriate visuospatial WM performance among children with SLI has been found, for instance, on visuospatial storage tasks involving the immediate recall of spatial position or a sequence of visual stimuli but also on visuospatial complex memory tasks (spatial span tasks) (Alloway & Archibald, 2008; Archibald & Gathercole, 2006a, 2006b; Baird, Dworzynski, Slonims, & Simonoff, 2009; Lum, Conti-Ramsden, Page, & Ullman, 2011; Riccio, Cash, & Cohen, 2007; Williams, Stott, Goodyer, & Sahakian, 2000). However, in the study by Archibald and Gathercole (2006a), the scores on the visuospatial storage task for the SLI group as a whole fell within the average range but, when the scores of the individual children were examined, 50% fell outside the average range and thus showed visuospatial storage deficits. In contrast, the results of several other studies have yielded evidence suggesting that the WM deficit observed so frequently in children with SLI may extend to the visuospatial domain of the WM system. Significant group differences have been reported for children with SLI versus children with TD language on a variety of visuospatial storage tasks including memory for hierarchical forms, pattern recognition, paired associates learning, pattern recall, the recall of locations, picture recognition, localization recall and visual symbol sequencing (Akshoomoff, Stiles, & Wulfeck, 2006; Bavin, Wilson, Maruff, & Sleeman, 2005; Hick, Botting, & Conti-Ramsden, 2005a, 2005b; Hoffman & Gillam, 2004; Menezes, Takiuchi, & Befi-Lopes, 2007; Nickisch & Von Kries, 2009). Longitudinal research by Hick et al. (2005a, 2005b), moreover, has shown the performance of children with SLI on a visuospatial storage (pattern recall) task to develop slower than that of their TD peers. Deficits have also been demonstrated on visuospatial CE tasks, including odd-one-out, spatial WM test, space visualization and position in space (Henry, Messer, & Nash, 2011; Hoffman & Gillam, 2004; Karasinski & Ellis Weismer, 2010; Marton & Schwartz, 2003).

1.2. A meta-analysis of visuospatial WM in children with SLI

Meta-analysis is a useful tool for statistically comparing a large set of results from—often quite divergent—individual studies (Glass, 1976). The results of a meta-analysis can help integrate research findings and, via the information provided on effect sizes, indicate the magnitude of those differences that are of interest. Within the context of the present research, this is the difference between the visuospatial WM performance of children with SLI versus their TD peers.

Assuming WM to be multicomponential, we asked ourselves the following questions. Do children with SLI show deficits in any of the components of visuospatial WM (i.e., visuospatial storage or visuospatial CE component)? When visuospatial storage or CE deficits are detected, do they relate to the inclusion criteria for SLI? And do any of the differences in the visuospatial storage or CE capacities of the children with SLI relate to their age?

The conflicting results on visuospatial WM in previous studies, raise the question of whether SLI is really language specific and thus confined to the verbal domain of WM as has been assumed for many years now. Perhaps the problems underlying SLI are actually more general and thus related to a more pervasive impairment of the children's WM capacity. If only the *verbal* WM of children with SLI is found to be affected, this is in keeping with domain-specific hypotheses, maintaining that a deficit in verbal storage underlies SLI (Gathercole & Baddeley, 1990). More recently Archibald and Gathercole (2006c) argued that a combination of problems in verbal storage as well as the CE component must be assumed to underlie SLI because a verbal storage deficit cannot explain the substantial deficits found in verbal complex memory tasks. If *both* the visuospatial WM and verbal WM are affected in children with SLI, then this is in line with domain-general hypotheses. More generally, if children with SLI exhibit deficits in both the verbal and visuospatial components of their WM, then SLI can be assumed to arise from a limitation on the general processing capacities of children—a limitation that will manifest itself on any task with a high processing load (Ellis Weismer, 1996; Fazio, 1998; Hoffman & Gillam, 2004; Marton, 2008; Marton & Schwartz, 2003; Montgomery, 2000, 2002). In this case, doubts can be raised about the specificity of the children's deficits to *language* and their status as having a *specific* language impairment.

Regarding our second question, the inclusion criteria for SLI used across studies are, unfortunately, not uniform. While the children identified as having SLI always show a substantial language delay, a variety of other inclusion criteria are typically also used. The number of language domains that must be affected, for example, can vary from 1 to a minimum of 3. The extent to which the children's language must be affected can vary from −1 to −1.5 standard deviations from the mean on standardized language tests. This might implicate that children with somewhat different language problems are included across studies. To complicate things further, some studies have reported greater variation in the visuospatial WM scores of children with SLI compared to their TD peers. This suggests that there might be a subgroup of children with SLI who have visuospatial WM problems (Archibald & Gathercole, 2006a; Menezes et al., 2007; Hick et al., 2005a, 2005b). Nickisch and Von Kries (2009), for example, found only visuospatial storage problems to occur in children identified as having a mixed set of language problems as opposed to a single set of language problems (i.e., both receptive and expressive language problems as opposed to only expressive language problems). Our hypothesis is therefore that the visuospatial WM performance of children with SLI will relate to the inclusion criteria used for SLI in a particular study and thereby to the nature of the language impairments. We further predict that the visuospatial WM deficit will be larger in children with more pervasive language impairments (i.e., studies that included children with multiple language deficits) than children with less pervasive language impairments (i.e., studies that included children in the SLI group with at least one language domain affected).

