THE JOURNAL OF
CHILD PSYCHOLOGY AND PSYCHIATRY

ACAMH

Journal of Child Psychology and Psychiatry 49:12 (2008), pp 1321–1330 doi:10.1111/j.1469-7610.2008.01917.x

Verbal short-term memory span in children: long-term modality dependent effects of intrauterine growth restriction

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Background: Recent reports showed that children born with intrauterine growth restriction (IUGR) are at greater risk of experiencing verbal short-term memory span (STM) deficits that may impede their learning capacities at school. It is still unknown whether these deficits are modality dependent. **Methods:** This long-term, prospective design study examined modality-dependent verbal STM functions in children who were diagnosed at birth with IUGR ($n = 138$) and a control group ($n = 64$). Their STM skills were evaluated individually at 9 years of age with four conditions of the Visual–Aural Digit Span Test (VADS; Koppitz, 1981): auditory–oral, auditory–written, visuospatial–oral and visuospatial–written. Cognitive competence was evaluated with the short form of the Wechsler Intelligence Scales for Children – revised (WISC-R95; Wechsler, 1998). **Results:** We found IUGR-related specific auditory-oral STM deficits ($p < .036$) in conjunction with two double dissociations: an auditory-visuospatial ($p < .014$) and an input–output processing distinction ($p < .014$). Cognitive competence had a significant effect on all four conditions; however, the effect of IUGR on the auditory-oral condition was not overridden by the effect of intelligence quotient (IQ). **Conclusions:** Intrauterine growth restriction affects global competence and inter-modality processing, as well as distinct auditory input processing related to verbal STM functions. The findings support a long-term relationship between prenatal aberrant head growth and auditory verbal STM deficits by the end of the first decade of life. Empirical, clinical and educational implications are presented. **Keywords:** Memory, growth restriction, longitudinal studies, auditory processing, prematurity, follow-up studies, information processing. **Abbreviations:** ADHD: attention deficit hyperactivity disorder; AO: aural–oral; AW: aural–written; BW: birth weight; EGA: estimated gestational age; IQ: intelligence quotient; IUGR: intrauterine growth restriction; MANOVA: multivariate analysis of variance; NS: not significant; STM: short-term memory; SDs: standard deviations; WISC-R95: Wechsler Scales of Intelligence-revised; VADS: Visual–Aural Digit Span Test; VO: visual–oral; VW: visual–written.

In view of the centrality of STM for multiple cognitive and socio-emotional functions (Curby & Gauthier, 2007; Wilding, Andrews, & Hejdenberg, 2007), recently there has been a growing interest in factors that affect STM. The current study is interested in modality-dependent effects on verbal STM in children with intrauterine growth restriction (IUGR). To the best of our knowledge, no studies based on a modality-dependent information-processing framework have previously been conducted on children with IUGR.

The study of high-risk populations may have important implications, both for the theoretical understanding of the systems involved in short-term memory (STM), and in the neuropsychological understanding of the developmental pathogenic processes affecting common resources and/or discrete STM systems in clinical populations (Gathercole, 1994; Pickering, Gathercole, & Peaker, 1998). STM is susceptible to an array of specific genetic, structural and nutritional aberrations [e.g., in children with Williams or Down syndrome (Purser & Jarrold, 2005; Vicari & Carlesimo, 2006); in children with autism (Mottron, Morasse, & Belleville, 2001), and in children who were diagnosed neonatally with IUGR (Geva, Eshel, Leitner, Fattal-Valevski, & Harel, 2006a].

Forward digit span tasks specifically, both verbal and visuospatial, have been shown to be sensitive to various risk factors, compared to other tasks that are more resistant to suboptimal congenital conditions (Wilde, Strauss, & Tulsky, 2004). Baddeley and Hitch's (1974) classical multi-component model offers a powerful framework for comprehending information processes required to manage a verbal STM, or a 'simple' working memory task (Repovs & Baddeley, 2006). According to this model, the phonological loop seems to be the most likely candidate to be activated in the processing of both auditory and visual verbal stimuli. Nevertheless, in visual conditions, activation of the bottom-up visual perceptual system related to the inner scribe component of the visuospatial sketch pad cannot be overlooked (Darling, Della Sala, & Logie, 2007). This component is responsible for active rehearsal of information held within a passive visuospatial cache,

Conflict of interest statement: No conflicts declared.

and is involved with extraction of information for execution of voluntary motor acts. Palmer (2000), who studied developmental changes in working memory phonological recoding of younger children (3–8 years of age), suggested that initially children use no strategy in recall. This is followed by a period in which a visual strategy prevails, followed by a period of dual visual–verbal coding before the adult-like strategy of verbal coding finally emerges. Thus, it seems that assumption of an immediate and automatic digit processing at the phonological loop needs to be carefully studied and validated in children who are diagnosed with an atypical neural-developmental process.