With regard to our final question and the course of the visuospatial WM deficits of children with SLI with age, it is well known that the language profiles of children with SLI change over time (Bishop, 2006; Leonard, 1998). It is therefore certainly possible that if children with SLI show deficits in visuospatial WM, the extent of these problems varies across the ages of these children and thus with development. Studies with TD children show the basics for all of the components of Baddeley's WM model to be in place and clearly measurable by the age of four years. Children's WM still develops after this age, and the developmental trajectories for the different components of Baddeley's model show linear increases from four to eleven years of age (Alloway, Gathercole, & Pickering, 2006; Luciana & Nelson, 1998). As far as we know, only one study took changes in the visuospatial WM capacities of children with SLI into account. When Hick et al. (2005a, 2005b) examined performance on a visuospatial storage task over time in young children with SLI (aged 3.06–5.0 years), the results showed slower development of visuospatial storage performance relative to TD children. This indicates a widening gap in the visuospatial WM skills of the children with SLI relative to their TD peers over time. In line with this finding, we expected within the context of the present study, deficits in visuospatial WM to be most profound in older children. This hypothesis receives further indirect support from the assumption that inefficient verbal coding of visuospatial information contributes to the problems in visuospatial WM in older children with SLI (Gillam, Cowan, & Marler, 1998). Children from the age of seven years normally use verbal coding strategies in visuospatial WM tasks (Gathercole, Adams, & Hitch, 1994). However, it is assumed that children with SLI use minimal or inefficient verbal coding strategies due to their language problems. If inefficient verbal coding contributes to the deficits in the visuospatial WM performance of children with SLI, visuospatial WM problems should stand out most among older children, as verbal coding is known not to occur in children until around the age of seven years

2. Methods

2.1. Identification of studies

In June and July of 2012, studies investigating the visuospatial WM of children with SLI and their TD peers were identified via computerized database searches of PubMed, PsychINFO, and Web of Science. As already noted, SLI is not defined uniformly across studies. In addition, measures of visuospatial WM are not always clearly labeled as such. We therefore employed broad search terms in our initial search: *specific language impairment* and *visuospatial working memory*, *specific language impairment* and *working memory*, *language impairment* and *visuospatial working memory*, *language impairment* and *working memory, language disorder* and *working memory*, *language impairment* and *memory*. We further searched for papers that were judged to be relevant from the reference lists for the articles identified in our database search.

To avoid publication bias and language bias the literature search targeted published articles as well as unpublished data in the public domain in all languages. However, publication bias against nonsignificant findings is likely to be less of a problem in the study of visuospatial WM in SLI. Since several authors assume that visuospatial WM is not affected in SLI, studies in which children with SLI show performances similar to that of their TD peers are also of interest (Alloway & Archibald, 2008; Archibald & Gathercole, 2006a; Archibald & Gathercole, 2006b; Baird et al., 2009; Williams et al., 2000).

A total of 894 papers were identified in the initial searches, of which 117 were duplicates, leaving 777 papers. The abstracts of all of the identified articles were reviewed in order to determine which of them examined the visuospatial WM of children with SLI and compared this to that of TD peers. When it was unclear that the study met this criteria, the full text for the article was reviewed. A total of 45 potentially appropriate articles were identified for further review. These articles were evaluated by the first author for inclusion in the meta-analysis. Afterwards, the total number of papers was re-evaluated by a second author, who did not take part in the initial search (JC). Agreement with the first author about whether or not a study met the inclusion criteria was 96%. Disagreements were resolved by consensus.

2.2. Inclusion criteria

For inclusion in the meta-analysis we used the following inclusion criteria:

1. Studies had to present original data comparing visuospatial WM of children with SLI to that of TD peers. We included studies in which children met the following criteria for SLI: impaired expressive and/or receptive language in combination with normal nonverbal intelligence. In addition to normal hearing, most studies reported no history of frank neurological impairments. In all of the studies, the children were required to show a substantial language delay, but a variety of criteria for the determination of the actual language impairment were used: clinical diagnosis by speech-language pathologist, significant discrepancy between language skills and nonverbal intelligence on standardized tests, and/or scores below age expectation on one or more standardized language tests (at least -1 sd below the mean). None of the reviewed studies included children with solely deficits in the phonological domain of language. One study compared TD children to children with a current SLI but also children with a past SLI. In this case, the results for the children with the current SLI were included in the meta-analysis (Baird et al., 2009). Studies in which the SLI group consisted of children with SLI in combination with other developmental disorders were excluded (Cohen et al., 2000; Jonsdottir, Bouma, Sergeant, & Scherder, 2005).
2. At least one of the comparison groups had to be composed of typically developing children. Studies that did not have a control group were excluded (Archibald & Gathercole, 2006a; Daal van, Verhoeven, & Balkom van, 2009) as well as studies that had a control group of children with other developmental disorders (Alloway & Archibald, 2008; Alloway, Rajendran, & Archilbald, 2009; Freed, Lockton, & Adams, 2012).

3. Each study had to include a task requiring the storage of visuospatial information or both the storage and processing of visuospatial information. The tasks had to use a span paradigm or, in other words, require the child to remember an increasing number of visuospatial stimuli—either alone or in combination with the processing of other visuospatial information; studies that did not use a span paradigm to assess the children's visuospatial abilities were excluded from our meta-analysis to facilitate comparison (Marton, 2008). In the case of visuospatial CE tasks, we only included studies in which the stimuli for storage and processing were of a visuospatial nature. Tasks requiring a combination of visuospatial stimuli with verbal stimuli were excluded (Archibald & Gathercole, 2006c; Hoffman & Gillam, 2004). The exact type of visuospatial task was not further restricted; a variety of visuospatial stimuli were employed in the studies (e.g., shapes, pictures, dots, block recall, hand movements). However, we excluded some tasks, stated to be tasks of visuospatial storage, that in fact measured a different construct, like for instance visuospatial associative learning (Bavin et al., 2005). Another study was excluded because the main measure was presentation duration and not visuospatial WM (Fazio, 1998). In order to be convinced that the tasks genuinely reflected visuospatial storage, moreover, we excluded tasks that easily invited for verbal coding of the visuospatial information (for instance color identification) (Hoffman & Gillam, 2004).
4. Studies had to report sufficient data to calculate an effect-size for each task; that is, the number of subjects, mean scores and standard deviations or standard error.

2.3. Data extraction

A total of 21 studies from the database searches met all the inclusion criteria en were included in the meta-analyses. These 21 studies reported data of 32 separate visuospatial storage tasks and 9 visuospatial CE tasks. For each task reported in each study, the following information was next coded by the first author: (1) statistics regarding differences in visuospatial WM (means, standard deviations, *t* tests and *F* tests); (2) SLI diagnosis criteria; (3) number of SLI and control group participants; (4) mean age of the participants; (5) type of control group (chronologically age-matched or developmentally language-matched); (6) type of visuospatial WM task (visuospatial storage or visuospatial CE). A random sample of 5 of the studies (24%) was also coded by a second coder (JC). Coder agreement was 98%. When disagreement occurred, consensus was achieved by re-examining the original data in the articles.

In order to have mutually exclusive (i.e., independent) samples in the meta-analysis, studies examining the same group of children were not both included in the analysis. In this case, we included data from the first study (Hick et al., 2005a, 2005b; Kleemans, Segers, & Verhoeven, 2011; Kleemans, Segers, & Verhoeven, 2012). Some studies compared the children with SLI to both chronologically age-matched and language-matched control children. To avoid multiple entries from the same group, only the effect sizes for the chronologically age-matched control groups were calculated; also, not all of the studies had language-matched control groups. In two studies, the SLI group was divided into subgroups and the data reported separately for these subgroups (Cowan, Donlan, Newron, & Lloyd, 2005; Nickisch & Von Kries, 2009). In these cases, means and standard deviations were pooled and entered for the SLI group as a whole.

2.4. Analyses

Analyses were conducted using comprehensive meta-analysis version 2 (Borenstein, Hedges, Higgins, & Rorthstein, 2005). Effect sizes were calculated per task for the 21 studies included in the meta-analysis. The effect size (*d*) is the difference between the scores of the two groups of children divided by the pooled standard deviation for the two groups. A positive effect size indicates a higher performance of the control group on visuospatial WM. Effect sizes are considered small for $d = .20$, medium for $d = .50$ and large for $d = .80$ (Cohen, 1988). Given that some of the included studies had small sample sizes, which can sometimes result in extreme values, all effect sizes were multiplied by a correction factor: $\mathrm{CF} = (1 - [3/(4 \times \mathrm{Ncontrol} + \mathrm{Nsli}) - 9]$. This correction reduced the possibility of bias from small samples by taking into account the sample size associated with each effect size (Robey & Dalebout, 1998).