Verbal STM is a significant factor in a wide range of cognitive and learning domains. Studies have recently debated whether children with attention and learning deficits have modality-dependent STM deficits: for children with attention deficit hyperactivity disorder (ADHD): Kilic, Sener, Kockar, & Karakas, 2007; Messina, Tiedemann, de Andrade, & Primi, 2006; for children with hyperactivity: Ison, 2001; and for children with learning disabilities: Swanson & Saez, 2003. As these clinical groups may have been affected by multiple risk processes (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), it is important to complement this line of research with studies of verbal STM systems of prospectively recruited groups, whose STM functions are hypothesized to result from a known pathogenic process.

A good test case involves children who had been exposed to an aberrant nutritional, hormonal and metabolic uterine environment that resulted in IUGR. Children with IUGR arouse growing interest, since the IUGR condition is a more prevalent phenomenon than considered previously. IUGR has been reported in 3–10% of all live births; it is apparent in up to 18% of live births in developing countries (de Onis, Blossner, & Villar,1988); and is on the rise in the Western world due to the gradual increase in *in-vitro* fertilization, and thus in multiple-offspring pregnancies (Chen, Vohr, & Oh, 1993).

Fetal programming processes triggered as a response to this extreme intrauterine challenge have lifelong effects (Godfrey & Barker, 2000). IUGR-related adaptive processes operate to spare fetal brain size and brain functions, increasing fetal viability (Baschat et al., 2006). However, these processes are not effective in preventing specific neurological and neuropsychological deficits (Geva, Eshel, Leitner, Fattal-Valevski, & Harel, 2006a, 2006b; Leitner et al., 2000). Recent reports have indicated that children born with IUGR are at greater risk of experiencing verbal STM deficits by the end of the first decade of life (Geva et al., 2006a).

The current study examined modality-related STM functions of non-referred children diagnosed with IUGR compared with a control group. The Visual Aural Digit Span Test (VADS) was used as an exhaustive empirical tool exploring verbal STM processing by attempting to control for input- and output-related processing factors (auditory vs. visual presentation; and oral vs. written recall). In view of greater susceptibility of males to neonatal neuro-developmental deficiencies, and specifically to deficient verbal learning in children with attention deficits (Cutting, Koth, Mahone, & Denckla, 2003), the effects of gender on performance in this population were also explored (Brito, Alfradique, Pereira, Porto, & Santos, 1998).

Four non-exclusive hypotheses that differ in degree of specificity were examined. Firstly, *a general verbal STM deficit* (Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005), evident by: (a) lower VADS total score in children with IUGR compared with controls; (b) lowered scores on all measures, irrespective of condition; (c) cognitive competence and gender effects accounting for differences in VADS; and (d) a significant relationship among VADS measures. Secondly, *an integration processing difficulty hypothesis*, evident by depressed inter- or intra-sensory integration scores in the IUGR group in relation to controls, and by a significant difference between the integration composite scores in the IUGR group. Thirdly, *a modality specific deficit hypothesis*, evident by a significant difference between auditory and visual input, and/or between the oral and manual output measures, as a function of the group. These two latter hypotheses were also tested by a correlation analysis, which probes differences in the strength of a relationship as a function of the group, among these respective measures. Finally, *a specific aural–oral* (*AO*) *difficulty hypothesis*, evident by a discrete deficit in this condition, even when general cognitive ability is treated as a covariate.

Methods

Participants

This investigation is part of an extensive, large-scale prospective study regarding the effects of IUGR on long-term outcome. Families and the participating children were fully informed and expressed their consent to participate. Recruitment procedures and approval of the review board have been detailed in previous reports (Geva et al., 2006b; Leitner et al., 2000). The current study concentrated on STM data derived from 202 children who were born in the Tel Aviv area between January 1, 1992, and December 31, 1995. The experimental group was comprised of 138 children with IUGR (birth weight [BW] < 10th percentile), without co-morbidities, such as extremely low BW (Valcamonico et al., 2007) and extremely preterm birth.