For the further analysis of the data, a random-effects model (allowing for heterogeneity between studies) was used (Hunter & Schmidt, 2000). In order to answer the first research question, the weighted mean effect sizes across all included studies of visuospatial storage and visuospatial CE were calculated. For this calculation we used the inverse variance of each effect size to weight the relative contribution of each study to the overall effect size (Hedges & Pigott, 2004). To avoid multiple entries from the same group, we averaged the effect sizes obtained from each WM task in studies that used multiple tasks of visuospatial storage or CE.

Homogeneity testing was conducted for the meta-analyses of visuospatial storage and visuospatial CE to determine the extent to which there was variation in findings between studies in each component of visuospatial WM. The I^2 statistics were calculated according to Higgins, Thompson, Deeks, and Altman (2003) to describe the amount of total variation across studies due to heterogeneity. To further investigate causes of heterogeneity, moderator analyses using a mixed effects model and meta-regression techniques were performed (Hedges & Pigott, 2004; Thompson & Higgins, 2002). These analyses examined two factors that are hypothesized to affect visuospatial WM in children with SLI: inclusion criteria for SLI and age.

Publication bias was investigated using funnel plots, Egger's linear regression approach, and the trim and fill method (Duval & Tweedie, 2000; Egger, Smith, Schneider, & Minder, 1997). The Egger's linear regression approach examines both the sample size and statistical power of each study in relation to the effect size. The trim and fill method corrects the meta-analyses by imputing the presence of missing studies to yield an unbiased pooled estimate.

3. Results

3.1. Overall effects

The characteristics and effect sizes for the 18 studies that measured visuospatial storage are presented in Table 1. The 18 studies included 32 visuospatial storage tasks. The weighted mean effect size across the 32 effect sizes of these tasks is 0.49, with a 95% confidence interval from 0.30 to 0.68. The characteristics and effect sizes for the 7 studies that measured visuospatial CE are presented in Table 2. The 7 studies included 9 visuospatial CE tasks. The weighted mean effect size across these studies is 0.63, with a 95% confidence interval from 0.27 to 0.99. Both weighted mean effect sizes were significant, which shows the children with SLI to perform significantly below their TD peers for both the visuospatial storage ($Z = 4.99$, $p = .000$) and visuospatial CE component ($Z = 3.39$, $p = .001$).

None of the analyses that examined the presence of possible publication bias indicated publication bias for either the effect sizes of visuospatial storage or the effect sizes of visuospatial CE. Egger's linear regression for visuosatial storage: $\beta_0 = -1.282$, $t(16) = 1.109$, $p = .284$ and for visuospatial CE: $\beta_0 = -2.133$, $t(5) = 1344$, $p = .237$. The trim and fill method detected no missing studies.

Table 1
Characteristics of 18 studies examining the visuospatial storage component in both children with SLI and TD peers.

Author	Tests	*N* SLI	*N* TD	Age SLI	Age TD	*d*
Akshoomoff et al. (2006)	Hierarchical forms memory task	29	26	119	115	0.774
Archibald and Gathercole (2006b)	Dot Matrix, AWMA	15	15	116	116	0.538
Archibald and Gathercole (2006c)	Visuospatial storage	14	14	122	123	0.341
Baird et al. (2009)	Finger windows, WRAML	51	26	122	112	0.233
	Design memory, WRAML	51	26	122	112	0.167
Bavin et al. (2005)	Pattern recognition, CANTAB	21	21	54.1	54	0.933
	Spatial recognition, CANTAB	21	21	54.1	54	0.585
	Spatial span, CANTAB	21	21	54.1	54	0.628
Briscoe and Rankin (2007)	Block recall	14	14	99.7	99.7	−0.018
Cowan et al. (2005)	Corsi span	55	57	98	98	0.576
Gray (2006)	Handmovements, K-ABC	15	15	43.3	42.7	0.920
Hick et al. (2005a)	Pattern recall	9	9	45	45	0.655
Hoffman and Gillam (2004)	Experimental task: No color ID	24	24	112.7	112.3	1.063
	Pointing	24	24	112.7	112.3	0.945
Hutchinson, Bavin, Efron, and Sciberras (2011)	Mazes memory, WMTB-C	18	24	93.2	92	0.114
	Block recall, WMTB-C	18	24	93.2	92	0.299
Kleemans et al., 2011	Memory span, RAKIT	61	111	73.9	72.7	1.210
Leclercq et al., 2012	Low number of dissimilar features	15	15	120.7	120.5	0.295
	Low number of similar features	15	15	120.7	120.5	1.426
	High number of dissimilar features	15	15	120.7	120.5	0.993
	High number of similar features	15	15	120.7	120.5	0.792
Lum et al. (2011)	Mazes memory, WMTB-C	51	51	117.6	118.2	0.097
	Block recall, WMTB-C	51	51	117.6	118.2	0.376
Nickisch and Von Kries (2009)	Handmovements, K-ABC	42	21	108	108	0.237
	Visual symbol sequential memory, ITPA-G	42	21	108	108	0.515
Petrucelli, Bavin, and Bretherton (2012)	Block recall, WMTB-C	24	32	63.3	63.2	0.240
	Picture locations, CMS	24	32	63.3	63.2	0.095
Riccio et al. (2007)	Dot locations, CMS	30	30	100	100	0.095
	Picture locations, CMS	30	30	100	100	0.090
Williams et al. (2000)	Spatial recognition, CANTAB	10	10	78	78	−0.501
	Pattern recognition, CANTAB	10	10	78	78	−0.325
	Spatial span, CANTAB	10	10	78	78	−0.349

Note. N, number of included children; SLI, specific language impairment; TD, typically developing; *d*, effect size; AWMA, automated working memory assessment; WRAML, wide range assessment of memory and learning; CANTAB, The Cambridge neuropsychological test automated battery; K-ABC, Kaufman assessment battery for children; WMTB-C, working memory test battery for children; RAKIT, revisie amsterdamse kinder intelligentie test; ITPA-G, German form of the Illinois test of psycholinguistic abilities; CMS, Children's Memory Scale.

Table 2
Characteristics of 7 studies examining the visuospatial CE component in both children with SLI and TD peers.

Author	Tests	*N* SLI	*N* TD	Age SLI	Age TD	*d*
Archibald and Gathercole (2006b)	Odd-one-out, AWMA	15	15	116	116	0.388
	Mister X, AWMA	15	15	116	116	0.685
	Spatial span, AWMA	15	15	116	116	−0.020
Archibald and Gathercole (2006c)	Visuospatial storage–visuospatial processing	14	14	122	123	−0.202
Bavin et al. (2005)	Spatial working memory, CANTAB	21	21	54.1	54	0.446
Henry et al. (2011)	Odd-one-out test	41	88	138.4	118	0.612
Karasinski and Ellis Weismer (2010)	Spatial working memory task	59	316	165	165	0.998
Miller and Wagstaff (2011)	Visual–spatial WM	29	20	120	123	1.530
Williams et al. (2000)	Spatial working memory, CANTAB	10	10	78	78	0.289

Note. N, number of included children; SLI, specific language impairment; TD, typically developing; *d*, effect size; AWMA, automated working memory assessment; CANTAB, The Cambridge neuropsychological test automated battery.

We conducted homogeneity analyses to see if the samples of effect-sizes shared a common effect size. Heterogeneity analyses revealed moderate I^2 values for the effect sizes of visuospatial storage and visuospatial CE (visuospatial storage $I^2 = 50.05$ and visuospatial CE $I^2 = 67.58$), indicating that there was substantial variability among the effect sizes within both components of visuospatial WM (Higgins et al., 2003).

3.2. *Interactions*

To explain the nonhomogeneity in the effect sizes found for the children's visuospatial storage, on the one hand, and their visuospatial CE, on the other hand, we examined factors that could possibly contribute to or interact with the visuospatial deficits observed in the children with SLI. To avoid a "fishing trip" or undirected search for possible correlations, we examined only two factors: the SLI inclusion criteria used in the studies and the ages of the children studied.

3.2.1. *Relations to inclusion criteria for SLI*

To investigate whether the variability in effect sizes related to the different inclusion criteria used for SLI, we divided the studies into two clusters: one cluster was composed of studies with the criterion of at least one affected language domain for inclusion in the SLI group; the other cluster was composed of studies with the criterion of two or more affected language domains for inclusion in the SLI group.

For the visuospatial storage component, the effect sizes for the two clusters were significant; the children in both clusters performed significantly below their TD peers ($Z = 3.34$, $p = .001$ for 1 language domain and $Z = 5.24$, $p = .000$ for 2 language domains). The cluster of studies that included children with deficits in two or more domains of language yielded the largest effect size ($d = 0.32$ for 1 language domain and $d = 0.70$ for 2 language domains). The between-groups homogeneity test was also significant ($Q = 5.59$, $p = .018$), which shows the inclusion criteria for SLI to explain a significant amount of the variability in the effect sizes for visuospatial storage.

For the visuospatial CE component, the effect size was nonsignificant for the cluster of studies that included children with deficits in at least one domain of language ($d = 0.78$, $Z = 1.95$, $p = .052$). The effect size for the cluster of studies that included children with deficits in two or more domains of language was significant ($d = 0.54$, $Z = 2.29$, $p = .021$). This shows the visuospatial CE of these children to be significantly below that of their TD peers. The between-groups homogeneity test was nonsignificant ($Q = 0.28$, $p = .597$). This indicates the inclusion criteria for SLI did not explain a significant amount of the variability in the effect sizes for visuospatial CE. Stated differently, the deficits in visuospatial CE are not related to the inclusion criteria for SLI.