Inclusion criteria were mid-second trimester to third-trimester onset IUGR (verified clinically and/or by ultrasound). Exclusion criteria were fetal infections, congenital malformations, and metabolic and chromosomal disorders at birth, e.g., fetal alcohol syndrome (Henderson, Gray, & Brocklehurst, 2007), and childhood central nervous system-related pathogenic processes unrelated to known fetal programming processes triggered by IUGR, such as meningitis, traumatic brain injury, or severe anomalies. Also excluded were children of teenage mothers (Wallace et al., 2006) or children of mothers who had poor prenatal or postnatal child-care (Ergaz, Avgil, & Ornoy, 2005). Thus, the effect of IUGR could be studied without effects of significant confounding infant- and familial-related factors.

The control group (n = 64) was comprised of children who were born with appropriate BW for their estimated gestational age (EGA). This group of 9-year-olds was randomly sampled according to birth registries in the same community in the Tel Aviv municipal area. The groups were comparable on multiple neonatal, familial and community-related variables (Table 1). As shown in Table 1, group means and distributions were comparable regarding neonatal/obstetrical, parental, familial and socioeconomic measures of EGA, maternal and paternal ages, maternal and paternal education, paternal occupation and socioeconomic variables regarding level of proficient work and family structure. As expected from the defining criteria, BW and head circumference differed in both groups. They also differed, as expected, in propensity for neonatal complications (Fattal-Valevski et al., 1999).

The groups were also similar in demographic and familial/parental stress measures and life stress, factors that may directly affect STM (Geva, Eshel, Leitner, Fattal-Valevski, & Harel, 2005; Table 2).

Mean cognitive competence of both groups was within normal range (Table 2). Cognitive competence that is lower than 2 standard deviations (SDs) below the expected range was rare (one participant from the IUGR group and none in the control group). Nevertheless, there were small differences in IQ between the groups. This finding corresponds with other IUGR cohorts (Paz et al., 2001).

Procedure

Digit span capacities were tested using the VADS. A standard administration procedure was selected (Kilic et al., 2007; Koppitz, 1975, 1981; Parasnis, Samar, Bettger, & Sathe, 1996). Each child was presented with digit spans of increasing lengths. After each trial was shown the child was asked to reconstruct the sequence in the same order. If performance matched the presented sequence, a ‘span + 1’ was

Table 1 Demographic description of the participating groups

Domain	Measure	IUGR (n = 138)	Control (n = 64)	p
Obstetric/neonatal	Birth weight	1839.8 ± 399.2 (<5th %tile)	2812.7 ± 755.4 (WNL)	<.001
	Neonatal head circumference (cm)	30.4 ± 1.9 (>10th %tile)	33.4 ± 4.2 (WNL)	<.001
	Complicated hospital stay (>3 complications)☐	18.1%	14.3%	NS
	Estimated gestational age	36.9 ± 2.4	37.6 ± 3.4	NS
	Prenatal complications score☐	8.7 ± 6.8	11.2 ± 8.1	NS
	Neonatal complications score☐	19.4 ± 12.2	15.9 ± 20.5	NS
	Prematurity (>37)	26.4%	26.6%	NS
	Extremely low birth weight (<750 g. %)	.009	0	NS
	Parity (%)	.23	.38	NS
Parental	Maternal age at delivery	30.5 ± 5.8	30.5 ± 4.6	NS
	Maternal education (years)	13.0 ± 2.3	13.5 ± 3.6	NS
	Maternal education (years)	13.0 ± 2.3	13.5 ± 3.6	NS
	Paternal education (years)	13.0 ± 2.6	13.2 ± 2.7	NS

IUGR = intrauterine growth restriction; WNL = within normal limits; NS = non-significant.
☐Adapted from Fattal-Valevski et al. (1999).

Table 2 Group characteristics at 9 years of age

Domain	Measure	IUGR (n = 138)	Control (n = 64)	p
Demographic	Gender (M)	44.9%	42.9%	NS
	Age at test (months)	112	111	NS
	Mean IQ	101.12 ± 13.8(WNL)☐☐	107.11 ± 10.8(WNL)	<.001
	IQ < 70	.6%	0%	NS
Parental	Parental stress index	208.7 ± 42.9(40th %ile)	209.4 ± 43.3(40th %ile)	NS
	☐☐Total			NS
	Child domain	95.2 ± 24.3(42nd %ile)	90.7 ± 21.2(27th %ile)	NS
	Parental domain	118.3 ± 29.8(60th %ile)	113.4 ± 21.9(47th %ile)	NS
	Life stress	8.7 ± 7.9(60th %ile)	6.8 ± 4.2(55th %ile)	NS
☐☐Familial-Community	Socioeconomic status$^{\Delta}$	1.5 ± 1.1	1.6 ± 1.2	NS
	Number of children in family	2.3 ± 1.0	3.8 ± 1.2	.001
	Child's place in family	2.0 ± 1.1	2.0 ± .8	NS