3.2.2. *Relations to age*

We next conducted meta regression to determine if the magnitude of the effect sizes in visuospatial storage and visuospatial CE possibly declines or increases with age. The regression models for both visuospatial storage and visuospatial CE were nonsignificant ($\beta = -.003$, Z = −0.73e, $p = .466$ and $\beta = .005$, $Z = 1.03$, $p = .303$, respectively). These results indicate that differences in age do not produce significant differences in the effect sizes for either the visuospatial storage or visuospatial CE component.

4. Conclusions and discussion

In this meta-analysis, we compared the visuospatial WM performance of children with SLI to that of TD peers. The weighted mean effect sizes for the visuospatial storage component ($d = .49$) and the visuospatial CE component ($d = .63$) were both significant. The children with SLI performed approximately one half standard deviation below their TD peers on average for both components of visuospatial WM. This finding suggests that children with SLI have not only smaller storage but also processing capacities for visuospatial information.

Although there was previously no consensus across studies on the role of visuospatial WM in children with SLI, the current findings clearly suggest that the visuospatial WM is affected in these children. This implies that the deficits in WM in children with SLI may not be not restricted to the verbal domain. However, when we compare the *magnitude* of the WM deficit in the two modalities, the deficit for visuospatial WM is not as large as the deficit for verbal WM. In a meta-analysis of non-word repetition as a measure of the verbal storage component of WM, Graf Estes, Evans, & Else-Quest (2007) found the weighted mean effect size for the deficit in verbal storage to be as large as $d = 1.27$. As it can be assumed that children with SLI are even more severely impaired on verbal CE than on verbal storage (Archibald & Gathercole, 2006a; Ellis Weismer et al., 1999; Marton & Schwartz, 2003), this suggests that the deficit in verbal WM is two to three times larger than the deficits in visuospatial WM that we found. Fifteen of the 21 studies that we analyzed also had verbal WM tasks available for analysis. We therefore took the time to calculate the effect sizes for these verbal tasks and found a weighted mean effect size of $d = 1.19$ with a range of $d = .57$ to $d = 3.14$. This confirms our suspicion that the deficit in the verbal WM of children with SLI can be two to three times larger than the deficit in their visuospatial WM.

The magnitude of the effect sizes for the 21 studies (including 32 visuospatial storage tasks and 9 visuospatial CE tasks) that we analyzed varied greatly and ranged from $d = -.50$ (showing children with SLI to perform one-half standard deviation better than their TD peers) to $d = 1.53$ (showing children with SLI to perform more than one and a half standard deviation below their TD peers). We therefore conducted moderator analyses in an attempt to explain some of this variation in the effect sizes.

The first moderator analysis addressed the question of whether the differences in the visuospatial WM for the children with SLI possibly relate to differences in the inclusion criteria used for SLI in the studies. This was found to be the case for visuospatial storage but not for visuospatial CE. The effect size for visuospatial storage was greater for studies that included children with deficits in two or more language domains ($d = .70$) than for studies that included children with a deficit in at least one language domain ($d = .32$). These results partially confirm our hypothesis that the visuospatial WM performance of children with SLI relates to the inclusion criteria used for SLI and thus the pervasiveness of language impairment. The deficit in visuospatial storage was found to be larger in children with widespread language impairment. These results are in line with a previous study showing a subgroup of children with SLI (i.e., children with more pervasive problems affecting both receptive and expressive language) to also experience visuospatial storage problems (Nickisch & Von Kries, 2009).

The results of this first moderator analysis, concerned with the relations between the inclusion criteria for SLI and the children's visuospatial WM, must be interpreted with caution. Firstly, the division of the studies in studies that included children with impairments in at least one domain of language in the SLI group versus those that included children with impairments in two or more domains of language may have allowed overlap. As not all of the studies in the first cluster included only children with an impairment in a single language domain (but, rather, at least one domain), it is possible that children with impairment in two or more language domains were inadvertently included in this first cluster. Second, the number of studies of visuospatial CE among children with SLI affected in a minimum of one domain of language was quite small. This could explain the finding of a nonsignificant effect size. Furthermore, the severity and nature (i.e., which linguistic domains are affected) of language impairments were not taken into account in this analysis although this could certainly be other important predictors of the pervasiveness of language impairment and thus relate to visuospatial WM. Finally, it cannot be completely ruled out that the included studies, besides differences in the inclusion criteria for SLI, also differed on other non-measured variables. So, the observed association between the inclusion criteria for SLI and the differences in visuospatial storage, might also reflect some other systematic influences.