†Adapted from Fattal-Valevski et al. (1999). Coded on a 9-level scale (1 = non-proficient, 2 = proficient, 3 = farmer, 4 = hand artisan, 5 = salesman, 6 = clerkship, 7 = managerial, 8 = free profession, 9 = academic research); $^{\Delta}$composite score based on maternal education parental occupation and welfare aid; ☐☐ = Parental Stress Index scores (3rd edition; Abidin, 1995); IUGR = intrauterine growth restriction; IQ = intelligence quotient; WNL = within normal limits; NS = non-significant.

administered; if the response was incorrect, an additional sequence with identical span length was introduced. Each subject was instructed to respond immediately after the series was completed. Each condition was terminated when two trials of equal spans were not recalled correctly. Scoring was dependent upon the maximum correct response to span length. The test comprised four conditions: 1) aural–oral (AO) span condition: Aural stimuli were presented at a rate of one digit per second in a monotone intonation and constant volume. The child was asked to repeat the sequence orally immediately after the examiner completed presentation of the full span. The interval between stimuli series and response was subject-controlled; 2) visual–oral (VO) span condition: the child was shown a series of white cards. Each card contained a printed (72-point black font) DS that was presented for 10 seconds. At that point, the card was instantly covered and the child reiterated the series orally; 3) aural–written (AW) span condition: Spans were presented aurally as depicted in condition AO, and the child was asked to write the sequence on a blank sheet of paper as soon as the examiner completed utterance of the sequence; 4) visual–written (VW) span condition: Stimuli were set as in condition VO. The child was asked to respond orally as in condition AW. All conditions were introduced in a fixed order. Administration order was conditions 1, 2, 3 and finally 4, as is advised in the test's manual (Koppitz, 1977). Live presentations were chosen in order to ensure maximal attention (Roebers, Gelhaar, & Schneider, 2004) and to comply with a standard administration mode.

The task yields four measures for testing conditions, and seven composite scores. The composite scores were four modality-dependent input–output summary scores [aural input=AO+AW; visual input = VO+VW; oral output = AO+VO; written output = AW+VW]; two integration scores [inter-sensory integration scores=VO+AW; intra-sensory integration scores= AO+VW], and finally, a total score = AO+VO+AW+VW].

The dependent measures were the number of items recalled. Since the range of scores could theoretically differ across conditions owing to procedural differences among conditions (e.g., different encoding times in aural and visual conditions), age-dependent standardized percentile scores (Koppitz, 1981) were used for analyses of differences among conditions.

Cognitive competence was evaluated using the Wechsler Intelligence Scale for Children – revised (WISC-R 95; Wechsler, 1998) (Hebrew version) short form (Ryan, Utley, & Worthen, 1988).

Results

All 202 subjects completed the full procedure. Descriptive statistics show that VADS mean raw scores on the four test conditions for the IUGR and the control groups were: for AO: 4.88 ± 1.0 for the IUGR and 5.21 ± .8 for the control group, $F = 5.917$, $p < .016$, respectively; for VO: 5.72± 1.0 and 5.89 ± .8, respectively, $F = 1.545$, p = NS; for AW: 4.94 ± 1.1 and 5.18 ± .8 respectively, $F = 2.552$, p = NS; and for VW: 5.52 ± 1.1 and 5.76 ± 1.0 respectively, $F = 2.25$, p = NS.

To test the hypotheses, the differences between conditions of the VADS were analyzed with group as an independent variable using a multivariate analysis of variance (MANOVA) of age-dependent standardized percentile scores. The analysis showed that the model is significant in explaining group differences in the variance, on six measures. The dependent measures that were significantly related to the effect of IUGR were: 1) VADS total score (Figure 1; $F = 3.89$, $p < .05$); 2) inter-sensory integration (rather than intra-sensory integration, Figure 1, $F = 8.924$, $p < .003$); and three of the four modality-specific variables (Figure 2), auditory input ($F = 11.039$, $p < .001$), visual input ($F = 5.977$, $p < .015$); and the written output measure ($F = 4.963$, $p < .027$, respectively). Of the four test conditions (Figure 3), the AO span and the AW span scores were significantly related to IUGR (Figure 3; $F = 5.937$, $p < .016$; and $F = 4.975$, $p < .027$, respectively).

In order to control for possible effects of gender and effect of global competence on outcome (Gathercole, Pickering, Ambridge, & Wearing, 2004), a multivariate analysis of covariance with estimated

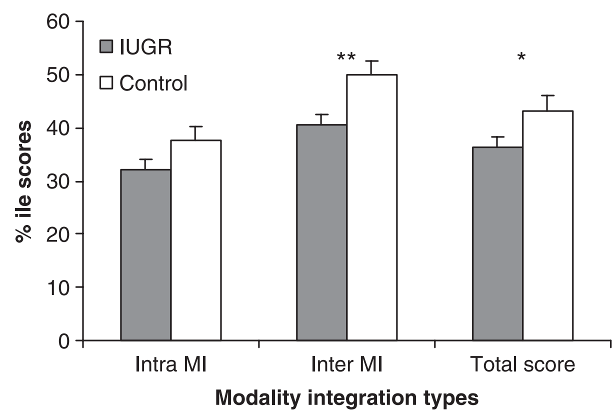

Figure 1 Total summary integration VADS scores as a function of group. MI = modality integration

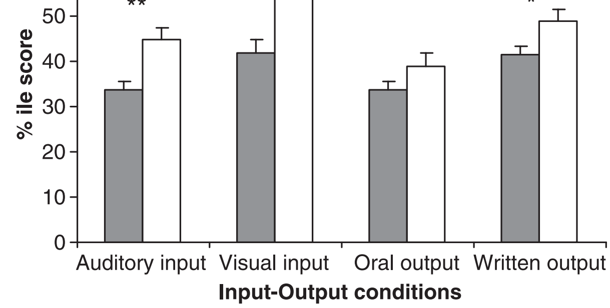

Figure 2 Input–output VADS summary scores as a function of group

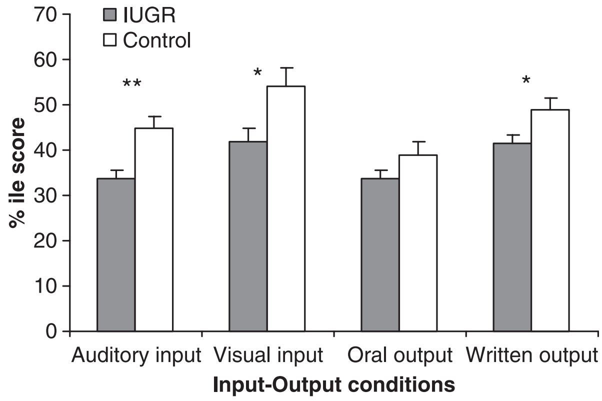

Figure 3 Span scores as a function of group and testing condition

IQ score and gender factor was conducted. Analysis showed that the significant effect of IUGR on the auditory input variable remained ($F = 4.133$, $p < .043$), even after the adjustment of the scores for the effects of general cognitive ability and gender. Performance on the auditory input measures of the IUGR group was below the expected level (mean percentile score for age = 33.757 ± 21.8794) and that of the control group was within expected percentile level for age (mean score = 44.734 ± 21.775; Figure 3).

Results of this analysis also showed that IQ, which was within normal range in both groups, but lower in the IUGR group (Table 2), was significantly related to *all* VADS-dependent measures (*F*s range between 33.567 and 8.831; all *p*s were < .001). The gender effect was significant on the written output measures ($F = 5.865$, $p < .016$). There was no significant interaction between IUGR and gender on any of the outcome measures. We thus proceeded to conduct a MANOVA on the gender effect, which revealed that males had lower scores than females on the written output measure (mean score for males was 39.323 ± 2.303 percentile and for females 46.839 ± 2.065 percentile; $F = 5.865$, $p < .016$).

Frequency of deficient performance as a function of IUGR

In view of the special interest in targeting susceptibility to perform below the typical range, a cross-table frequency analysis as a function of group was conducted. Raw spans that were between 0 and 3 in each of the four VADS conditions were scored as atypical (cutoff point based on the distribution function by Karakas, Yalin, Irak, & Erzengin, 2002); a span of four items was scored as borderline; and spans of at least five items were scored as typical. Chi square analysis for distribution differences between the groups showed that spans of up to three items were *extremely rare* in the control group: only 1 of the 64 subjects in the control group scored within this range in the AO and VW conditions.

Atypical spans in the IUGR group were significantly more frequent. Atypical spans were noted in the AO condition (8.7% of the IUGR group vs. 1.6% in the control group) and in the AW (7.2% of the IUGR group vs. 0% in the control group). The risk for atypical/borderline spans was at least twofold greater for children in the IUGR group, in relation to children in the control group. This risk totaled one-third of the group in the AO and the AW conditions (34.8% of the IUGR group vs. 17.2% of the controls, $\chi^2 = 7.470$, $p < .024$; and 37.6% vs. 17.2%, respectively, $\chi^2 = 10.231$, $p < .006$, respectively).