The second moderator analysis addressed the question of whether age differences in the visuospatial WM capacities of children with SLI exist. We found no significant association between the age of the children with SLI and the effect sizes for either visuospatial storage or visuospatial CE. This means that age cannot explain the variation in the effect sizes across studies. This finding does not support our hypothesis that the visuospatial WM deficit in children with SLI would be larger in older children. The visuospatial WM performance of children with SLI apparently does not decline with age but, rather, remains stable. This finding is in line with other findings regarding the verbal WM of children in general and those with SLI in particular. In their meta-analysis of children's nonword repetition, Graf Estes et al. (2007) found the magnitude of the deficit in the verbal storage component of WM also remains stable across age. The present cross-sectional findings must still be interpreted with caution and further conclusions can only be drawn when we have longitudinal insight into the visuospatial WM performance of children with and without language impairments.

Taken together, the results of our meta-analysis demonstrate deficits for both visuospatial storage and visuospatial CE in children with SLI. This outcome suggests that children with SLI have a smaller capacity for both the storage and processing of visuospatial information than children without SLI. More generally, this outcomes suggests that the WM deficits of children with SLI are not restricted to the verbal domain, and that SLI may thus be associated with domain-general impairments of WM. The results of our meta-analysis also show the deficit in visuospatial WM to be stable across development. The magnitude of the deficit in visuospatial storage, in particular, is correlated with the inclusion criteria for SLI: greater impairment of the children's visuospatial storage capacity was associated with more pervasive language impairment.

Our finding of apparently general WM impairments in children with SLI suggests that the language-specific nature of the diagnosis can be brought into question. "*Specific* language impairment" may no longer be the most appropriate term for the pattern of impairments demonstrated by children with so-called SLI. Although children with SLI show more substantial deficits on tasks requiring verbal WM than on tasks requiring visual WM (i.e., the extent of the deficit in verbal WM is two to three times larger than the extent of the deficit in visuospatial WM), their impairments are increasingly being seen to not be completely specific to language or the processing of strictly verbal information. The current results suggests that—for at least some children—the term "primary" language impairment might be more appropriate than "specific" language impairment (Edwards & Munson, 2009).

The implications are not straightforward for our finding of domain-general impairment of WM in children with SLI because different explanations are available for this outcome. One possibility is that the impairments in the visuospatial WM capacities of the children with SLI reflect limitations on their general processing capacity. Children with SLI may actually shows problems in *both* verbal and visuospatial domains when processing load is high (Ellis Weismer, 1996; Fazio, 1998; Hoffman & Gillam, 2004; Montgomery, 2000, 2002). Stated differently, children with SLI can adequately process single bits of information but encounter problems when they have to process multiple bits of information or, in other words, more complex information. Evidence for this account comes from studies showing children with SLI to indeed have problems on both verbal and visuospatial tasks with higher processing loads (Ellis Weismer, 1996; Fazio, 1998; Hoffman & Gillam, 2004; Marton & Schwartz, 2003; Montgomery, 2000, 2002). In a recent study by Leclercq, Maillart, Pauquay, and Majerus (2012), children with SLI were more strongly affected by stimulus complexity defined in terms of visual similarity and the number of similar/dissimilar features in a visuospatial storage task when compared to age-matched children without SLI. The authors suggest that stimulus complexity is a critical factor of the poor visuospatial storage performances in children with SLI and may therefore explain the conflicting results of previous studies with regard to the visuospatial WM performance of children with SLI. More research is required to identify whether visuospatial WM tasks requires 'more' processing in children with SLI in some way and what the exact role of factors like stimulus complexity is.

Another possibility is that the visuospatial WM system of the children with SLI is intact but that the steering of this system by the language system is problematic due to the children's SLI. This explanation hinges on whether the performance of the children on the visuospatial WM tasks genuinely reflects their visuospatial storage and processing, as we assumed, or possibly verbal mediation of visuospatial information. Some experts have indeed hypothesized that children with SLI show inefficient verbal coding during visuospatial WM tasks (Archibald & Gathercole, 2006b; Gillam et al., 1998). Given their language problems they may use less efficient verbal strategies or rely more than other children on visual codes when actually phonological codes are preferable. Although we excluded studies that easily invite for verbal coding in this meta-analysis, the possibility of verbal coding during the performance of visuospatial WM tasks can never be completely ruled out. However, inspection of the effect sizes shows deficits in visuospatial WM in several studies of children with SLI before the age of seven (Bavin et al., 2005; Gray, 2006; Hick et al., 2005a, 2005b; Kleemans et al., 2011). Given that verbal coding in visuospatial tasks is known not to occur in children before the age of about seven years, this does not support the inefficient verbal encoding explanation of the children's visuospatial WM impairments (Gathercole et al., 1994).