Analysis of performance in the atypical range also showed a significant gender effect on the AO condition, such that 11.1% of the males vs. 2.7% of the females scored in the atypical level ($\chi^2 = 7.175$, $p < .028$).

Relationships among modality-dependent verbal STM conditions

To assess the hypothesis that a general storage capacity of STM may be reflected in significant relationships among the dependent measures of the test, a correlation matrix was examined (Table 3). The table showed that there were significant correlations between VADS comparison variables in both groups. Significant moderate correlations were found between auditory conditions in both groups ($r = .477$, $p < .001$ for the IUGR and $r = .362$, $p < .003$ for the controls) and a similar slightly stronger correlation between visual conditions in both groups ($r = .527$, $p < .001$ and $r = .460$, $p < .001$, respectively).

The input–output correlation comparisons revealed a difference between the groups. For comparison between oral conditions: A moderate correlation was found between the oral conditions for the IUGR group ($r = .461$, $p < .001$), but there was *no* correlation between the oral conditions in the control group. Similarly, comparison between written-output conditions showed that there was a moderate correlation in the IUGR group ($r = .458$, $p < .001$) and a weaker relationship in the control group ($r = .299$, $p < .016$). This difference between the groups in degree of relationship between each output modality condition may indicate a significant limiting factor, such as a greater dependence on input encoding in the IUGR group relative to the controls. We thus tested the correlations between auditory and visual input conditions and found that they were strong in the IUGR group ($r = .618$, $p < .001$) and moderate in the control group ($r = .431$, $p < .001$). A somewhat stronger relationship was found in both groups between output modalities relative to the correlations between the input conditions ($r = .618$, $p < .001$ vs. $r = .653$, $p < .001$ for the IUGR group; and $r = .431$, $p < .001$ vs. $r = .584$, $p < .001$ for the controls, respectively).

Finally, the correlation between the two integration scores, the intra- and inter-sensory integration

Table 3 Correlation matrix among VADS-dependent measures for the intrauterine growth restriction (IUGR) and control groups

VADS-dependent measures comparisons	Pearson r in IUGR group (p<)	Pearson r in control group (p<)	Fisher Z	p (2-tailed)
Inter modality and Intra modality- integration	**0.572 (0.001)**	**0.819 (0.001)**	**−3.26**	**0.0006**
Auditory-oral/Auditory-written	**0.477 (0.001)**	**0.362 (0.003)**	0.91	0.362 NS
Auditory input/Visual input	**0.618 (0.001)**	**0.431 (0.001)**	1.69	0.091 NS
Oral expression/Written expression	**0.653 (0.001)**	**0.584 (0.001)**	0.73	0.465 NS
Auditory-oral/Visual-oral	**0.461 (0.001)**	0.206 (0.102 (NS)	1.88	0.060 NS
Auditory-written/Visual-written	**0.458 (0.001)**	**0.299 (0.016)**	1.21	0.226 NS
Visual-oral/Visual-written	**0.527 (0.001)**	**0.460 (0.001)**	0.57	0.568 NS

VADS = Visual–Aural Digit Span Test; NS = non-significant; Bold = $p < .05$.

conditions, revealed a moderate relationship in the IUGR group and a *strong* relationship in the control group ($r = .572$, $p < .001$ and $r = .819$, $p < .001$, respectively).

The significance of the differences between correlation coefficients in each of these comparisons was calculated using the Fisher Z transformations with a VassarStats program (Lowry, 1999; Ramseyer, 1979) (Table 3). Analysis showed that the correlation between the intra- and inter-sensory integration scores in the control group was significantly higher than this correlation in children with IUGR. Fisher *Z* transformation test for the difference between the *r*-values of the two groups was highly significant ($Z = -3.26$, $p = .0006$).

Pearson correlation for the two groups regarding modality-dependent inputs, modality-dependent outputs, and modality type (auditory or visual) were moderate for both groups, ranging from .206 to .673, *p* ranged from not significant (NS) through $p < .001$. Fisher *Z* transformations for the differences between *r* value comparisons between the two groups regarding modality-dependent inputs–outputs, and modality type (auditory or visual) showed that these correlations were not different from each other.

Predicting models of VADS performance as a function of IUGR

In order to test the predictive power of the group to account for VADS total score, a hierarchical regression analysis was conducted (Table 4). The group factor was entered in the first step, gender in the second, and estimated concurrent IQ score in the third step. The analysis showed that the group factor predicted VADS total score significantly and its effect was essentially irrespective of gender. However, the group factor was no longer significant after IQ score was entered into the analysis in the final step, indicating that the effect of IUGR on the VADS total score is accounted for by a covariance between the IUGR variable and IQ.

The same hierarchical regression analysis was conducted to predict the auditory input variable, with group entered into the first step, gender in the second and finally the concurrent IQ score. This revealed a different pattern of results (Table 4). The analysis showed that IUGR significantly predicted auditory input. Gender had no significant effect on this measure. Addition of IQ in the model weakened the effect of IUGR. However, the effect of IUGR on auditory input remained significant (Table 4).

Table 4 Summary of hierarchical regression analysis for variables predicting VADS total score and the auditory input score ($n = 202$)

Model	Total score	AI
Variable	β	β
Step 1		
Group	0.193**	0.232***
Step 2		
Group	0.189***	0.230***
Gender	0.136*	0.087 NS
Step 3		
Group	0.085 NS	0.135*
Gender	0.139*	0.090 NS
IQ at 9 years	0.421***	0.384***

VADS = Visual–Aural Digit Span Test; NS = non-significant; IQ = intelligence quotient; AI = auditory input score.
Notes: Total score prediction model: $R^2 = .037$ for step 1 ($p < .006$); $\Delta R^2 = .019$ ($p < .05$) for step 2; $\Delta R^2 = .175$ ($p < .001$) for step 3; *$p < .05$; **$p < .01$, ***$p < .001$; *Auditory input model:* $R^2 = .057$ for step 1 $p < .001$); $\Delta R^2 = .008$ (NS) for step 2; $\Delta R^2 = .139$ ($p < .001$) for step 3; *$p < .05$; ***$p < .001$.

Discussion

The primary aim of this study was to explore modality-dependent verbal STM in children with IUGR, using comparable verbal stimuli presented either orally or visually, and a requirement for oral or written responses. All subjects ($n = 202$) engaged well with the interactive nature of the task, and completed all items. Nevertheless, children with IUGR had greater verbal STM difficulties than those of a carefully matched control group. Analysis showed that of the four VADS test conditions, the AO condition was most susceptible to effects of IUGR. Four hypotheses, gradually ranging from global resource abilities to a discrete deficit, were tested as possible mechanisms that accounted for the AO STM deficit: global competence-related difficulty, integration-processing deficit, modality specific deficit, and a specific AO difficulty.

The results showed that modality-specific effects on STM were noticeable in the IUGR group. More specifically, IUGR was related to difficulties with verbal STM conditions that were dependent upon auditory input relative to visuospatially presented digit stimuli. Can this finding be theoretically understood in view of Baddeley and Hitch's (1974) model? Further research is required to address this question. The current observations seem to be in line with the idea that visual conditions may have more readily evoked dual coding, yielded better performances in both groups, and minimized IUGR effect on STM, even when scores were not analyzed in absolute values, but as standardized percentile scores.

However, this effect may be due to procedural differences. In the current paradigm used, in the visual encoding conditions the digits were presented simultaneously, and not sequentially, as in the auditory encoding conditions. This difference may have evoked dissimilar encoding strategies. Even though analysis was conducted using standardized percentile scores rather than a count of the items recalled, procedural difference may have allowed children to better compensate for their relative difficulty, so that their performance in visual conditions approached a typical level of performance – a level expressed more frequently by children in the control group.

This explanation assumes a greater credence for an encoding difficulty in children with IUGR. It would lead to a prediction of a significant input–output discrepancy as a function of the group (i.e., significant IUGR effect on input, and not on output variable). This discrepancy has indeed been partially supported by the current data. Initial analysis showed an IUGR effect on both input measures but there was also an IUGR effect on the written output measure. Further analysis with gender and IQ as covariates showed that the IUGR outcome affected the auditory input domain beyond the variance explained by cognitive competence. Nevertheless, since auditory stimuli were presented for short durations, a processing speed deficit hypothesis selectively affecting the auditory stimuli may not yet be fully excluded.

Is the difficulty restricted to an IUGR-related input effect, or is it evident in integration and processing of output? A portion of the analysis also points to a possible processing and trans-coding effect. A strong correlation was found at the .8 level between inter- and intra-sensory integration variables in the control group. This relationship was significantly weaker in the IUGR group. The difference between correlation strengths was highly significant. Following Gathercole et al.'s (2004) interpretation of similar correlation analyses, the high correlation observed in the control group may indicate a strong effect from a common source. A good candidate for a common source active in this STM input–output integration process in the control group may be the activation effect of the phonological loop (Baddeley & Hitch, 1974). Hence, it is theoretically plausible that the current data of the controls is related to activation of the phonological loop, almost irrespective of modality. At the same time, it may very well be that the presence of a much weaker relationship between inter- and intra-modality scores in the IUGR group could be a reflection of a deficient activation of the phonological loop across conditions in the IUGR group. The current data set cannot fully address this issue without additional research.