Yet another possibility is that that the impairments in the visuospatial WM capacities of the children with SLI are the reflection of limitations in attentional control. From this perspective, attentional control is assumed to be a regulator that plays an important role in the coordination of storage and processing in WM. This view is in line with accounts of WM that that highlight the notion of limited attentional resources (Courage & Cowan, 2009; Engle et al., 1999). It is known that visuospatial WM places particularly high demands on processes regulated by attentional control (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). And, in turn, the problems encountered by children with SLI in visuospatial WM tasks may therefore stem from problems with attentional control. This possibility is supported by the finding of attentional problems in children with SLI (Dodwell & Bavin, 2008; Finneran, Francis, & Leonard, 2009; Spaulding, Plante, & Vance, 2008; Noterdaeme, Amorosa, Mildenberger, Sitter, & Minow, 2001). In addition, when Marton (2008) compared children with SLI and good versus poor attentional control, the children with poor attentional control also showed greater problems on a visuospatial WM task. These findings call for additional research to explore the exact contribution of attention control to visuospatial WM in children with SLI.

The inclusion criteria used for SLI in the different studies included in our meta-analysis explained some of the variation in the effect sizes found for particularly visuospatial storage. Nevertheless, a significant amount of variation in the effect sizes remained unexplained. This indicates that there are other factors that affect the magnitude of the effect sizes found in the different studies. One additional factor that was not taken into account in the present meta-analysis is the type of control group. For inclusion in our meta-analysis, the performance of the children with SLI had to be compared to that of chronologically age-matched children without SLI. This was done because developmentally language-matched control groups were not available in all of the studies. We did not include type of control group as a factor in our moderator analyses because the inclusion of data from both age- and language-matched control groups would have violated the assumption of independent samples, which is a prerequisite for such an analysis. Four of the studies included in our meta-analysis nevertheless used both age- and language-matched control groups, which allows us to compare the effect sizes for visuospatial storage and visuospatial CE control. All of the effect sizes for the children with SLI compared to language-matched control children were negative (varying from $d = -.14$ to $d = -2.04$). This shows the children with SLI to perform better than the younger, language-matched children on visuospatial storage and visuospatial CE. In other words, children with SLI appear to be perform significantly worse than age-matched children and better than younger, language-matched children on visuospatial WM tasks. An important restriction on this conclusion is that differing linguistic skills were used across the studies to determine the language-matched control groups.

Other factors that might have affected the magnitude of the effect sizes discerned in this meta-analyses could be task characteristics, such as: type of stimuli, nature of the stimuli, duration of stimulus presentation, and task duration. Leclercq et al. (2012) have recently shown both degree of visual similarity (i.e., the overlap of visual features between two objects) and the number of features to determine visuospatial storage performance in children with SLI. Information on these variables was not included in our meta-analysis because the information was not provided in all studies and, in those studies that did provide task and stimulus information, the information was so different that systematic comparison was impossible. But in future research, this information should certainly be attended to.

In closing, the present findings obviously have some important implications for the assessment and treatment of children with SLI. For assessment in the future, visuospatial in addition to verbal WM tasks should probably be administered. The WM deficits of children experiencing language problems may not be restricted to verbal WM, and it is obviously important to know if the problems being experienced by a child are also with visuospatial WM. For treatment, interventions should probably not focus on language alone but also on strategies for the storage and processing of both verbal and visuospatial information. It is important that WM demands be minimized during teaching and treatment in order to limit the adverse effects of the WM deficits. For the use of visual support, which is a common intervention strategy adopted for children with SLI, the current findings indicate that children with SLI might not benefit from visual support as normal children do. This means that only certain types of visual support may be suited, namely: simple visual information that does not exceed the child's WM capacity. These clinical implications may particularly be important for children with complex pervasive language impairments. As children with more widespread language impairments appear to be more resistant to interventions, and the current results show greater impairment of visuospatial WM (or at least visuospatial storage) in these children, it might be valuable additions to more traditional interventions (Boyle, McCartney, O'Hare, & Law, 2010).

Finally, the present findings suggest a number of possible directions for future research. As the results of our meta-analysis show, the deficit in visuospatial storage might be larger in children with more pervasive language impairments. The associations between the impairments in visuospatial WM and different linguistic domains in children with SLI should therefore be examined in future research. Differences in the inclusion criteria for SLI reflected differences in the pervasiveness of the language impairments in the present research and were found to be associated with significant differences in the children's visuospatial WM performance. The association between receptive language problems and visuospatial WM might in particular be something to consider in future research. As the results of a previous study showed visuospatial storage to *only* be affected in children with a mixed pattern of receptive/expressive language problems, it might suggest a role of visuospatial WM in the receptive language problems of children (Nickisch & Von Kries, 2009). Furthermore, the role of attentional control certainly calls for further research as such a limitation may indeed contribute to problems with visuospatial WM.

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