Is it possible that this hypothesis of an inefficient activation of the phonological loop in children with IUGR represents a deficit, or a developmental lag? Resolution of this issue is, yet, premature as well. The automatic and immediate activation process of the phonological loop is a developmental process that is expected to stabilize from 7 years of age onward (Gathercole, 1998). Findings of the present study may indicate a lack of stability of phonological loop activation in 9-year-old children neonatally diagnosed with IUGR. The findings are in line with either a deficit in the development of a phonological loop network, or a significant developmental lag in the maturation of this system due to a long-term fetal programming process. Indeed, lifespan changes in digit span capacity are expected in 'typically' developing adults (Karakas et al., 2002). A longer follow-up, prospective study on these subjects with IUGR may shed further light on this issue.

Is this difficulty with auditory stimuli, compared to visual stimuli, to be developmentally expected? It does not appear to be so. Studies show a consistent advantage of the verbal span over the spatial span in typically developing children aged 5–13 years of age (Marcell & Weeks, 1988; Nichelli, Bulgheroni, & Riva, 2001). This difference, otherwise known as 'the modality effect', does not support the hypothesis that the visuospatial advantage demonstrated by children with IUGR reflects a developmental lag, but rather a deficit.

The fourth hypothesis regarding a specific deficit in the AO combination was also supported. The AO condition was the most susceptible, as evident by the existence of a degree of vulnerability in both groups, but significantly more affected by IUGR. It is likely that the deficit seen in children with IUGR in processing stimuli in the auditory modality is not restricted to STM processing, but rather is an integral part of a verbal deficiency related to IUGR. This hypothesis merits further research with other auditory processes, as it complements recent findings regarding clinically referred children diagnosed with ADHD (Messina et al., 2006).

Clinical implications

The findings underscore the susceptibility of children, diagnosed neonatally with IUGR, to an auditory input-dependent deficient verbal STM. It has been shown that an AO deficit accounts for some of the increased risks of developing reading and spelling disabilities (Amitay, Ahissar, & Nelken, 2002; von Suchodoletz, Berwanger, & Mayer, 2004). In view of the importance of auditory STM skills in conversing in general and in class, this may account for some of the reported difficulties experienced in school by children with IUGR (Low et al., 1992; van Wassenaer, 2005; Geva et al., in press).

The current findings have direct intervention implications in view of preserved intra-sensory integration found in the current study, and previous reports of spared learning from repeated exposure (Geva et al., 2006a). To improve processing and learning by children born with IUGR, intervention may prove more successful when teaching efforts are not necessarily directed at presenting simplified sequences, but rather via use of complementary visuospatial cues.

Future directions of research

To better equate similar encoding opportunities of auditory and visual stimuli, a presentation of sequential visual items on a computer screen may be considered. Furthermore, to test whether the effect seen is limited to verbal auditory STM, or is a more generalized auditory deficit, it is advisable to test non-verbal auditory spans of children with IUGR. Further work with non-verbal stimuli using other modalities may shed light on this new direction of research in children with IUGR. Finally, a thorough study of verbal skills of children with IUGR may indicate whether this deficit is a discrete one or rather part of a deficient verbal system.

Conclusions

Overall, we have presented support for concurrent effects of both global resources (cognitive competence and inter-modality processing), as well as distinct auditory input processing-related functions that are related to a prenatal intrauterine environment. The findings complement reports that are indicative of the relationship between aberrant head growth and STM deficits (Geva et al., 2006a) and reports for specific genetic syndromes and congenital conditions that compromise STM (Purser & Jarrold, 2005; Vicari & Carlesimo, 2006). Comparison between performances on the STM tasks in previous studies demonstrated evidence of a neurogenetic double dissociation between short-term STM for verbal and visual-spatial stimuli (Wang & Bellugi, 1994). The current findings are in line with the thought that dissociation between modalities may occur also *within* the verbal system following adverse intrauterine conditions. In light of the findings, studies of stimuli type and modality-dependent information processing deficits in populations who are susceptible to deficient development due to prenatal and/or postnatal challenges are encouraged.

Acknowledgements

We would like to express our warmest gratitude to the participating families who persevered with us throughout a decade, and the laboratory staff at the Lis Maternity Hospital and the Child Development Center for their assistance in conducting the research. This study was funded by the Gulton Foundation, New York, USA.

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Manuscript accepted 12 February 2008